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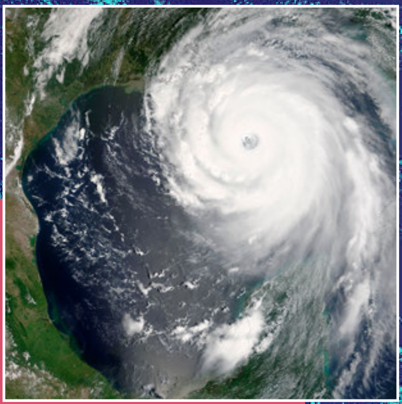
SPACE TECHNOLOGIES FOR EARLY WARNING SYSTEMS

UNITED NATIONS



Hurricane Katrina
approaching the Gulf Coast
Credit: NASA

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Foreword

Credit: UNOOSA/Andrew Peebles

For decades, the space community has helped save lives, prevent and mitigate damages, and reduce disaster risks by contributing to and improving the global understanding of natural hazards. Today, space assets, varying in typology and orbital placement, observe all regions of the Earth and transmit signals from sensors in remote areas to observatories for subsequent monitoring and early warning across continents in case of tsunamis and other hazards. Disaster response and recovery also rely significantly on global navigation satellite systems (GNSS) as they allow for the monitoring of surface processes and the precise location of critical infrastructure and places essential for providing humanitarian assistance.

This transformative power of space assets must be made available to everyone. Universal access to these space solutions, however, remains far from reality despite great strides globally. The Office for Outer Space Affairs, through the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), which was established in 2006, works to advance access to a vast range of space-based information and services relevant to disaster management to support the full disaster management cycle.

The Office is proud to have supported over 40 countries since the inception of the programme in advancing their preparedness to tackle disaster risks and we remain committed to making the benefits of space, not least for disaster management and emergency response, universally accessible through our capacity-building efforts. With the adoption by the General Assembly in 2021 of the "Space2030" Agenda: space as a driver of sustainable development, the mandate was further solidified as Member States set as one of the goals to strengthen the use of integrated space applications to facilitate the observation of the climate and the assessment of disaster risks, to improve early warning disaster systems, and to use space-based technologies in all phases of the disaster management cycle.

This publication on *Space Technologies for Early Warning Systems* compiles many examples of ways in which the space community is broadening the spectrum of applications of space-based data, information, services and products in all areas of effective, people-centred early warning systems. The publication serves as a contribution from the Office and its UN-SPIDER programme to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030, and to the "Early Warnings for All" initiative recently launched by the Secretary-General.

The information contained in this publication can be used by agencies and institutions that are contributing to enhancing the resilience of communities worldwide through the implementation and routine operation of effective early warning systems. From the perspective of the Office, we look forward to the implementation of the global frameworks and the achievement of their pledges and remain committed to delivering high-quality capacity-building activities and engaging with the international space community for the benefit of United Nations Member States. I hope that this publication inspires the space community to continue exploring novel efforts and solutions to advance our disaster preparedness and promote their adoption and utilization around the world.

Aarti Holla-Maini
Director, Office for Outer Space Affairs

Foreword

Credit: UNISDR/Antoine Tardy

The rising human and economic cost of disasters is a threat both to people everywhere and to the achievement of the Sustainable Development Goals. These disasters, which have nearly doubled this century as a result of climate change and unsustainable development, impact all countries but are especially devastating for the poorest, who continue to suffer the highest disaster mortality rates.

Among the solutions for countries to adapt and reduce the risks of such disasters, early warning systems stand as among the best. They not only contribute to a significant reduction in disaster mortality but are cost-effective and can cut disaster losses and damages. To expand this solution to every community in the world, the Secretary-General announced in 2022 the launch of the "Early Warnings for All" initiative, which the United Nations Office for Disaster Risk Reduction is proud to co-lead with the World Meteorological Organization. The initiative aims to protect every person on the planet with inclusive and multi-hazard early warning systems by the year 2027.

Achieving this ambitious goal requires resources, partnerships and the latest data and technologies, including space-based technologies. Satellite observation data can strengthen countries' understanding of the risks they face, improve their ability to monitor and forecast hazards, and identify the populations and assets that are most at risk. Overall, satellite observations can strengthen every aspect of the early warning and early action chain.

This is why I am grateful to the UN-SPIDER programme of the United Nations Office for Outer Space Affairs for the production of this report on Space Technologies for Early Warning Systems. The publication explains the importance of using space technologies, products and services to confront the challenges posed by natural hazards while demonstrating how the space community contributes to the effectiveness of multi-hazard early warning systems.

I welcome this publication as a solid contribution from UNOOSA and its UN-SPIDER programme to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 and to the "Early Warnings for All" initiative, and I call on Governments and practitioners to make full use of it to enhance the resilience of communities worldwide, so that no one is left behind when disaster strikes.

Mami Mizutori

Special Representative of the Secretary-General for Disaster Risk Reduction and Head of the United Nations Office for Disaster Risk Reduction

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Executive summary

Over the centuries, communities throughout the world have experienced disasters triggered by natural hazards. In the past these disasters were considered inevitable. However, since the 1990s, there has been a paradigm shift, recognizing that such disasters reveal not only the exposure of such communities to natural hazards, but also their physical, social and economic vulnerability.

In recent decades, experts in environmental science have carried out research that has allowed societies to improve their understanding of those natural hazards that can trigger disasters. Structural engineers have identified improved building techniques and introduced construction materials with superior qualities that can reduce the physical vulnerability of infrastructure. Social scientists and economists have also pinpointed the root causes and dynamic factors that unfortunately give rise to social and economic vulnerability. Despite these advances, natural hazards continue to trigger disasters in developed and developing countries alike. Furthermore, climate change is aggravating the behaviour of hydrometeorological hazards.

To address the challenges related to such disasters, since 1990 the United Nations has been spearheading international efforts to increase the understanding that while societies cannot really prevent natural hazards from taking place, they can prepare themselves better to mitigate the impacts of those hazards.

Early warning systems are an example of measures that allow communities to improve the way they confront and minimize the impact of such hazards, reducing the loss of lives and the damage and loss of essential assets. These systems rely on sound scientific knowledge regarding the spatial and temporal dynamics of natural hazards and can be improved through:

- **The use of information on exposure and vulnerability of communities, their livelihoods and assets**
- **An improved capacity to disseminate and communicate warnings, and**
- **A more proactive anticipated response to warnings by those at risk**

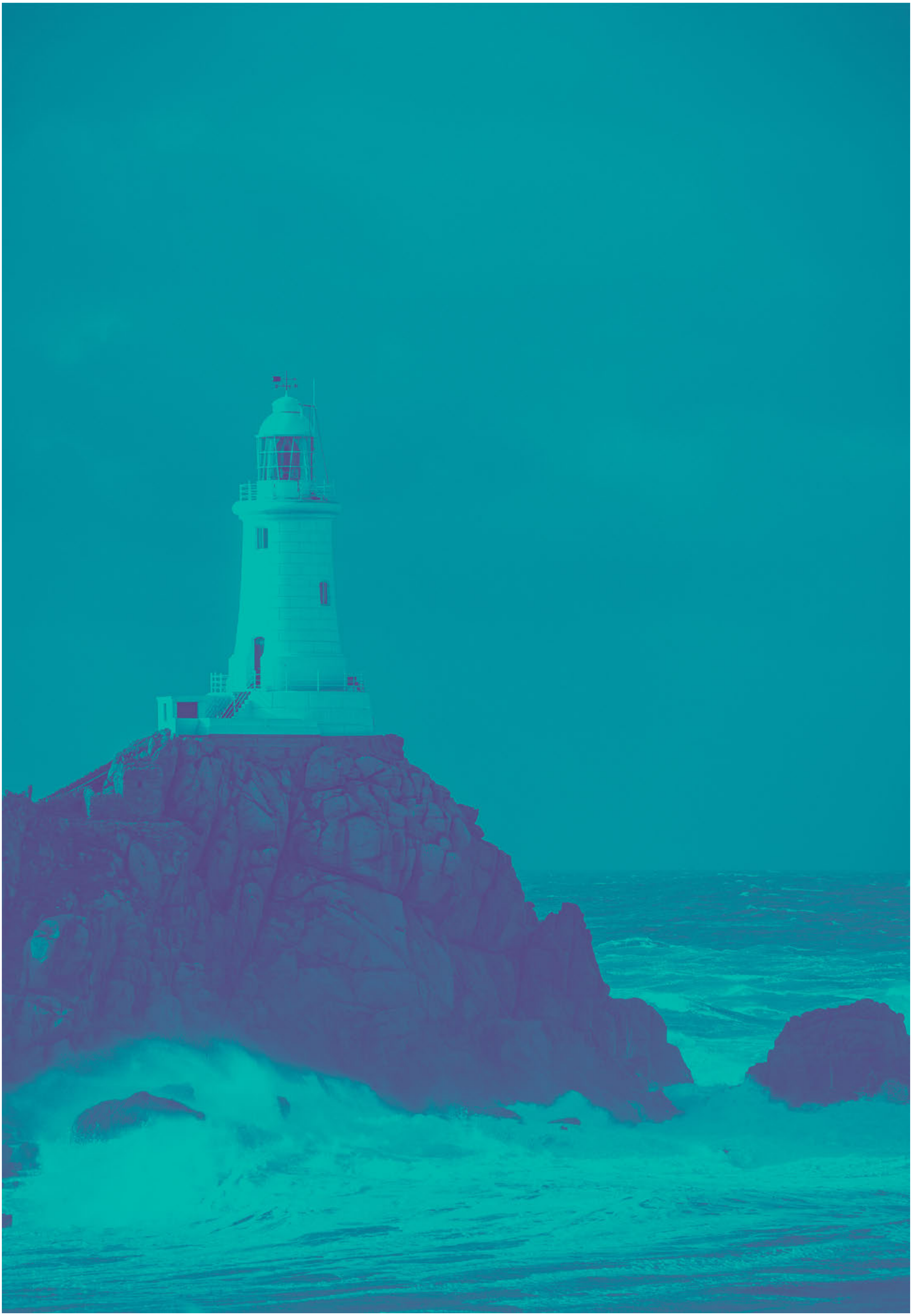
Since the 1960s, the space community has been contributing to an improved understanding of natural hazards. Meteorological satellites now measure more than one hundred parameters that increase our understanding of hydrometeorological phenomena. Other Earth observation satellites contribute to the monitoring of the dynamics of geological, environmental and coastal hazards, and to the assessment of the exposure of vulnerable elements such as critical infrastructure, crops and pastures. Satellite telecommunications are essential for transmitting data from sensors in remote areas to national observatories where such data are analysed in order to monitor natural hazards and transmit warnings from one continent to another one. Furthermore, global navigation satellite systems allow us to pinpoint the location of essential assets.

This publication on space technologies for early warning systems, compiled by the UN-SPIDER programme of the United Nations Office for Outer Space Affairs (UNOOSA), presents examples of the use of space-based data, products and services in early warning systems that address hydrometeorological, geological, extraterrestrial, health, biological, environmental and coastal hazards. It presents numerous examples of ways in which the space community and experts in many areas are broadening the spectrum of applications in all areas of effective, people-centred early warning systems.

It serves as a gateway for readers to familiarize themselves with the efforts carried out by many national and regional space agencies, universities, organizations and private companies to improve early warning systems. It includes 81 case studies that provide information on efforts by these institutions and more than 350 links to websites where readers can find additional information on these efforts.

The publication is also intended as a contribution from the Office and its UN-SPIDER programme to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030, and to the "Early Warnings for All" initiative launched by the Secretary-General of the United Nations in 2022.

With this publication UN-SPIDER aims to provide advice to Governments and disaster management stakeholders and practitioners on how space technologies can contribute to enhancing the effectiveness of early warning systems. In a complementary fashion, UNOOSA presents this publication as an example of ways in which the space community is bringing the benefits of space to humankind.



Credit: AdobeStock/Grzegorz Kordowski

Introduction

Natural and technological hazards continue to trigger disasters in many countries of the world, making no distinction between developed or developing nations. In the year 2022, Pakistan experienced unprecedented floods and the Government, the United Nations Development Programme (UNDP) and other regional and international organizations estimated losses in the order of US$15.2 billion.[1] In contrast, the western region of the United States was experiencing one of its worst droughts in recent history.[2] And since the beginning of 2020, the corona virus disease (COVID-19) pandemic began to impact people around the world. By the end of March 2023, the World Health Organization reported that more than 760 million people had been infected with the COVID-19 virus, leading to the deaths of nearly 7 million people.[3]

While several decades ago disasters were perceived as unavoidable, in the 1990s, efforts began to change this paradigm introducing the notions of natural, technological and anthropogenic hazards; vulnerability, exposure and risk. Some of these efforts were carried out under the umbrella of international frameworks launched by the United Nations such as the International Decade for Natural Disaster Reduction 1990–1999, the Hyogo Framework for Action 2015–2014, and the most recent Sendai Framework for Disaster Risk Reduction 2015–2030.[4] According to the United Nations Office for Disaster Risk Reduction (UNDRR), efforts carried out worldwide have led to fewer deaths being caused by such disasters,[5] noting that early warning systems (EWS) have played a considerable role in the reduction of mortality rates. However, despite these advances, hazards continue to result in major economic losses in developed and developing countries.

Over many decades, national institutions have established EWS to forecast the occurence of potentially catastrophic events related to hydrometeorological, geological, environmental and biological hazards. More recently, early warning efforts have also been carried out at the regional and international levels in the case of severe weather, tsunamis, locust swarms, near-Earth objects (NEOs) and space weather. The role of space technologies in EWS has proven to be pivotal and continues to be essential for disaster management in a changing climate.

[1] United Nations Development Programme, "Pakistan Floods 2022: Post-Disaster Needs Assessment (PDNA)". Available at www.undp.org/pakistan/publications/pakistan-floods-2022-post-disaster-needs-assessment-pdna.

[2] United States, National Oceanic and Atmospheric Administration. *Record drought gripper much of the U.S. in 2022.* Available at www.noaa.gov/news/record-drought-gripped-much-of-us-in-2022.

[3] World Health Organization. "WHO Coronavirus (COVID-19) Dashboard". Available at https://covid19.who.in

[4] More information on these frameworks is available at www.undrr.org

[5] United Nations Office for Disaster Risk Reduction, "Sendai Framework for Disaster Risk Reduction 2015-2030". Available at www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

At the international level, the topic of early warning systems has been addressed since the 1990s, with the launch of the United Nations International Decade for Natural Disaster Reduction (IDNDR).[6] The Hyogo Framework for Action (2005–2015, launched in 2005, included a specific priority calling for efforts to enhance early warning.[7] This framework recognized the need for risk assessments to develop early warning systems; and called for the use of space-based Earth observations, space technologies, remote sensing and geographic information systems to contribute to such risk assessments and early warning. It also called for the promotion of the use of space-based technologies and related services, as well as Earth observations, to build a culture of safety and resilience at all levels.

In 2006, the former Platform for the Promotion of Early Warning (PPEW) introduced the notion of people-centred early warning systems with the aim "to empower individuals and communities threatened by hazards to act in sufficient time and in an appropriate manner so as to reduce the possibility of personal injury, loss of life, damage to property and the environment and loss of livelihoods". [8] The framework for people-centred early warning systems was structured using four key elements:[9]

- Risk knowledge
- Detection, monitoring, analysis and forecasting
- Warning dissemination and communication
- Preparedness and response capability

Over time these four elements have evolved, and include notions of impact-based forecasts and forecast-based financing. In the last decade, the early warning community began to introduce the notions of multi-hazard early warning systems (MHEWS), and the Sendai Framework for Disaster Risk Reduction 2015–2030 included the aim to "Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030" as one of its seven global targets.

International early warning conferences were organized under the umbrella of the United Nations in 1998 in Potsdam, Germany; in 2003 and 2006 in Bonn, Germany; in 2017 in Cancun, Mexico; in 2019 in Geneva, Switzerland; and more recently in 2022 in Bali, Indonesia.

In the year 2022, Secretary-General Antonio Guterres set the goal to ensure that every person on Earth would be covered by EWS by 2027 and thus encouraged "Member States to substantially increase the availability of and access to multi-hazard early warning systems (...), including through the provision of technology".[10] To achieve this goal and to implement global coverage of EWS, the United Nations launched the "Early Warnings for All" initiative, which is co-led by the World Meteorological Organization (WMO) and the United Nations Office for Disaster Risk Reduction (UNDRR), with support from the International Telecommunication Union (ITU), the International Federation of Red Cross and Red Crescent Societies (IFRC) and other partners. .[11]

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[6] General Assembly, "United Nations Forty-second Session: International Decade for Natural Disaster Reduction", resolution 42/169. Available at https://digitallibrary.un.org/record/152704?ln=en.

[7] United Nations International Strategy for Disaster Reduction. "Hyogo Framework for Action 2005-2015". Available at www.unisdr.org/2005/wcdr/intergover/official-doc/L-docs/Hyogo-framework-for-action-english.pdf

[8] United Nations, "Global Survey of Early Warning Systems". Available at www.unisdr.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf

[9] World Meteorological Organization, "International Network for Multi-hazard Early Warning Systems (2018) Multi-hazard Early Warning Systems: A Checklist". Available at https://public.wmo.int/en/our-mandate/focus-areas/natural-hazards-and-disaster-risk-reduction/mhews-checklist

[10] General Assembly, "International cooperation on humanitarian assistance in the field of natural disasters, from relief to development". Available at https://documents-dds-ny.un.org/doc/UNDOC/GEN/N22/728/90/PDF/N2272890.pdf?OpenElement

[11] World Meteorological Organization, "Early Warnings for All Executive Action Plan 2023–2027". Available at https://library.wmo.int/doc_num.php?explnum_id=11426

Since the 1960s, the space community has dedicated efforts to contribute to an improved understanding of natural hazards. The world's first dedicated weather satellite, the Television Infrared Observation Satellite (TIROS), was launched by the United States on 1 April 1960.[12] Subsequently, national space agencies of several countries launched other satellites to monitor hydrometeorological phenomena from space, and telecommunication satellites. Subsequently, several space agencies began to launch global navigation satellite systems (GNSS).

Since then, space technologies have played an important role in improving EWS and in reducing the impact of many types of natural hazards. Space technologies contribute to each of the four key elements mentioned above of efficient, people-centred early warning and the space community is continuously developing new tools to contribute to such early warning efforts.

Satellite observations have been contributing to the improvement of weather forecasts for decades, and data acquired from a variety of satellites are now used to develop weather forecasts for severe weather on land and at sea. Other types of satellite observations allow disaster managers to have the most up-to-date view of the exposure of vulnerable elements to hazards of various types, and the combination of archived and up-to-date observations allow disaster managers to track the dynamics of such exposure, including land use changes that may affect the behaviour of hazards such as floods and landslides. Earth observation data is also being used to map the distribution of human population, buildings, strategic infrastructure and roads.

Furthermore, the combination of a specific type of satellite imagery permits experts in geological observatories to track the deformation of volcanic cones prior to eruptions, and the motion of slow-moving landslides.

In a complementary fashion, satellite telecommunications play an essential role in transmitting data on a continuous basis from sensors deployed in remote areas to monitor hazards. A key example is the use of satellite telecommunications to transmit information from buoys located in the ocean that emit data on tsunamis to warning centres. Global navigation satellite systems also allow for improved location services and will soon be used to transmit warnings to areas that may be impacted by some types of hazards.

In addition, products such as digital elevation models derived from satellite observations allow experts to develop flood hazard maps, landslide susceptibility in mountainous areas, and for the modelling of how tsunamis and storm surges will impact coastal communities.

In recent years, the space community has begun to implement services that facilitate access to space-based information that is useful in early warning systems. These include the Copernicus Global Flood Awareness System (GLoFAS), the Global Drought Observatory (GDO)and the Global Wildfire Information System (GWIS). Furthermore, the private sector also offers access to high-resolution satellite imagery, satellite telecommunications and other services equally useful in early warning systems.

With this publication UN-SPIDER aims to provide advice to governments, disaster management stakeholders and practitioners on how space technologies can contribute to enhancing the effectiveness of EWS. The publication provides information on the use of various types of space technologies to improve different components of such systems for a range of natural hazards.

[12] United States, National Aeronautics and Space Administration, *Launch of TIROS 1, World's 1st Weather Satellite — This Week in Goddard History: March 31–April 6*. Available at www.nasa.gov/feature/goddard/2019/launch-of-tiros-1-worlds-1st-weather-satellite-this-week-in-goddard-history-march-31-april-6.

The publication includes examples of the use of space-based data, products and services which can contribute to improving early warning systems for hydrometeorological phenomena including fast- and slow-onset events; geological phenomena including landslides, volcanic activity and earthquakes; coastal hazards including tsunamis and storm surges; extraterrestrial hazards such as space weather and near-Earth objects; health hazards and other biological hazards that affect humans and agriculture; and environmental hazards such as forest fires. Several examples presented are already in use, while others are still in the development and testing phases. Others could be employed, and awareness-raising efforts are needed to encourage their use. The final chapter presents information on upcoming developments to be implemented in the coming years.

Some of these technologies can contribute to an improved understanding of natural hazards in terms of their spatial and temporal dynamics. They can monitor these hazards and can be used in a complementary fashion with other in situ data to forecast potentially catastrophic events. Other technologies will allow early warning managers to take note of the most-up-to-date information on exposed infrastructure, crops and other assets. In the case of agriculture, the combined use of archived and up-to-date information compiled from satellite imagery allows those in charge of this sector to ascertain the severity of a current drought in comparison to historic droughts which may have taken place in previous decades.

Satellite telecommunications play a crucial role in transmitting essential data to observatories, meteorological departments and geological surveys, where the data are used to forecast potentially catastrophic events. And as is to be expected, satellite communications contribute to the dissemination of warnings across oceans and vast regions.

Global navigation satellite systems are also contributing to the improvement of early warning systems through the more precise geolocation of exposed infrastructure and assets, and some of these systems will be used to transmit warnings in the near future as well.

But more importantly, the publication serves as a gateway for the reader to become aware of the efforts that are being carried out by many national and regional space agencies, universities, organizations and private companies on this topic. It includes 81 case studies that provide information on efforts by these institutions that are contributing to the improvement of early warning systems around the world using satellite imagery, products and services. The publication includes more than 350 links to websites where the reader can find additional information on these efforts.

This publication is a contribution of UN-SPIDER to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030 and the Paris Climate Agreement, as these global frameworks call for efforts to improve early warning systems. The publication is also a contribution to the "Early Warnings for All" initiative that was launched by the Secretary-General in 2022; and the midterm review of the implementation of the Sendai Framework, carried out by the United Nations Office for Disaster Risk Reduction between 2022 and 2023. Finally, the publication serves as a contribution to the implementation of the “Space 2030” Agenda: space as a driver for sustainable development, and to the mission of the United Nations Office for Outer Space Affairs regarding the promotion of international cooperation in the peaceful uses of outer space for economic, social and scientific development for the benefit of developing countries.

TIROS 1 satellite during its testing phase

Image courtesy of NASA

Chapter 1.
A brief history of international collaboration on the use of space technologies in early warning systems

"On 4 October 1957, the former Union of Soviet Socialist Republics (USSR) launched the first Earth-orbiting satellite SPUTNIK-1, followed later in the same year by SPUTNIK-2. On 2 January 1958 the EXPLORER-1 was satellite launched by the United States of America (USA). The world's first dedicated weather satellite, the Television Infrared Observation Satellite (TIROS-1), was launched by the United States on 1 April 1960. These launches effectively marked the beginning of a new era of observational data coverage for the whole globe".[13]

The launch and operationalization of weather satellites triggered the inception of the World Weather Watch (WWW), a programme designed to facilitate the development, operation and enhancement of worldwide systems for observing and exchanging meteorological and related observations. H. Wexler and V. Burgaev prepared a report outlining the feasibility of using satellites to monitor the weather and forecast potentially catastrophic events. The report was submitted to the World Meteorological Organization (WMO) and at its fifth Congress in 1967, the WWW Plan and Implementation Programme was approved.[14]

By 1972, the Coordination of Geostationary Meteorological Satellites (CGMS) had been established by Japan, the United States, Europe and WMO.[15] CGMS established a constellation of five geostationary satellites to track the weather worldwide. Since then, the number of satellites launched by its members has increased substantially and more than 100 parameters are measured from space.

Equally important to using satellite technology to monitor and observe meteorological processes is the effort to develop weather prediction models to enhance the use of satellite data, and the need to ensure the quality of satellite data for its use in hydrometeorological forecasting and warning.

[13] World Meteorological Organization, "World Weather Watch". Available at https://public.wmo.int/en/programmes/world-weather-watch

[14] World Meteorological Organization, "The Global Satellite Observing System: a Success Story". Available at https://public.wmo.int/en/bulletin/global-satellite-observing-system-success-story

[15] European Organisation for the Exploitation of Meteorological Satellites, *The Coordination Group for Meteorological Satellites (CGMS)*. Available at www.eumetsat.int/international-cooperation/coordination-group-meteorological-satellites-cgms

Today, the WWW also generates and disseminates analyses and forecast products, as well as severe weather advisories and warnings, and related operational information. In addition, CGMS "globally coordinates meteorological satellite systems. This includes protection of in orbit assets, contingency planning, improvement of quality of data, support to users, facilitation of shared data access and development of the use of satellite products in key application areas."[16]

As the potential for using satellite technology was dawning on the meteorological community, another disaster was about to strike that would change the role of satellites in warning for geological hazards. On 22 May 1960, a Mw 9.5 earthquake occurred off the coast of southern Chile, followed by a devastating tsunami. The tsunami hit southern Chile and, half a day later it impacted Hawaii, and nearly a day later it struck Japan and the Philippines. In Chile, the earthquake and tsunami combined are estimated to have caused up to 5,700 fatalities, made some 2 million people homeless, and caused US$ $550 million in damage.[17]

Concerned countries set out the requirements for an international tsunami warning system and, in 1965, the International Coordination Group for the Tsunami Warning System in the Pacific was formed. "Now 50 years in existence, the Tsunami Warning System in the Pacific is an example of how, through international cooperation, the tsunami hazard impact has been mitigated by properly evaluating in real time potentially tsunamigenic earthquakes and by issuing timely informational bulletins and warnings".[18] The development of space technologies over the past 50 years has played a significant role in the real time evaluation and communication of tsunami information and warnings (chapter 7).

As time progressed and satellite technology evolved, the space community increasingly saw the potential for space technologies in disaster management applications.

In 1989, the General Assembly launched the International Decade for Natural Disaster Reduction (IDNDR). This decade-long effort, carried out from 1990 to 1999, was adopted with the objective "to reduce through concerted international action, especially in developing countries, the loss of life, property damage, and social and economic disruption caused by natural disasters …".[19]

As one of those activities carried out under the umbrella of IDNDR, the General Assembly requested the IDNDR secretariat to coordinate a review of existing early warning programmes. The secretariat established six international expert groups, including one on Earth Observation, Hazard Analysis and Communications Technology for Early Warning. In its 1997 report,[20] the experts of this group recognized the benefits of the use of Earth observation, satellite telecommunications and GNSS in early warning systems.

In July 1999, at the third United Nations Conference on the Exploration and Peaceful Uses of Outer Space, held in Vienna, participants noted that "Space technologies can play an important role in early warning and management of the effects of disasters".[21] It was noted that "Satellite remote sensing offers several advantages over alternative

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[16] Coordination of Geostationary Meteorological Satellites, *About*. Available at https://cgms-info.org/about-cgms

[17] United States National Oceanic and Atmospheric Administration, "Southern Chile Earthquake and Tsunami 22 May 1960". Available at www.ngdc.noaa.gov/hazard/22may1960.html

[18] International Tsunami Information Centre (ITIC), *PTWS 50th Book*. Available at http://itic.ioc-unesco.org/index.php?option=com_content&view=article&id=1941&Itemid=2633

[19] General Assembly, "International Decade for Natural Disaster Reduction", resolution 44/236, *44th Session of the General Assembly*. Available at https://digitallibrary.un.org/record/82536?ln=en

[20] United Nations Office for Disaster Risk Reduction, "IDNDR Early Warning Programme (1997). Report on Earth Observation, Hazard Analysis and Communications Technology for Early Warning". Available at http://lib.riskreductionafrica.org/bitstream/handle/123456789/1256/4045.Report%20on%20earth%20observation%20hazard%20analysis%20and%20communications%20technology%20for%20early%20warning.pdf?sequence=1&isAllowed=y

[21] United Nations, "Report of UNISPACE III", Official document A/CONF.184.6. Para. 105. Page 39. Available at https://digitallibrary.un.org/record/287788?ln=en

means of data collection, such as airborne and ground surveys".[22] The conference participants also recognized that the potential of space technologies for civil protection was not being utilized by the disaster management community. A key recommendation from the conference was to implement activities to facilitate the use of space techniques by the civil protection authorities.

The use of space technologies by civil protection in disaster risk reduction, including early warning efforts, has been encouraged by the Committee on the Peaceful Uses for Outer Space (COPUOS) in its deliberations. Following the recommendation of this Committee to enhance the use space technologies in disaster risk reduction, preparedness and response, the General Assembly established in 2006 the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER). UN-SPIDER is implemented by the Office for Outer Space Affairs (UNOOSA) and it provides universal access to a vast range of space-based information and services relevant to disaster management to support the full disaster management cycle.[23]

Since 2007, UN-SPIDER has been encouraging the use of space technologies to contribute to the early warning efforts and the programme has organized specific international conferences on this topic. Together with Member States, UN-SPIDER was able to incorporate explicit text on the use of space technologies to contribute to the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030.[24]

The Sendai Framework was launched during the World Conference on Disaster Risk Reduction held in Sendai, Japan in March 2015. The framework includes four Priorities for Action and seven targets. Priority Area 1, labelled Understanding Disaster Risk, calls for regional and international organizations "to promote and enhance, through international cooperation, including technology transfer, access to and the sharing and use of non-sensitive data and information, as appropriate, communications and geospatial and space-based technologies and related services; maintain and strengthen in situ and remotely-sensed Earth and climate observations."

Taking advantage of this conference, UNOOSA, and its UN-SPIDER programme, joined forces with other organizations of the United Nations to launch the International Network on Multi-Hazard Early Warning Systems (IN-MHEWS).[25] The role of UN-SPIDER in this network is to raise awareness about the use of space technologies in such early warning systems. In addition, UN-SPIDER has been working with partners in many regions of the world to improve the routine operation of early warning systems through the incorporation of novel satellite technologies, products and services.

The Committee on the Peaceful Uses for Outer Space continues to promote and encourage international collaboration in the use of satellite technology, most recently in the "Space2030" Agenda: space as a driver of sustainable development.[26] The "Space2030" Agenda includes harnessing the potential of space to solve everyday challenges and leverage space-related innovation to improve the quality of life (Overarching Objective 2). The agenda calls for efforts to be carried out to strengthen the use of integrated space applications to improve early warning systems.

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[22] United Nations, "Report of UNISPACE III". Official document A/CONF.184.6. Para 112. Page. 40. Available at https://digitallibrary.un.org/record/287788?ln=en

[23] General Assembly, "United Platform for Space-based Information for Disaster Management and Emergency Response", resolution 61/110. Available at www.un-spider.org/sites/default/files/General%20Assembly%20Resolution%2061-110.pdf

[24] United Nations Office for Disaster Risk Reduction, "Sendai Framework for Disaster Risk Reduction 2015-2030". Available at www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

[25] More information on the International Network on Multi-Hazard Early Warning Systems is available at www.un-spider.org/network/in-mhews and in https://mhews.wmo.int/en/welcome

[26] General Assembly. "Space2030 Agenda: space as a driver of sustainable development". Available at www.unoosa.org/res/oosadoc/data/resolutions/2021/general_assembly_76th_session/ares763_html/A_RES_76_3_E.pdf

Practitioners are finding innovative ways to use Earth observation to assess disaster risk, including exposed elements, the location of vulnerable groups and critical infrastructure. Up-to-date risk data is critical for effective early warning systems as it enables key information to be incorporated into the forecasting of impacts for early warnings and the design of measures such as evacuation routes.

In 2015, the Committee on Earth Observation Satellites (CEOS), stated that satellite technologies offer several advantages over in situ observations, specifically the acquisition of data:[27]

- At the global level that is consistent and comparable from country to country
- At multiple scales, including in the case of transboundary hazards
- Useful for multi-hazard disaster risk reduction efforts
- In areas that may be inaccessible or too hazardous for human presence
- In a setting that is not vulnerable to the events that trigger disasters
- Collected over a period of several decades at regular, frequent intervals, to be able to track changes in the environment, on land and at sea to facilitate temporal comparisons over time

Improvements in space technologies, and the increasing uptake of these technologies in countries is leading to improvements in early warning systems and disaster risk reduction measures around the world.

Most recently, the use of satellite-derived data has improved sufficiently to enable EWS to issue impact-based forecasts. In addition, satellite technologies are enabling EWS that trigger the pre-emptive allocation of resources to mitigate impacts from these hazard events through programmes such as forecast-based financing and index-based insurance.

As space technologies evolve, providing greater resolution, more accurate data and greater accessibility, EWS continue to benefit and harness state-of-the-art satellite capabilities to improve the timeliness and accuracy of hazard warnings. In turn, EWS around the world continue to become more accurate and effective, providing life-saving information with sufficient notice to enable pre-emptive mitigation and prevention measures to be implemented to minimize the impact of hazardous events.

Developments in space technologies are now leading to pilot programmes and operational testing of capabilities that are benefiting warning systems for potentially devastating hazards that have previously been deemed unforecastable.

The publication includes examples of space technologies, data, services and products which can feature in early warning systems for hydrometeorological phenomena including fast-onset and slow-onset events; geological phenomena including landslides, volcanic activity and earthquakes; coastal hazards including tsunamis and storm surges; extraterrestrial hazards such as space weather and near-Earth objects; health hazards and other biological hazards that affect humans and agriculture; and environmental hazards including forest fires. Several examples presented are already in use, while others are still in the development and testing phases. Others could be used, and awareness-raising efforts are needed to encourage their use. The final chapter presents information on upcoming developments to be implemented in the coming years.

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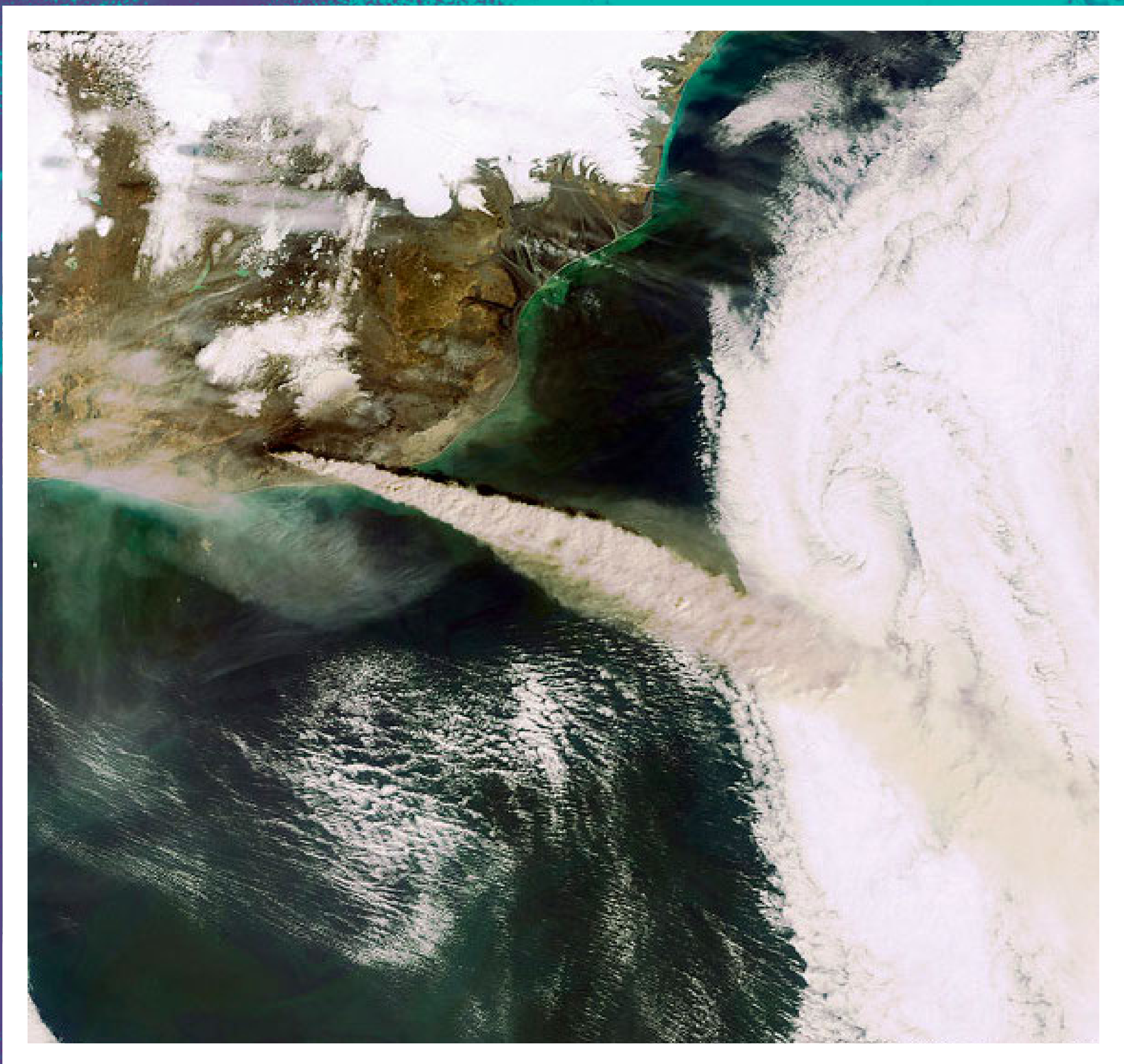
[27] Committee on Earth Observation Satellites, "Satellite Earth Observations in support of Disaster Risk Reduction, Special 2015 WCDRR Edition". Available at www.eohandbook.com/eohb2015/files/CEOS_EOHB_2015_WCDRR.pdf



Eyjafjallajokull volcano in south-east Iceland, image of the eruption captured by ENVISAT on 8 May 2010

Image courtesy of ESA

Chapter 2.
Building blocks of early warning systems

Early warning can be defined as a service that conveys critical information on potentially catastrophic events and potential impacts to people and institutions, so that specific actions can be taken to minimize the impact of such catastrophic events. As such, these systems have contributed to reducing the number of fatalities, injuries and other losses. However, there are still gaps that need to be addressed and room for improvement in such systems.

EWS have been designed and implemented to target a variety of hydrometeorological, geological, extraterrestrial, coastal, health, agricultural, environmental and biological hazards. In addition, the constant invention of new technologies, including space technologies, is allowing agencies to improve their early warning capacities.

Improved dissemination tools and the Internet are widening the capacity of agencies to advocate such systems, to display related information and to carry out awareness campaigns. At the same time, improved monitoring networks and modelling capacities allow experts to track the dynamics of natural hazards in a more precise fashion, leading to more precise forecasts of events both in terms of their geographical extent, their temporal manifestation and impact.

In general terms early warning systems use data from a variety of sources to monitor precursors that are used to forecast the occurrence of potentially catastrophic events. Figure 2.1 illustrates the general flow chart of typical EWS.[28, 29] Newer systems are making use of information derived from satellites, in situ networks in the field, and additional sources available through the Internet. The use of satellite communications is also now essential when it comes to transmitting data and warnings for rapid-onset and intercontinental-range hazards such as tsunamis.

Once a potentially catastrophic event is forecasted, a warning is issued and communicated to the population which could be impacted. Communication of early warnings involves the use of sirens, mass media, including radio and television networks, and, more recently, massively distributed SMS messages over commercial telephone networks.

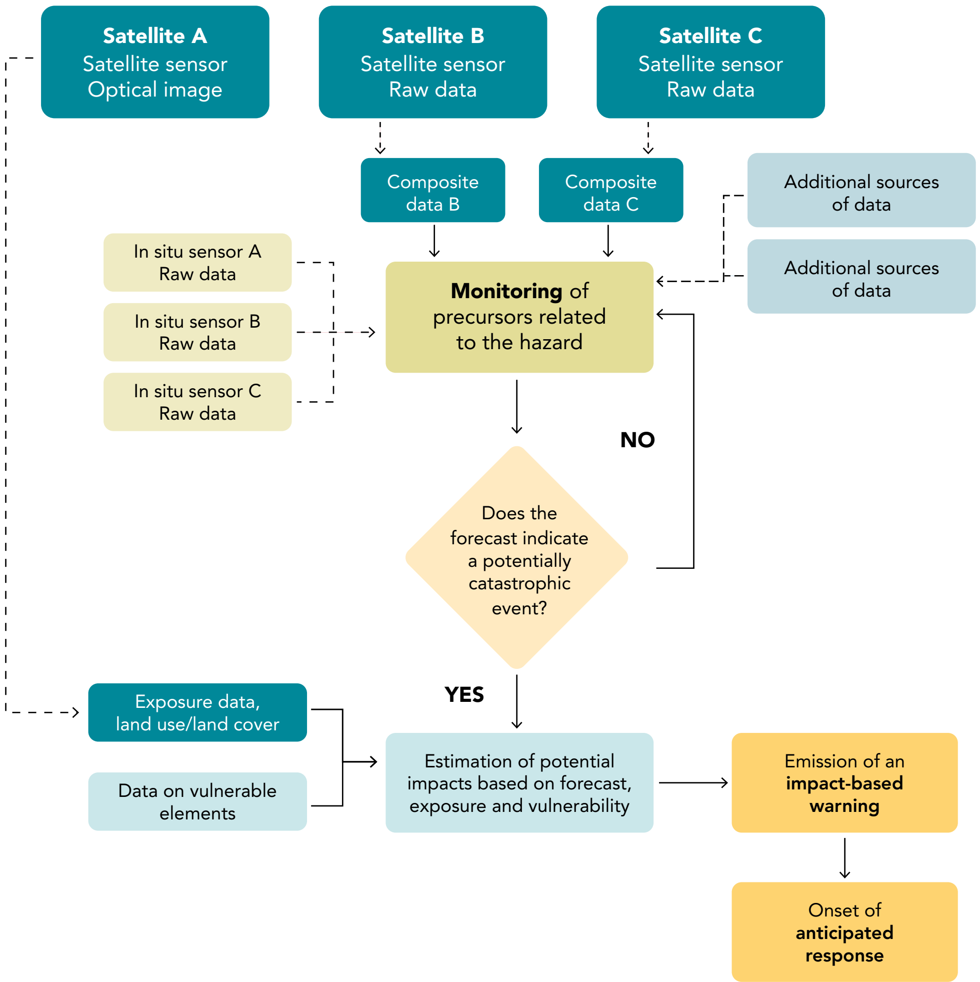
[28] Juan Carlos Villagran de Leon, Inundaciones: Lineamientos para su manejo. (Guatemala, Guatemala, CIMDEN-VILLATEK, 2001). Available at https://catalogosiidca.csuca.org/Record/CR.UNA01000309818/Details

[29] Juan Carlos Villagran de Leon, Janos Bogardi, Stefanie Dannenmann, and Reid Basher, Early Warning System in the context of disaster risk management. Available at www.unisdr.org/2006/ppew/info-resources/docs/ELR_dt_23-25.pdf

While there are many advances regarding ways to communicate warnings, technology alone is not enough to ensure that people at risk will respond quickly and proactively to warnings.

There are ongoing efforts to incorporate the use of information on exposure and vulnerability within the warning message, raising awareness of potential impacts that the hazard may trigger. The expectation is that such impact-based warnings will lead those at risk to respond to warnings more proactively.

Figure 2.1 Components of early warning systems



Source: UN-SPIDER

The anticipated response to early warnings includes evacuation to safe areas before the hazard impacts exposed areas, the minimization of potential impacts through the implementation of additional measures, and the mobilization of financial and in-kind resources to assist vulnerable communities to minimize the impact of such events.

2.1 People-centred, efficient early warning systems

In 2006, the former Platform for the Promotion of Early Warning set up by the former International Strategy for Disaster Reduction (PPEW) introduced the notion of people-centred, efficient early warning systems, and defined four elements of people-centred early warning.[30] Figure 2.2 presents these four elements proposed by PPEW to be considered in the design and operation of people-centred early warning systems. When taken into consideration, these four elements allow for the transformation of any technical early warning system into a people-centred system.

Figure 2.2 Four elements of an end-to-end, people-centred early warning system

DISASTER RISK KNOWLEDGE
Prior knowledge of the risk faced by communities

Are the risks well known by communities exposed to hazards?
Are maps and data widely available?
Is this knowledge used to improve early warnings?

WARNING SERVICE
Hazard monitoring and warning service

Are the right parameters being monitored?
Is there a sound scientific basis for making forecasts?
Can accurate and timely warnings be generated?

WARNING DISSEMINATION AND COMMUNICATION
Dissemination of warnings to those at risk

Do impact-based warnings reach those at risk?
Do people understand the impact-based warnings?

RESPONSE CAPABILITY
Knowledge and preparedness to act by those threatened

Do those at risk know how to react to warnings?
Are drills and simulations carried out as part of early warning efforts?

Source: UN-SPIDER, adapted from UNDRR

In recent years, people-centred systems are also evolving to incorporate impact-based forecasts and forecast-based financing measures. Furthermore, the partners of the International Network for Multi-Hazard Early Warning Systems (IN-MHEWS) adapted the four elements and produced a checklist for multi-hazard early warning systems to become user-centred and impact-based.[31]

[30] United Nations, "Global Survey of Early Warning Systems". Available at www.preventionweb.net/files/3612_GlobalSurveyofEarlyWarningSystems.pdf/

[31] World Meteorological Organization, "Mult-Hazard Early Warning Systems: A Checklist". Available at https://library.wmo.int/doc_num.php?explnum_id=4463

2.1.1 Disaster risk knowledge

Risk knowledge implies an understanding of the hazards, the exposure and the vulnerabilities of those at risk. It represents the know-how concerning the types of events which can manifest themselves in a particular geographic region, and the way in which such events can impact communities.

Space technologies contribute to risk knowledge through information on hazards and exposure of vulnerable elements. For example, the most up-to-date, high-resolution optical image provides the most precise and timely information on elements that are exposed to a hazard. A comparative overview of high-resolution satellite imagery of a specific area over many years provides information on how the exposure of vulnerable elements has changed over time. This improves the understanding of the dynamics of risks.

In parallel, data gathered from different types of satellites is currently used in combination with in situ data to model hazards and develop hazard maps. Digital elevation models derived from satellite observations are used to develop flood, landslide, storm surge and tsunami hazard maps, which, in turn, provide valuable information for understanding the potential impact of hazardous events and the measures needed to reduce their impact.

The use of satellite technologies to assess risk assists operators of early warning systems to establish impact-based forecasts. These include important information about the extent, type, severity and the likelihood of impacts occurring. In addition, impact-based forecasts include valuable advice and guidance on the response actions that people can take to prevent and mitigate the impacts of hazard events.

Including risk information to generate impact-based forecasts is considered best practice for multi-hazard early warning systems. This approach is being adopted across a range of hazards, from slow-onset hazards, such as droughts, to more near-time onset hazards such as river flooding. For large rivers, the Global Flood Awareness System (GLoFAS) of the Copernicus programme is beginning to be used by hydrometeorologists around the world to issue impact-based forecasts about impending floods in their area of responsibility.

2.1.2 Monitoring and forecasting

Monitoring of phenomena which can trigger potentially catastrophic events, or their precursors, is usually carried out using arrays of instruments of different kinds. For example, networks of satellites and ground-based sensors in the field track the path and the characteristics of potentially catastrophic hurricanes in the Caribbean and the eastern Pacific, and typhoons or cyclones in the western Pacific and the Indian Ocean. In the case of floods, a variety of instrumentation is used to monitor and assess precipitation and river behaviour to produce flood warnings. For example, weather stations, rain gauges, rainfall intensity derived from satellite data and discharge gauges are all used to forecast potential floods in rivers.

Since the 1960s, meteorological satellites have contributed to the monitoring of potentially severe weather over land and at sea. More recently, different types of satellites are used to monitor other hazards, and research is ongoing to develop new procedures to use satellites to expand the monitoring capabilities of observatories in charge of forecasting potentially catastrophic events.

Recently launched satellites can monitor gas emissions from active volcanoes, which could be used to forecast the dispersion of ash clouds. In a similar fashion, multitemporal radar interferometry is being used in several active volcanoes to track the deformation of their domes to detect changes in the morphology that can suggest potential eruptions. These are of critical importance for volcanoes at sea, where lateral eruptions that are accompanied by a large mass displacement that may trigger tsunamis, as in the case of the Anak Krakatoa eruption in 2018, and the Tonga eruption in 2022.

Satellite telecommunications are used to transmit data from the monitoring sensors located in remote areas to observatories, where the data are analysed to elaborate forecasts. For rapid-onset events, such as flash flooding, tsunamis or earthquakes, the speed at which satellite technologies can transmit monitoring data is crucial.

2.1.3 Warning dissemination and communication

Once a forecast has been made concerning a potentially catastrophic event, a warning is issued based on this forecast. The warning is a notification that is typically issued when a hazard is expected to exceed a level of magnitude and scale that will cause impacts. Official warnings are typically issued by a specific government department, government agency, civil protection agency or local authority.

Once a warning has been issued by the appropriate authorities, it is disseminated and communicated to all communities at risk through a range of channels, including the media and telecommunication networks. The effectiveness of early warning systems is enhanced if warnings reach the target audience as quickly as possible, allowing sufficient time to act to minimize the impact of the hazard event.

Recognizing the need for rapid transmission of warnings, particularly in rapid-onset hazard events, WMO agreed to allow its satellites to be used to transmit tsunami warnings between regions that could be impacted, in 2006. Since then, satellite technologies continue to be explored and developed to improve the rapid dissemination of warning information. For example, satellites which are part of the constellations of GNSS in Europe and Japan will soon be used to transmit warnings to people at risk (see chapter 12).

2.1.4 Preparedness and response capability

Preparedness is essential for minimizing damages and losses once a warning is issued. Rapidly disseminated warning information, using satellite technology, can provide a window of opportunity to implement fast response actions to save lives.

Successful preparedness and response are not just a function of timely warning information. Communities and disaster management organizations must also be ready to respond, knowing what actions should be taken to minimize the impact of a hazardous event. In recent years, vulnerable communities in countries such as Bangladesh, India and Viet Nam, which are exposed to cyclones, have responded in a timely fashion to warnings, based on the lessons learned from previous events and improvements in the warning systems. This has led to a drastic reduction in the number of fatalities and injuries when comparing impacts from recent and historic cyclones.

Before disasters strike, high-resolution satellite imagery and data from global navigation satellite systems can be used to improve risk knowledge. These can be used to identify among others: the location of vulnerable groups, such as children in schools or the elderly in retirement homes; places where large numbers of people congregate, such as commercial areas, public markets or train and bus stations; and critical infrastructure, such as hospitals, government buildings, power stations, etc.[32] Such information can be used to develop warning strategies for vulnerable groups, including evacuation routes to safe areas. Similar information on the location of vulnerable assets can be used to plan for and take pre-emptive actions before the impacts occur to minimize damages and losses.

2.2 An introduction to space technologies used in early warning systems

Since the 1960s, space agencies of different countries have been launching satellites to contribute to early warning efforts. Countries such as Japan, the Russian Federation and the United States have launched a series of satellites over time to provide continuity to their observations. This continuity has been very useful in the context of hazard monitoring and climate change. In recent years, the European Commission launched its Copernicus programme that includes a constellation of a variety of satellites that is already enhancing early warning efforts spanning several types of hazards.

Subsequently, several countries joined forces to establish international efforts such as the Coordination Group for Geostationary Satellites (CGMS), which began its activities in 1972,[33] the Committee on Earth Observation Satellites (CEOS), which was launched in 1984,[34] and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), which began its operations in 1986.[35]

The role of space technologies in supporting disaster management operations has been recognized for several decades. Consequently, three notable mechanisms have been established by the space community to support disaster management efforts worldwide. These are the International Charter Space and Major Disasters, established in 2020,[36] the Sentinel Asia mechanism, established in 2005,[37] and the Copernicus Emergency Management Service.[38] These mechanisms have been set up to provide space-based information free of charge to national emergency management agencies to contribute to disaster response efforts worldwide.

The number of satellites launched into outer space has been increasing every year and by the end of 2022, more than 70 countries and two international organizations had launched a satellite. According to the Register of Objects Launched into Outer Space, which is maintained by the Office for Outer Space Affairs, by the year 2022, nearly 13,000 satellites had been launched into Earth orbit or beyond.

An important contribution regarding the use of satellites in early warning systems is the role of the International Telecommunications Union of the United Nations, which "oversees the allocation of the radio frequencies required

[32] Juan Carlos Villagran de Leon, *Rapid Assessment of Potential Impacts of a Tsunami: Lessons from the Port of Galle in Sri Lanka*. United Nations University Institute for Environment and Human Security SOURCE Publication No. 9/2008. Available at https://collections.unu.edu/eserv/UNU:1876/pdf3777.pdf

[33] Coordination of Geostationary Meteorological Satellites, "History and Achievements". Available at https://cgms-info.org/about-cgms/history-and-achievements

[34] Committee on Earth Observation Satellites, "Overview". Available at https://ceos.org/about-ceos/overview

[35] European Organisation for the Exploitation of Meteorological Satellites, "Convention for the establishment of a European Organization for the Exploitation of Meteorological Satellites". Available at www.eumetsat.int/media/40625

[36] More information on the International Charter Space and Major Disasters is available at https://disasterscharter.org/web/guest/home

[37] More information on Sentinel Asia is available at https://sentinel-asia.org/aboutsa/AboutSA.html

[38] More information on Copernicus Emergency Management Service is available at https://emergency.copernicus.eu

to meet the continuously evolving needs of the satellite industry".[39] For this purpose, Member States established the "Radio Regulations" that govern the use of radio frequencies worldwide, including those employed by satellites. The aim of the radio regulations is to prevent harmful interference among satellites in orbit, and to achieve a rational, equitable, efficient and economical use of the radio frequency spectrum.

Satellites can be classified in various ways: according to mass or size, type of orbit and use. The types of orbits used by satellites include:

- Geostationary orbit, also known as high-Earth orbit
- Medium-Earth orbit
- Polar orbit and sun-synchronous orbit
- Low-Earth orbit (LEO)

Satellites in geostationary orbit remain in situ over the same spot on Earth, rotating around the Earth once every 24 hours, at an altitude in the order of 36,000 km above the Equator. The orbits are in the plane of the equator, as the aim of these satellites is to hover over the same region of the Earth all the time and are used for State and commercial telecommunications as well as for meteorological applications.

Satellites in medium and low-Earth orbits have a higher frequency of rotation around the Earth and may have inclined orbits with respect to the equatorial plane.

There are three types of satellites according to their use:

- Earth observation satellites
- Telecommunication satellites
- Global navigation satellite systems (GNSS)

These types of satellites can be used in a complementary fashion to contribute to early warning efforts.

2.2.1 Earth observation satellites

Meteorological satellites

The first satellites launched were meteorological satellites. These were used to observe the atmosphere and to understand global and regional weather patterns. The first weather satellite launched into orbit was the Television InfraRed Observational Satellite (TIROS). It was launched by the National Aeronautics and Space Administration (NASA) of the United States in the spring of 1960 with the aim of testing experimental television techniques for meteorological observation. It provided the first satellite observation of cloud cover and cloud dynamics around the world during its 78 days of operation.[40]

[39] International Telecommunications Union, "Regulation of satellite systems". Available at www.itu.int/en/mediacentre/backgrounders/Pages/Regulation-of-Satellite-Systems.aspx

[40] More information on TIROS 1 is available at www.nasa.gov/multimedia/imagegallery/image_feature_1627.html

Since the 1960s, several countries have launched meteorological satellites to contribute to an improved understanding of the weather and the climate globally. Satellites in orbit now measure more than 100 parameters that help meteorologists understand a variety of hydrometeorological processes, including the interactions between the oceans and the atmosphere, and between land and the atmosphere.

Recognizing the usefulness of meteorological satellites, WMO established its World Weather Watch (WWW) programme[41] to facilitate the use of meteorological satellites launched by individual countries and more recently, WMO launched its Integrated Global Observing System (WIGOS). Through WIGOS, WMO members are now able to "better respond [to] natural hazards, improve weather, water, climate and related environmental monitoring, and adapt to climate change and human-induced environmental impacts".[42]

Similarly, a consortium of European countries established the regional EUMETSAT programme to operate a system of meteorological satellites to observe the atmosphere, the ocean and land surfaces.

Currently, there are many meteorological satellites in geostationary and low-Earth orbit. Those in geostationary orbit allow for a continuous monitoring of the atmosphere and its dynamics over the same spot continuously, but as they are nearly 36,000 km above the surface of the Earth, they are not used for high-spatial-resolution monitoring. Geostationary meteorological satellites include optical, infrared and microwave sensors, which provide a range of options for monitoring aspects of the atmosphere.

Meteorological satellites are usually placed in a geostationary orbit around 36,000 km above the surface of the planet, and in the Equatorial plane. They provide data on weather on land and at sea. Data is processed to generate information on a wide range of meteorological phenomena and processes. Cloud data is one of the most well known, but satellites also provide data including, but not limited to, wind speed and direction, temperature profiles for ocean and land areas, ocean wave heights, humidity profiles and lightning.

Using satellites, meteorologists can measure the state of the oceans and the atmosphere and forecast where tropical storms may form. Subsequently, these satellites can track the path of hurricanes and provide a more precise location of the areas where such storms will make landfall.[43] In recent decades, satellite observations in the microwave regime have allowed for estimates of rainfall amount and intensity, which are contributing to flood early warning systems.

[41] More information on WMO's World Weather Watch programme is available at https://public.wmo.int/en/programmes/world-weather-watch

[42] More information on WMO's WIGOS system is available at https://public.wmo.int/en/resources/bulletin/wmo-integrated-global-observing-system-wigos

[43] More information on how satellites are used to forecast hurricanes is available at www.nasa.gov/feature/goddard/2020/satellites-have-drastically-changed-how-we-forecast-hurricanes

CASE STUDY

The National Oceanic and Atmospheric Administration Geostationary Operational Environmental Satellites [a]

For nearly 50 years, the National Oceanic and Atmospheric Administration (NOAA) of the United States has been operating its constellation of Geostationary Operational Environmental Satellites (GOES) to contribute to improving weather forecasts, storm tracking, and for other applications in agriculture, oceanography, atmospheric physics and space weather observations. Figure 2.3 shows a satellite image from the American hemisphere acquired in August 2023.

The first three GOES satellites were launched between 1975 and 1993 and contributed to monitoring weather on land and at sea. The GOES 4, 5, 6 and 7 satellites were launched between 1980 and 1996 and included sensors to obtain vertical profiles of temperature and moisture at various elevations and allowed for improved forecasting of the intensity and extent of storms.

The GOES 8, 9, 10, 11 and 12 satellites were launched between 1994 and 2014 and were fitted with higher resolution sensors and larger capacity for data collection. The GOES 13, 14 and 15 satellites were launched between 2006 and 2020 and included even better resolutions that enabled the location of intense storms to be pinpointed. These were also the first satellites fitted with instruments to monitor space weather.

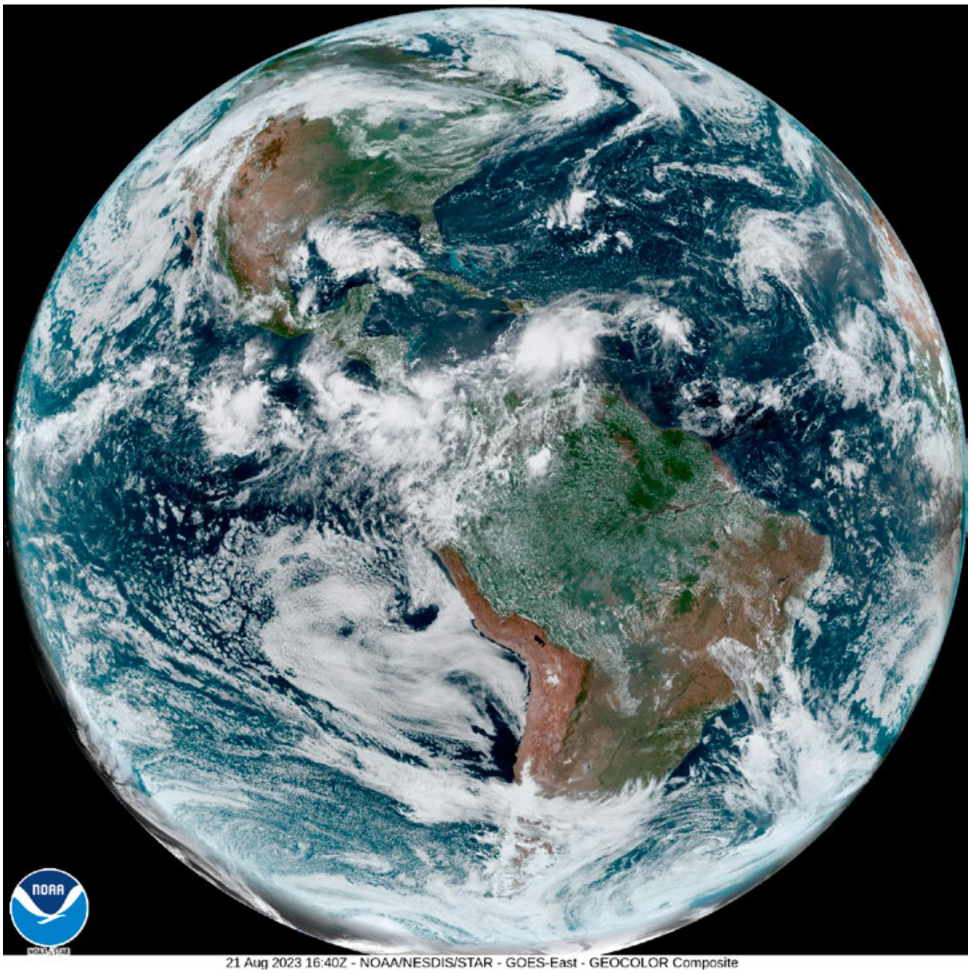
The newest GOES 16, 17 and 18 satellites were launched between 2016 and 2022 and are used to monitor different regions of the planet (GOES East and GOES West). The GOES 16 satellite included an Advanced Baseline Imager (ABI) that can scan the full disc of the planet and more localized areas as often as every 30 seconds to enhance the accuracy of short-term weather forecasts. The ABI includes 16 different spectral bands in the visible and infrared segments of the electromagnetic spectrum.

Meteorological offices and institutes around the world continue to benefit from the data generated by the GOES constellation. In addition, the National Hurricane Centre combines satellite observations from GOES and other satellites, aerial observations from reconnaissance aircraft, and data acquired from sensors in ships, buoys, radar and other land-based platforms to monitor the spatial and temporal characteristics of tropical storms and hurricanes.[b]

[a] United States, National Oceanic and Atmospheric Administration, *History of NOAA Satellites*. Available at www.nesdis.noaa.gov/current-satellite-missions/history-of-noaa-satellites

[b] Jonathan Zawislak and others, "Accomplishments of NOAA's Airborne Hurricane Field Program and a Broader Future Approach to Forecast Improvement". Available at https://journals.ametsoc.org/view/journals/bams/103/2/BAMS-D-20-0174.1.xml

Figure 2.3 GOES East image of Earth at 16:40Z on 21 August 2023



Source: NOAA

The Applications Technology Satellite-1 was the first environmental satellite launched into geostationary orbit by the United States in 1966. It included the spin scan cloud camera that produced visible images of the Earth every 20 minutes.[44] As satellite sensor and communication technology have advanced, meteorology satellites can produce ever more frequent rapid-scan imagery.

Rapid-scan data are vital for monitoring and forecasting a range of rapidly changing, impactful events such as tropical storms, cyclones, typhoons and hurricanes, snowstorms and blizzards, storm surges, floods, forest and wildfires, and even sand or desert storms.

[44] World Meteorological Organization, "NOAA's Eyes in the Sky - After Five Decades of Weather Forecasting with Environmental Satellites, What Do Future Satellites Promise for Meteorologists and Society?". Available at https://public.wmo.int/en/resources/bulletin/noaa%E2%80%99s-eyes-sky-after-five-decades-of-weather-forecasting-environmental

CASE STUDY

The role of satellite observations in weather forecasting: the European Centre for Medium-Range Weather Forecasts [a]

What is the role of satellite observations in weather forecasting?

The European Centre for Medium-Range Weather Forecasts (ECMWF) uses satellite data for climate monitoring, atmospheric composition monitoring and forecasts as part of the European Commission's Copernicus programme. Satellite data also help to monitor the quality of forecasts and to identify and remedy deficiencies in Earth system models. As indicated by ECMWF, satellite observations make a crucial contribution to the quality of today's weather forecasts. Their global coverage means that they provide information on the atmosphere, the land surface, the ocean and sea ice that cannot be provided by in situ measurements. Through a process called data assimilation, they help to produce the best possible estimate of the current state of the Earth system. That estimate is used as the initial condition on which weather forecasts are based.

What are the main areas of research in satellite data assimilation at ECMWF?

Active areas of research include the development of techniques to fully exploit hyperspectral infrared instruments, which have many channels: all-sky assimilation for infrared radiances, the use of more of the information that satellites provide on the wider Earth system, such as surface conditions, the ocean and atmospheric composition, and the treatment of random and systematic errors in satellite observations. In addition, the Centre works on new generations of instruments with partners such as the European Space Agency (ESA) and EUMETSAT in Europe and similar agencies in China, Japan and the United States. ECMWF has, for example, begun to assimilate Doppler wind light detection and ranging (LiDAR) observations from the ground-breaking Aeolus satellite, and it is preparing the ground for the assimilation of cloud profile observations from the EarthCARE mission planned by ESA and the Japan Aerospace Exploration Agency (JAXA).

What types of satellite observations are there?

Some satellites carry passive instruments, which measure radiation emitted naturally, and other satellites use active instruments, which send out signals and measure the backscatter. Natural radiation contains information, for instance, on temperature, humidity, clouds and surface conditions. It can also provide information on winds by tracing motions of humidity or cloud features in successive observations. Active instruments use radar or LiDAR to probe the surface, clouds and winds. Radio occultation observations are unique in that they involve sending signals from one satellite to another. The bending angle of such signals crossing the troposphere or stratosphere depends on temperature and humidity.

How has the use of satellite observations at ECMWF evolved?

The use of satellite data has greatly increased over the last few decades. Today such data collectively make the biggest contribution to forecast quality at ECMWF compared to other types of observations, such as those made with weather stations or aircraft data. Satellite observations do not measure variables such as temperature or ocean wave height directly. Instead, they measure quantities linked to these variables, such as radiances or radar echoes. ECMWF has come to play a leading role in extracting the maximum amount of information from such observations.

How are radiances assimilated into the Earth system model used by ECMWF?

Currently most satellite data used at ECMWF come from passive instruments measuring infrared or microwave radiances. Such radiances typically reflect conditions in a rather deep layer of the atmosphere and could be the result of any number of atmospheric states. To be able to compare the observations with the state of the atmosphere in the forecasting model, it is necessary to know what radiances would be observed if the model correctly stated the atmosphere. Such simulated radiances are produced by what is known as an observation operator. By comparing simulated radiances with those observed, the 4D-Var data assimilation system used by ECMWF can work out how the model state needs to be adjusted to pull it more closely towards the observations.

What is "all-sky" satellite data assimilation?

ECMWF has pioneered the use of satellite observations of microwave radiances affected by clouds and precipitation. Today such all-sky observations are routinely used at ECMWF and make a huge contribution to the quality of weather forecasts. All-sky assimilation requires a good representation of raindrops, snowflakes and other hydrometeors in the model, and some knowledge of how they affect microwave radiances. Only then can we successfully simulate the radiances a satellite instrument would measure if the state of the atmosphere corresponded to the model state.

[a] European Centre for Medium-Range Weather Forecasts Fact sheet: "ECMWF's use of satellite observations". Available at https://www.ecmwf.int/en/about/media-centre/focus/2020/fact-sheet-ecmwfs-use-satellite-observations

Other Earth observation satellites

In addition to meteorological satellites, space agencies and private companies have launched many satellites that also observe the surface of the Earth for other purposes, including for land cover/land use, agriculture and environmental monitoring (deforestation/reforestation efforts).

In general terms, these Earth observation satellites can be divided into two classes:

- Those that operate in the optical and near-infrared regimes of the electromagnetic spectrum using the sun as a source of light (passive)
- Those that operate in the microwave segment of the electromagnetic spectrum that send their own signal to the surface of the Earth and receive the reflection of that signal (active)

Many Earth observation satellites launched by consortiums, individual countries and private operators include sensors that cover the optical and near-infrared segments of the electromagnetic spectrum. These satellites offer the most up-to-date view of elements exposed to natural hazards, as well as imagery of storms, hurricanes, cyclones and typhoons, active volcanoes, forest fires, landslides and other hazards. The continuous daily monitoring of the Earth's surface also allows the data to be used to monitor land use/land cover changes. For example, the combination of optical and near-infrared imagery allows professionals and experts to identify the impacts of drought on vegetation.

CASE STUDY

Landsat satellites

Landsat is a constellation of passive satellites launched by the National Aeronautics and Space Administration (NASA) of the United States that started in the 1970s. The passive sensors on the Landsat satellites have acquired millions of medium-resolution multispectral images with global coverage and are provided free of charge to users. The images, archived in the United States and at Landsat receiving stations worldwide, are a unique resource for global change research and applications in agriculture, cartography, geology, forestry, regional planning, surveillance and education. In addition, imagery can be accessed through the Earth Explorer website of the United States Geological Survey (USGS).

From 1970 to 2021, NASA launched nine satellites of this constellation to improve the Earth's land surface observations that are useful for monitoring land-use change and environmental impacts caused by global warming, droughts, urbanization and wildfires.[a]

Landsat's current temporal resolution is 16 days.

The various Landsat series could be divided into different categories based on the sensors adopted in each satellite:

- Landsats 1, 2 and 3 were equipped with the Multispectral Scanner System sensor capable of detecting visible and near-infrared wavelengths.
- Landsats 4 and 5 were provided with the Thematic Mapper sensor capable of returning two additional bands for reflected infrared and one band for thermal infrared.
- Landsats 6 and 7 were adapted with the Enhanced Thematic Mapper Plus sensor, and panchromatic band eight was introduced, with a broader detection spectrum (green to near-infrared) allowing for better spatial resolution.
- Landsat 8 receives data in 11 separate bands from two different sensors: the Operational Land Imager (OLI) and the Thermal InfraRed Sensor.
- Landsat 9 is an improved copy of the Landsat 8 sensors.

Figure 2.4 shows an illustration of the Landsat 8 satellite in orbit. At the time of publication, both Landsat 8 and Landsat 9 satellites are in orbit. The millions of Earth images support decision makers in fostering early warning systems procedures, disaster management cycle strategies and increase the resilience of communities.[b]

Furthermore, Landsat Earth observations are crucial to detect the land surface before and after a disaster. The data are useful for assessing hazard risk, mapping the damage extension, evaluating the severity of a specific hazard or climate change consequence, and increasing the preparedness for response and recovery.

Some examples of Landsat's applications of space-based observations related to disasters include:

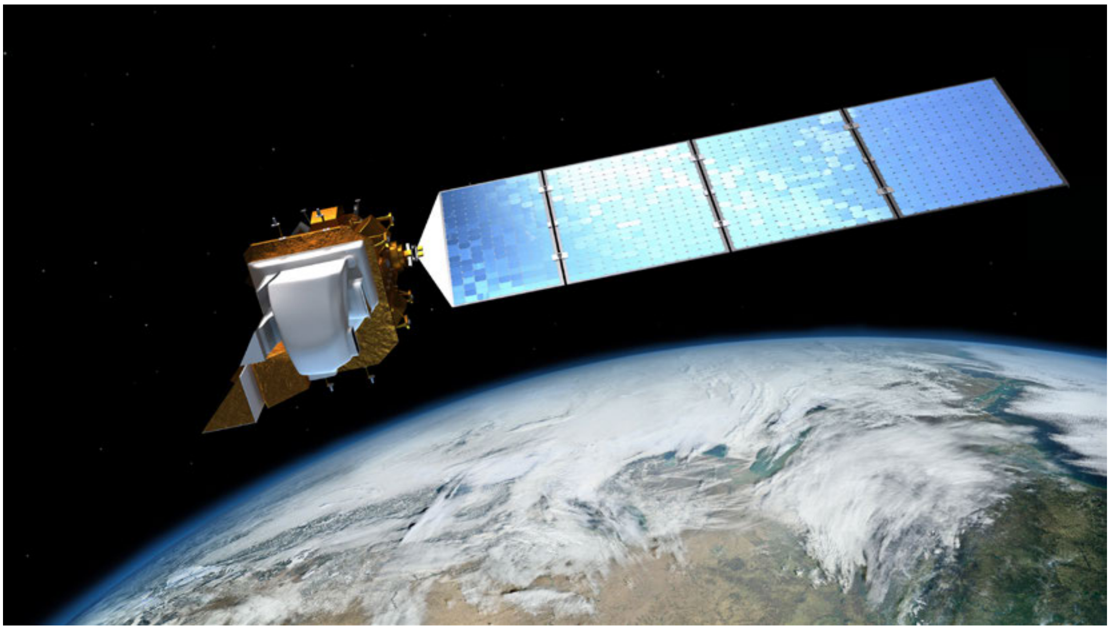
- Analysis of the heat from fires both during and after the burns
- Location and extent of lava flows
- Elaboration of flood extent maps and flood depth maps
- Analysis of drought impact, drought hazard, drought duration and frequency

Other Landsat satellite observations related to climate change outcomes include monitoring the extent of glaciers and the physical conditions of glacial lakes, and deforestation rates.

[a] United States, National Aeronautics and Space Administration, *Landsat Science. About section*. Available at https://landsat.gsfc.nasa.gov/about/

[b] A. J. Marx, T. V. Loboda, "Landsat-based early warning system to detect the destruction of villages in Darfur, Sudan". *Remote-Sensing Environment.* Vol. 136. (September 2013), pp126-134. Available at https://doi.org/10.1016/j.rse.2013.05.006

Figure 2.4. Illustration of the Landsat 8 in orbit



Source: EROS Date Centre, United States Geological Service

Optical imagery can be classified according to its resolution in terms of pixel size and the frequency of the electromagnetic spectrum that is being used. The resolution ranges from low to high, with low resolution pixel sizes covering 1 to 5 km and high resolution with pixel sizes of around one metre or less. Optical imagery is limited to the visible, near- and mid-infrared ranges of the electromagnetic spectrum.

While some space agencies have implemented open data policies that allow for open and free of charge access to low and moderate resolution satellite imagery, many space agencies have not yet implemented such policies. Furthermore, in most cases, the generation and provision of high-resolution optical imagery has been allocated to the private sector.

The combination of archived and up-to-date optical imagery is allowing practitioners to track the effects of hazards on vulnerable elements.

CASE STUDY

Planet.com – Commercial Earth observation for early warning systems[a]

Planet is a leading Earth observation company, providing the highest frequency satellite data available and foundational analytics to derive insights that empower users across the world to make impactful, timely decisions. Planet's platform processes and distributes a global, near-daily stream of high-resolution satellite data into the workflows of customers and partners, enabling them to quickly build applications that evolve and respond to our rapidly changing world.

Planet has built and successfully deployed over 450 satellites, with over 200 currently in orbit, collecting 350 million square kilometres of imagery every day. The satellites are operated in two "constellations", with unique spatial, temporal and radiometric resolutions. This allows Planet to capture the Earth's surface from multiple perspectives and dimensions. Planet operates two types of satellite in its two constellations: Doves and SkySats.

Doves weigh approximately five kilograms and are roughly the size of a showbox, much smaller than traditional satellites. These satellites are typically launched in large groups, called "flocks".

The SkySat constellation can image any point on Earth in high resolution of 50 centimetres at subdaily intervals. Stereo imagery and video footage of up to 90 seconds can also be captured. SkySats have an internal propulsion system, allowing Planet to maintain desired altitudes and optimize global coverage.

The satellite data collected is processed and made available for five different areas of application:

- Planet monitoring – to see and understand daily changes on Earth
- Planet tasking – providing near-real-time intelligence to proactively identify blind spots, anticipate events and have confidence in the next mission critical decisions
- Planet basemaps – visually consistent and scientifically accurate imagery that informs time series analysis and machine learning powered analytics
- Planet analytics feeds – identifies objects and features of interest to enable resource prioritization and decision-making based on the most recent insights available
- Planet archive – monitor areas of interest, validating information on the ground and discovering trends of relevance

The 3.7 m resolution images in four multispectral bands (red, blue, green and near-infrared), the greater visibility offered by Planet to obtain ground-truth data from opaque, dispersed or remote geographies, the 200 orbits every 90 minutes, and the continuous coverage mean that the commercial offering from Planet has potential for EWS.

[a] Planet, "The leading provider of global daily Earth data". Available at www.planet.com

While optical satellites cannot make observations below the clouds, synthetic aperture radar (SAR) sensors in dedicated satellites operate in a microwave segment of the electromagnetic spectrum that is unimpeded by clouds. Such sensors send signals to the Earth which bounce back to the satellite. This allows these active sensors to monitor hazards during day or night conditions, even under cloud cover.[45]

Like optical imagery, SAR imagery is useful to understand the dynamics of natural hazards such as floods, droughts, earthquakes, landslides and other types of mass movements, oil spills and volcanic activity.

Figure 2.5 presents an illustration of the Sentinel 1 satellites of the Copernicus constellation. Such satellites are frequently used to map the geographic extent of floods, to detect the deformation of land triggered by earthquakes and volcanic activity and are beginning to be used in early warning efforts in case of floods, landslides and volcanic activity.

Figure 2.5 One of the Sentinel 1 satellites in orbit.

Source: ESA

Aperture radar sensors are operated in in a narrow portion of the microwave segment of the electromagnetic spectrum. The typical frequency ranges have been designated with letters. Table 2.1 presents typical frequency ranges:[46]

[45] European Space Agency, "Synthetic Aperture Radar (SAR) (ERS) Overview". Available at https://earth.esa.int/eogateway/instruments/sar-ers/description

[46] United States, National Aeronautics and Space Administration, "Earth Data. Synthetic Aperture Radar". Available at https://earthdata.nasa.gov/learn/backgrounders/what-is-sar

Table 2.1 Frequency bands for SAR satellites and typical applications

Band designation	*Frequency range (GHz)*	*Typical application*
L	1–2	Moderate resolution SAR. Geophysical monitoring, vegetation
S	2–4	Agriculture
C	4–8	Change detection, ice, oceans
X	8–12	High-resolution SAR Used in urban monitoring, ice and snow

Source: Adapted from NASA

One technique used in radar imagery is the combination of sequential images of the same satellite in the same orbit to track minute changes in the elevation or subsidence of land. This procedure, called interferometric SAR (InSAR), can be used to monitor the deformation of volcanic domes, active landslides, relative motion of tectonic plates and subsidence in urban or rural areas.[47]

CASE STUDY

The Joint Italian-Argentinian Satellite System for Disaster Management (SIASGE)[a, b]

The Joint Italian-Argentinian Satellite System for Disaster Management (SIASGE) is an international cooperation effort to deploy active satellites to contribute to disaster management efforts. The cooperation agreement was signed in 2005 and the satellite constellation includes four Italian COSMO-SkyMed satellites and two Argentinian SAOCOM satellites.

The six satellites are positioned in polar orbit at the same altitude for a near-real-time monitoring of hazards with an expected update every 12 hours. The radar satellites can monitor forest fires, floods, volcanic eruptions, earthquakes, avalanches, landslides and mass movements day and night, even under cloud cover. The sixth satellite of the constellation is the SAOCOM 1B satellite and it was launched in August 2020. Figure 2.6 presents a schematic diagram of SIASGE.

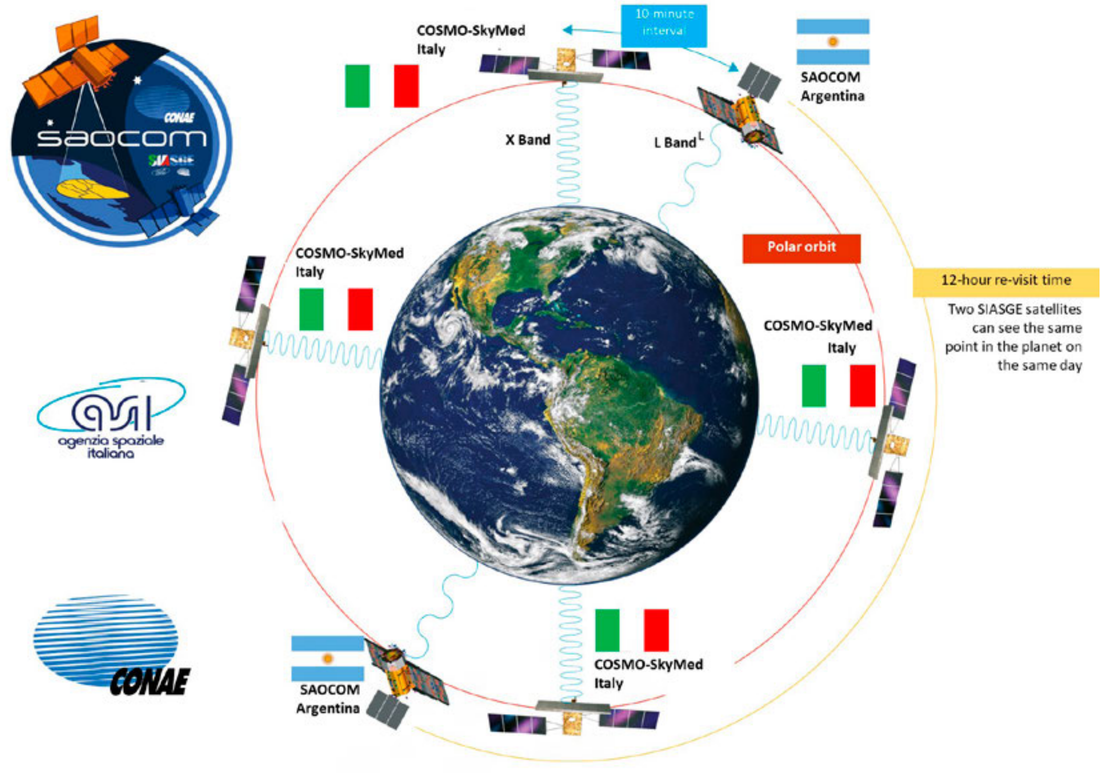
A few years ago, the Copernicus programme began to launch a constellation of active and passive satellites to contribute to an improved understanding of the dynamic nature of the planet and to map changes over time driven by societies around the world.

[a] Argentina, National Space Activities Commission. Sistema Ítalo Argentino de Satélites para la Gestión de Emergencias (SIASGE). Available at www.argentina.gob.ar/ciencia/conae/misiones-espaciales/siasge

[b] Italian Space Agency. Italian-Argentinian satellite system for disaster management. Available at www.asi.it/scienze-della-terra/cosmo-skymed/siasge

[47] Further information on radar interferometry is available from ESA at: https://www.esa.int/About_Us/ESA_Publications/InSAR_Principles_Guidelines_for_SAR_Interferometry_Processing_and_Interpretation_br_ESA_TM-19, from NASA at: https://appliedsciences.nasa.gov/sites/default/files/Session4-SAR-English_0.pdf, from Copernicus Sentinel programme at: https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-1-sar/product-overview/interferometry, from ALOS PALSAR InSAR at: https://asf.alaska.edu/wp-content/uploads/2019/03/asfnn_4-4.pdf

Figure 2.6 SIASGE satellite constellation.



Source: SIASGE, CONAE

CASE STUDY

The Copernicus Satellite Constellation[a, b]

Recognizing the usefulness of satellite observations for a variety of applications, the European Commission established its Earth observation programme naming it Copernicus. The programme includes a constellation of optical and infrared radar and other types of satellites to contribute to an improved monitoring of the atmosphere, the land and marine environments. It also addresses those challenges posited by climate change and natural hazards, as well as security concerns. The first satellite of the constellation was launched at the end of 2014, and nearly 20 satellites are expected to be in orbit by 2030. Figure 2.7 presents the services offered by Copernicus.

The Sentinel 1 satellites are radar-type satellites that are useful for monitoring a variety of natural hazards. For instance, these satellites can track the geographical extent of water bodies. This information is useful in the case of floods and droughts. These satellites also have the capability to track minute deformations of the surface of the planet through what is known as radar interferometry. In the case of early warning applications, radar interferometry allows experts to track the deformation of volcanic domes before eruptions, to monitor slow-moving landslides, and to monitor the subsidence of land due to natural or anthropogenic factors.

The Sentinel 2 satellites, operating in the optical and near-infrared regimes, complement the Sentinel 1 satellites in monitoring many types of hazards. These satellites contribute to monitoring vegetation, soil and water cover. They are very useful in the case of droughts, floods, forest fires and to monitor some geological hazards.

The Sentinel 3 and 6 satellites include optical sensors and altimeters. The Sentinel 6 satellite provides high accuracy altimetry for oceanography and climate studies.

The Sentinel 4 and 5 satellites will include atmospheric chemistry sensors that will be useful in the case of forest fires and to track the dynamics of volcanic ash clouds.

Recognizing the need to enhance the use of the data generated by these satellites, the European Commission implemented an open data policy that allows researchers and professionals around the world to download and use the imagery for many purposes. In addition, the Commission is facilitating the generation of services to address the challenges posed by floods, droughts and forest fires, as well as products such as digital elevation models than can be used for flood, storm surge, tsunami and landslide hazard assessments.

[a] European Union Copernicus Programme. "Europe's Eyes on Earth". Available at www.copernicus.eu/en

[b] European Union Copernicus Programme. "What is Copernicus". Available at www.copernicus.eu/sites/default/files/Brochure_Copernicus_2019%20updated_0.pdf

Figure 2.7 Services provided by Copernicus.

Copernicus

- Climate change
- Marine monitoring
- Atmosphere monitoring
- Land monitoring
- Security
- Emergency management

Source: Copernicus, background imagery courtesy of NASA

2.2.2 Satellite telecommunications

The first telecommunications satellite launched into orbit was Telstar 1. This was a joint effort between the National Aeronautics and Space Administration (NASA) and the former AT&T Bell Telephone Laboratories of the United States. Launched in July 1962, it facilitated the transmission of television and telephone signals between the United States and Europe.

Since then, different companies and space agencies have launched a variety of telecommunication satellites. As the need and use of telecommunications satellites increased, private companies such as COMSAT began to emerge.

While the typical application of these satellites is to contribute to telephone communications, television and radio broadcasting, the role of satellite telecommunication in early warning systems cannot be underestimated. Satellite communications play an essential role in transmitting raw data from sensors to the early warning centres for subsequent analysis and then disseminating early warnings to those at risk. The use of satellites to send data for early warning systems is particularly beneficial where sensors are deployed in remote areas that are used to monitor hazard events and precursors to hazard events.

2.2.3 Global navigation satellite systems

Global navigation satellite systems (GNSS) have been designed to provide positioning, velocity and timing services for terrestrial users, and are now being increasingly utilized for autonomous navigation in space.[48] GNSS include constellations of Earth-orbiting satellites that broadcast their locations in space and time and networks of ground control stations and receivers that calculate ground positions by trilateration.

GNSS are used in all forms of transportation: aviation, maritime, rail, road and mass transit. Positioning, navigation and timing play a critical role in a vast range of sectors, including telecommunications, land surveying, law enforcement, emergency response, precision agriculture, mining, finance and scientific research.

As indicated by UNOOSA, "GNSS includes two fully operational global systems: the Global Positioning System (GPS) of the United States and the GLObal NAvigation Satellite System (GLONASS) of the Russian Federation, as well as the developing global and regional systems, namely the European Satellite Navigation System (GALILEO) and the COMPASS/Bei-Dou system of China, the Regional Navigation Satellite System (IRNSS) of India and the Quasi-Zenith Satellite System (QZSS) of Japan. Once all these global and regional systems become fully operational, the user will have access to positioning, navigation and timing signals from more than 100 satellites."[49]

In early warning systems, GNSS is an essential enabling technology for the mapping and precise monitoring of deformations of the ground. For example, GNSS is used by the United States Geological Service (USGS), and other organizations around the world, for monitoring flank movements and lava dome growth. Any changes in growth can be indicative of magma movement, which could result in an eruption.[50]

[48] More information on global navigation satellite systems is available at www.unoosa.org/oosa/en/ourwork/psa/gnss/gnss.html

[49] United Nations Office for Outer Space Affairs, "Global Navigation Satellite Systems (GNSS)". Available at www.unoosa.org/oosa/en/ourwork/psa/gnss/gnss.html

[50] United States Geological Survey, *Earthquakes and Other Natural Hazards: GNSS for Disaster Management*. Available at www.unoosa.org/pdf/icg/2011/icg-6/21-1.pdf

2.3 Using space technologies

Space-based data comes in a range of types and formats, and, over the years, the space community has generated products that extend the use of such data in early warning systems. More recently, the space community and other geospatial agencies have begun to implement services that facilitate access to ready-to-use, or nearly ready-to-use, geospatial information. Figure 2.8 presents an example of this trend in the case of drought.

Figure 2.8 The transition from satellite imagery to products and then to services in the case of droughts

Evolution of contributions from the space community in applications in early warning systems

Raw data

Satellite image

A view of Africa

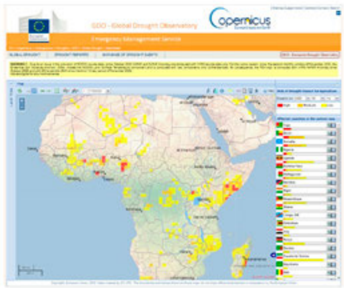
Products

Land use/land cover maps

Type of vegetation that may be exposed to droughts

Services

Global Drought Observatory (GDO)



Regions within countries at risk of drought impact for agriculture

Source: ESA, EUMETSAT and Copernicus Drought Observatory

2.3.1 Accessing the data

Satellite imagery

Satellite imagery is downloaded in the form of files which are subsequently processed by the receiving organization. This process includes ortho-rectification procedures, which process the images to apply corrections for optical distortions from the sensor system, and apparent changes in the position of ground objects caused by the perspective of the sensor view angle and ground terrain.[51] As the data are accessed in a raw format, they need to be processed using dedicated software to generate useful information that is often presented in the form of maps.

Some space agencies, such as the National Aeronautics and Space Administration (NASA) of the United States, the European Space Agency (ESA) and the Copernicus programme, have implemented open data policies that facilitate the use of such imagery. An example is the imagery from the moderate resolution imaging spectroradiometer (MODIS) sensors on board the TERRA and AQUA satellites. MODIS composite products are used in several applications including agriculture and environmental management, where there is no need for high-resolution imagery. UN-SPIDER and other organizations have developed specific procedures to combine archived and up-to-date composite products such as the Enhanced Vegetation Index (EVI) and the Normalized Difference Vegetation Index (NDVI) to track the severity of a specific drought in comparison to historic droughts since the year 2000.[52]

[51] Esri, "What is orthorectified imagery?" Available at www.esri.com/about/newsroom/insider/what-is-orthorectified-imagery

[52] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practices". Available at www.un-spider.org/advisory-support/recommended-practices

High-resolution satellite imagery could offer potential advances for the monitoring and warning of hazards, as the pixel size ranges from 5 to 6 metres down to 50 cm. However, most of this capability is only currently available commercially.

Open source satellite imagery is available through these providers:

- Copernicus Ecosystem https://dataspace.copernicus.eu
- USGS - Landsat satellite imagery www.usgs.gov/landsat-missions/landsat-data-access and www.usgs.gov/landsat-missions/data
- NOAA - GOES satellite imagery www.star.nesdis.noaa.gov/goes/index.php
- ESA https://earth.esa.int/eogateway/catalog

Location-based data

Location-based data acquired from the constellation of GNSS satellites are available in the form of numerical coordinates, indicating the geographic position of a point using latitude and longitude.

2.3.2 Products

In recent decades, the space community has realized the usefulness of preprocessing satellite imagery to generate a variety of products. Examples of products used in early warning systems include digital elevation models (DEM). These are used in flood and landslide hazard mapping and for hydrological flood modelling. In a complementary fashion, land-use and land-cover products are used to track changes in the use of land in environmental applications and can also be used in flood and landslide hazard mapping.

CASE STUDY

Digital elevation modelling for risk knowledge and monitoring in early warning systems[a]

Satellite data can be processed to create a wide range of services and products. One example is the use of elevation data from Earth observation satellites to monitor changes indicative of natural hazards, such as landslides and volcanic eruptions.

UN-SPIDER has collated user cases involving space technologies for disaster risk reduction into its Knowledge Portal. Examples include the use of the digital elevation model (DEM) called WorldDEM™, which has been developed by Airbus Defence and Space, and covers the entire land surface of the Earth. WorldDEM™ can be used in hazard modelling in case of floods, landslides, tsunamis and storm surges to support EWS.

Inundation modelling for sea level rise

Climate change-driven sea level rise is a global phenomenon that is affecting communities in coastal and island regions as well as marine and terrestrial ecosystems. Currently sea levels rise around 3mm per year on a global scale and the rate is expected to intensify in the future. The global coverage of the WorldDEM™ elevation products and the detailed extraction of the world ocean shoreline (map scale 1:20,000) enable the modelling of sea level rise for every region of the world. Understanding the potential implications of sea level rise is vital for coastal hazard early warning systems, such as tsunami and storm surge.

Flood hazard mapping

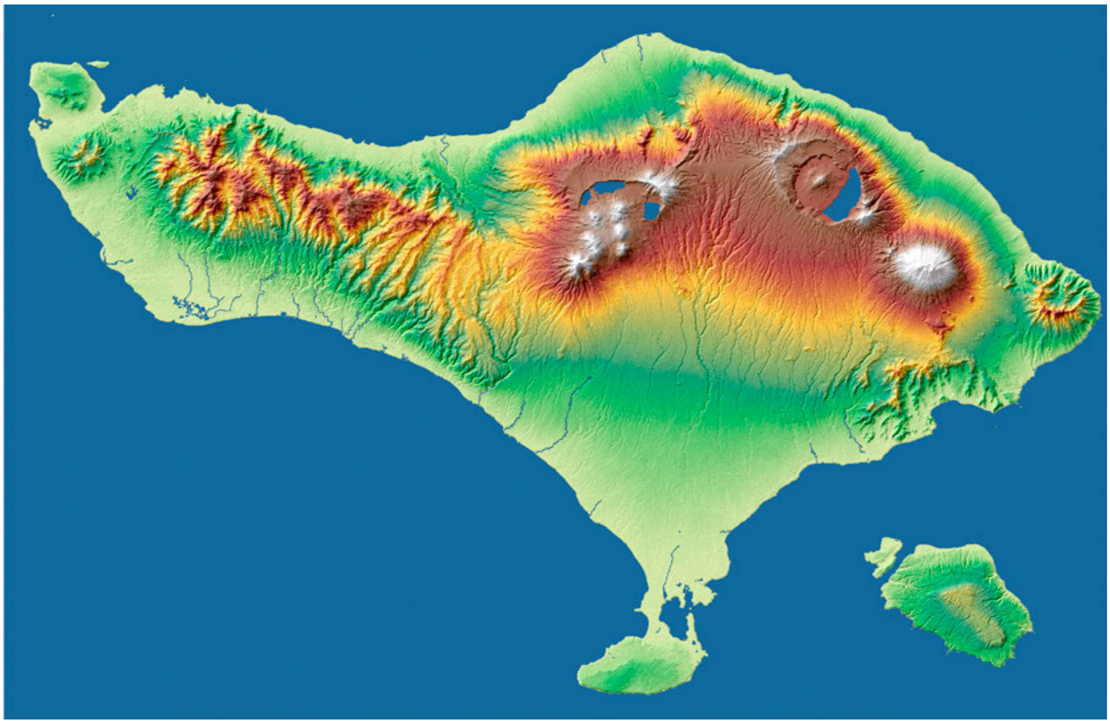
Another application of the WorldDEM™ data is flood hazard mapping. Modelling for floods is required to identify areas exposed to hydrological risk or to capture flood-prone areas. At the suggestion of UN-SPIDER, the Space Application Centre for Response in Emergency and Disasters (SACRED) of the Space and Upper Atmosphere Research Commission (SUPARCO) of Pakistan developed a recommended practice for the elaboration of flood hazard maps using the WorldDEM™. This recommended practice is available in this link: https://un-spider.org/advisory-support/recommended-practices/recommended-practice-flood-hazard-assessment

Landslide hazard mapping

To assess risks of landslides in mountainous regions, information about the topography is required. WorldDEM™ elevation products offer high-resolution topographic information for the entire landmass of the world. Based on WorldDEM™ terrain elevation, the secondary relief parameters slope and aspect can be derived and used to determine the flow direction of rock, debris or earth. In combination with information about geology, tectonics, soil and vegetation cover, the monitoring of landslides is possible on the local, regional and global scale. Figure 2.9 presents an example of a digital elevation map of the island of Bali in Indonesia.

[a] AIRBUS Defence and Space, "WorldDEM Neo-World-DEM". Available at www.intelligence-airbusds.com/en/5751-image-gallery-details?img=35255

Figure 2.9 WorldDEM™ digital elevation model of the island of Bali in Indonesia



Source: AIRBUS

Elevation data produced using satellites are generally less accurate than airborne and ground surveys.[53] However, many satellite-derived elevation data are free and open at a coarser grid size ranging from 30 to 90 metres with the best vertical accuracies of 4 metres.[54] For example, the Shuttle Radar Topography Mission (SRTM) provides DEM at 30- and 90-metre grid size with a vertical accuracy of 6 metres. The Advanced Land Observing Satellite (ALOS) AW3D30 offers DEM at a 30-metre grid size with vertical accuracy of 4.3 metres. ALOS also provides a commercial product at a 5-metre grid size with a vertical accuracy of 2.7 metres. The list of some of the most common free and commercial global DEMs is presented in table 2.2.

The National Oceanic and Atmospheric Administration (NOAA) of the United States makes available composite products derived from the satellite imagery from the MODIS sensors, which are finding applications in drought early warning systems. Some of these include the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), which are subsequently combined to generate long-term series such as the Vegetation Condition Index (VCI) and the Standard Vegetation Index (SVI).

In addition to these products, researchers in the space and the academic communities have expanded the use of satellite imagery and location-based data to generate long-time sequences. One example is satellite altimetry, measuring the level of the oceans, which is significant for use in climate change applications.

Table 2.2 Examples of free and commercial global digital elevation models

Name	*Type*	*Resolution (m)*	*Link for additional information*
ALOS AW3D30	Free	30	www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm
ASTER GDEM	Free	30	www.earthdata.nasa.gov/news/new-aster-gdem
Copernicus DEM	Free	30 and 90 outside Europe, 10 in Europe	https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model
SRTM	Free	30 and 90	www.jpl.nasa.gov/news/us-releases-enhanced-shuttle-land-elevation-data
TANDEM-X	Free	90	https://geoservice.dlr.de/web/dataguide/tdm90/
PlanetDEM	Commercial, Planet	30	www.planetobserver.com/global-elevation-data
WorldDEM™	Commercial, Airbus Defence and Space	5 and 12	www.intelligence-airbusds.com/imagery/reference-layers/worlddem/

Source: UN-SPIDER

The composite products from MODIS now cover a series of over 20 years of continuous observation. This relatively long series is proving to be extremely useful in drought early warning systems.

[53] J. Griffin and others, "An evaluation of onshore digital elevation models for modelling tsunami inundation zones". *Frontiers in Earth Sciences*, vol. 3. (18 December 2018). Available at https://doi.org/10.3389/feart.2015.00032

[54] L. Hawker, P. Bates, J. Neal, and J. Rougier, "Perspectives on Digital Elevation Model (DEM) Simulation for Flood Modelling in the Absence of a High-Accuracy Open Access Global DEM". *Frontiers in Earth Science*, vol.6. (18 December 2018). Available at https://doi.org/10.3389/feart.2018.00233

In addition to products that visualize hazard information for use in EWS, satellite technology can be used to provide data on other variables that are critical to understanding the risk picture ahead of a hazardous event. For example, estimates of population derived from satellite imagery are available from the Global Human Settlement Layer (GHSL) of the Joint Research Centre of the European Commission and the World Settlement Footprint (WSF) of the German Aerospace Centre (DLR). Understanding the size and location of populations is finding application in risks assessments associated with early warning systems, and the implementation of impact-based forecasts.

2.3.3 Services

In addition to the growing availability of satellite imagery and products, the space community is facilitating access to space-based data via services that already include pre-processed satellite imagery. Examples of these are detailed below.

Human settlements

For the last decade, efforts have been undertaken to process satellite imagery to locate and map human settlements. Two examples are the World Settlement Footprint of the German Aerospace Center and the Global Human Settlement Layer developed by the Joint Research Centre of the European Commission. The information provided by these services is gradually being used in impact-based forecasts, and they provide information on settlements exposed to hazards.

CASE STUDY

The World Settlement Footprint: global trends in urbanization informing early warning systems [a]

The population of the world is expected to reach 9.7 billion in 2050, according to the United Nations Department of Economics and Social Affairs. Urban areas are already home to 55 per cent of the world's population and that figure is expected to grow to 68 per cent by 2050. Rapid and unplanned urbanization can lead to higher vulnerability to disasters, as well as issues related to the management of resources such as water, raw materials and energy.

To improve the understanding of current trends in global urbanization, the German Aerospace Center (DLR) and the European Space Agency (ESA), in collaboration with the Google Earth Engine team, are jointly developing the World Settlement Footprint – the world's most comprehensive data set on human settlement.

The WSF suite consists of several different products, two of which were publicly released during the United Nations Climate Change Conference (COP26) for the Cities, Regions and Built Environment Day: The World Settlement Footprint 2019 and the World Settlement Footprint Evolution. These products were built using millions of hours of compute time with Google Earth Engine. Figure 2.10 presents an example of the World Settlement Footprint 2019 focusing on Port-au-Prince, Haiti.

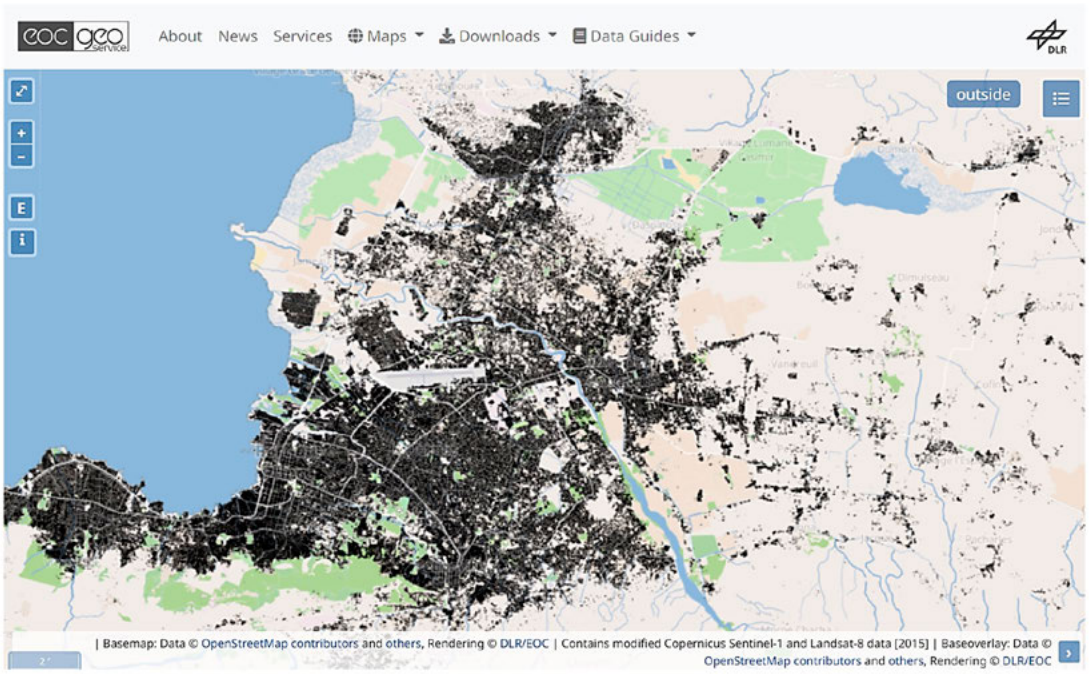
The WSF 2019, which provides information on global human settlements with unprecedented detail and precision, features data from the Copernicus Sentinel-1 and Sentinel-2 missions, while WSF Evolution was generated by processing seven million images from the United States Landsat satellite collected between 1985 and 2015 and illustrates the worldwide growth of human settlements on a year-by-year basis. This unprecedented collection of global products on human settlement advances our understanding of urbanization on a global scale.

CASE STUDY (*continued*)

WSF Evolution has been used by the World Bank's Urban, Disaster Risk Management, Resilience and Land Global Practice to track the flood risk exposure of growing cities around the world, such as Bangkok. The data suggest that new and unplanned settlements in high-risk flooded areas have grown significantly, especially in low and middle-income countries. The high-resolution data allows World Bank to work with partners around the world to determine how this risk is evolving and identify the drivers of such high-risk urban growth.

[a] European Space Agency, "Mapping our human footprint from space". Available at www.esa.int/Applications/Observing_the_Earth/Mapping_our_human_footprint_from_space

Figure 2.10 World Settlement Footprint 2019 of Port-au-Prince, Haiti



Source: German Aerospace Centre DLR

CASE STUDY

The Global Human Settlement Layer [a, b]

The Global Human Settlement Layer (GHSL) provides global spatial information about human presence on the planet over time. The data are in the form of built-up maps, population density maps and settlement maps. This information is generated with evidence-based analytics and knowledge using new spatial data mining technologies.

The GHSL processing framework uses heterogeneous data including global archives of fine-scale satellite imagery, census data and volunteered geographic information. The data are processed fully automatically and generate analytics and knowledge reporting objectively and systematically about the presence of population and built-up infrastructures.

GHSL data were developed to meet the needs and support applications along the whole disaster risk management cycle, including crisis management and disaster response. Built-up area and population are two essential societal variables for understanding the exposure of people and human settlements to natural and man-made disasters. In turn, understanding exposure is critical to impact-based early warning systems which use exposure and vulnerability data to assess the potential for impacts by type and severity.

[a] European Commission, "GHSL – Global Human Settlement Layer". Available at https://ghsl.jrc.ec.europa.eu/about.php

[b] European Commission, "Global Human Settlement Layer. Understanding Human Presence on Planet Earth". Available at https://ghsl.jrc.ec.europa.eu/documents/GHSL_Brochure.pdf?t=1639151473

Earth Observation Center Geoservice

The Geoservice[55] of the Earth Observation Center (EOC) of the German Aerospace Center (DLR) provides discovery, visualization and direct download services for a selection of geospatial data hosted by the German Satellite Data Archive (D-SDA). Using web technologies based on standardized interfaces defined by the Open Geospatial Consortium (OGC), data and associated catalogue information are accessible through Web Mapping Services (WMS), Web Coverage Services, and a Catalogue Service Web. Each geospatial data set is accompanied by metadata compliant with Infrastructure for Spatial Information in the European Community and Geo Data Infrastructure Germany.

The EOC Geoservice has been developed to allow for fast, easy and state-of-the-art access to the high-resolution geospatial data of D-SDA. The latter maintains a huge database of Earth observation data supplied by national and international Earth observation missions. Selected data sets, such as a global mosaic of the digital elevation model of the DLR Shuttle Radar Topography Mission (SRTM X), atmospheric products from the EUMETSAT Ozone Satellite Application Facility, as well as thematic products of the advanced very high-resolution radiometer of the NOAA POES satellite series are already available through the EOC Geoservice.

[55] Federal Republic of Germany, German Aerospace Centre, "EOC GEOservice. Welcome to the EOC Geoservice". Available at https://geoservice.dlr.de/web

The geospatial data of the EOC Geoservice are accessible through standardized OGC services which can be used directly by customers to discover and extract data. Additionally, Geoservice data can be discovered and accessed by OGC-based clients and portals, such as the Earth observation on the WEB Portal, the Geoportal.DE or the Global Earth Observation System of Systems (GEOSS) Data Portal.

In recent years, the Copernicus programme, together with partners in some cases, have launched three services that are useful in early warning efforts related to floods, droughts and forest fires.

Global Flood Awareness System

The Global Flood Awareness System (GLoFAS) was developed by the Copernicus programme to contribute to flood forecasting around the world. It provides information on expected magnitudes of floods in segments of channels of rivers and is updated daily. More recently, GLoFAS is being used in combination with in situ data on historic impacts of floods and additional information on vulnerability of elements to generate impact-based forecasts. More information on GLoFAS will be presented in chapter 3.

Global Drought Observatory

The Global Drought Observatory (GDO) is another Copernicus programme, developed by the team of the European Drought Observatory and provides a freely available service, designed to support emergency response challenges.[56] It provides a global view of the prevailing drought conditions that is useful to the international humanitarian community to foresee where it will need to be engaged (chapter 4). Additional services include heat waves and low flows for Europe and drought observatories for South and Central America and Africa.

GDO also supports regional-based drought services, such as the East Africa Drought Watch. The East Africa drought platform is a service developed as part of the Intra-ACP Climate Services Project in collaboration with the drought group of the Natural Disaster Risk Unit at the Joint Research Centre of the European Commission. The system is adopted from the European Drought Observatory and adapted to the conditions in the East Africa region.[57] More information on the Global Drought Observatory will be presented in chapter 4.

Global Wildfire Information System

The Global Wildfire Information System (GWIS), set up by the Copernicus programme, NASA, and the Group on Earth Observations (GEO), also provides useful information for early warning systems targeting forest fires.[58]

GWIS brings together existing information sources at regional and national level to provide a comprehensive view and assessment of fire regimes and fire effects at global level and provides tools to support operational wildfire management from national to global scales. More information on GWIS will be presented in chapter 10.

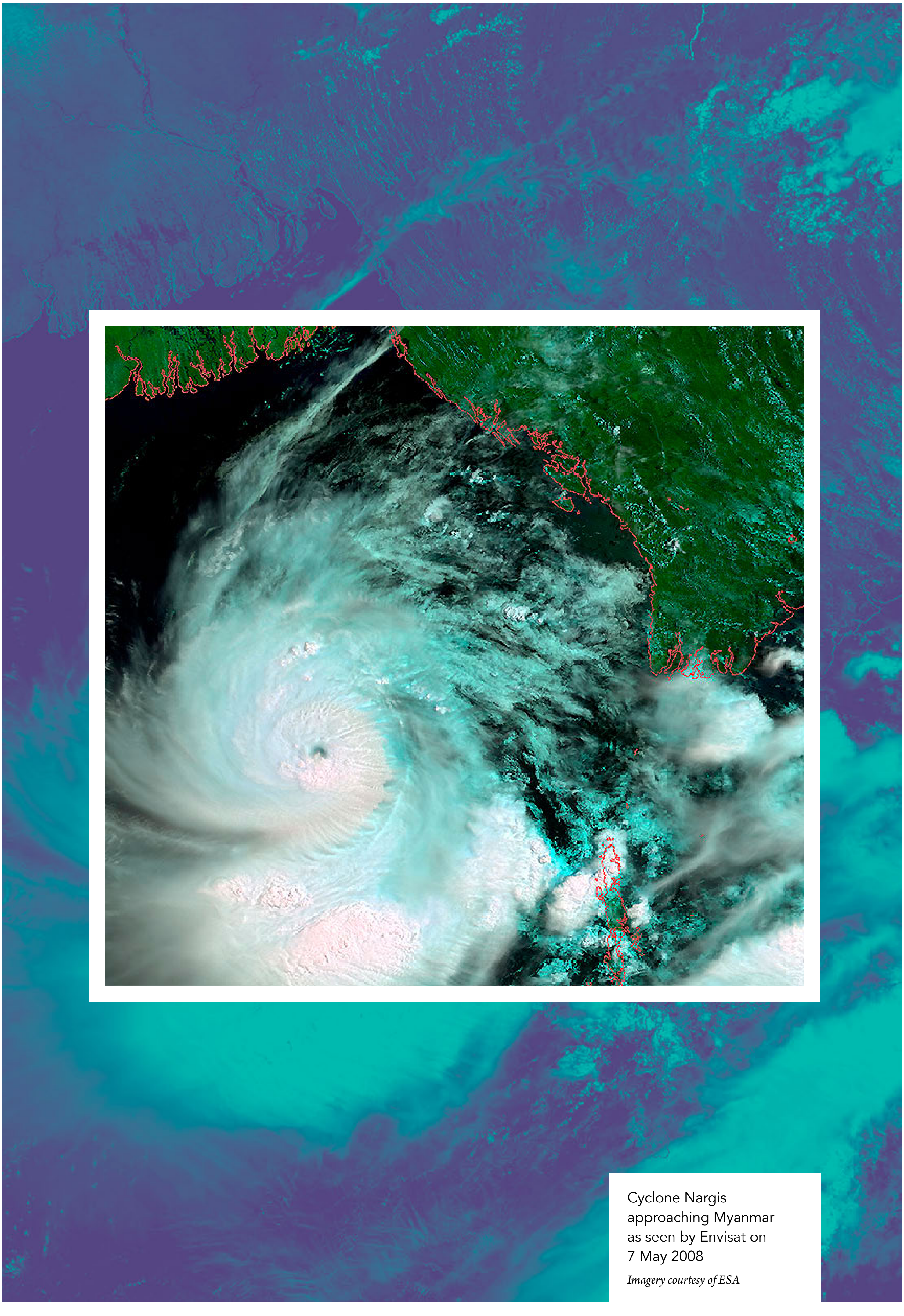
[56] European Commission Copernicus Programme. "GDO- Global Drought Observatory". Available at https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2001

[57] East Africa Drought Watch, "About Page". Available at https://droughtwatch.icpac.net/about

[58] European Commission Copernicus Programme, "Global Wildfire Information System GWIS". Available at https://gwis.jrc.ec.europa.eu

2.3.4 Services from the private sector

In addition to the examples provided above, the private sector is actively contributing to early warning efforts through the provision of relevant information on a timely basis. The next chapters of this publication will present examples of the use of public and private sector space technologies in specific early warning systems addressing a variety of hazards.



Cyclone Nargis approaching Myanmar as seen by Envisat on 7 May 2008

Imagery courtesy of ESA

Chapter 3.
Space technologies for rapid-onset hydrometeorological hazards

Hydrometeorological hazards result from the state and behaviour of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate produced and the resulting distribution of water resources.[59] The most frequent and impactful hydrometeorological hazards are typically storms, floods and droughts. These types of hazards can emerge, develop and cause impacts quickly (rapid-onset) or gradually build over time before effects are realized (slow-onset – see chapter 4). The required capability from space technologies for early warning systems depends on the type and characteristics of the hazard. For example, rapidly forming thunderstorms require high-resolution, rapid-scan Earth observations and fast, reliable satellite telecommunications to issue warnings quickly.

In recent decades, the contribution of space technologies to EWS for hydrometeorological hazards has been significant. Continuously evolving satellite capability has enabled Earth observations, providing valuable data on the current state and behaviour of the atmosphere and its interaction with oceans and land. Furthermore, the continual development of space technologies is increasing the accuracy of EWS.

More than 100 satellites have been launched to monitor the Earth's atmosphere. Half have been designed to support weather forecasting, whereas the others have been more research focused. Short-term weather-prediction science has advanced significantly through active microwave instruments, as these operate through cloud cover and without daylight. Microwave and infrared sensors can now map atmospheric temperature profiles, water vapour distribution, surface pressure and precipitation.

Satellite observations make a crucial contribution to the quality of today's weather forecasts. Their global coverage means that they provide information on the atmosphere, the land surface, the ocean and sea ice that cannot be provided by in situ measurements. Through data assimilation, they help to produce the best possible estimate of the current state of the Earth system. The assimilated data is ingested into forecasting models, providing the initial conditions for numerical weather prediction (NWP) and climate modelling. In turn, NWP and climate modelling then provide forecasts and early warnings of hazardous events that may occur in a matter of hours to days, weeks or months ahead.

[59] United Nations Office for Disaster Risk Reduction, "Hazard Definition & Classification Review: Technical Report". Available at www.irdrinternational.org/knowledge_pool/publications/858

The European Centre for Medium-Range Weather Forecasts (ECMWF), for example, uses satellite data for climate monitoring, atmospheric composition monitoring and forecasts as part of the Copernicus programme of the European Commission. Satellite data also help monitor forecast quality and identify and remedy deficiencies in Earth system models.

Medium-range weather forecasts that provide information five to seven days in advance were impossible before satellites began making global observations routinely available in real time, particularly over remote regions, such as the ocean waters of the Southern hemisphere. Global forecasting models developed at the United States National Center for Atmospheric Research, ECMWF and the United States National Meteorological Center became the standard during the 1980s, making medium-range forecasting a reality. Global weather forecasting models are also routinely run by national weather services worldwide, including those of Canada, Japan and the United Kingdom, all made possible by the development of satellite technology.

Near-real-time hydrometeorological satellite data measuring the current state of the atmosphere is also archived and catalogued to provide a time series of data used by hydrometeorological and climate specialists to build, test and improve numerical weather prediction, and hydrological and climate models. These models are critical to forecast potential impactful hydrometeorological hazards and issue early warnings.

The following segment of this chapter present information and examples on how space technologies contribute to early warning in the case of storms and floods.

3.1 Storms

The term storm is usually applied to any violent atmospheric disturbance and covers a range of meteorological systems, from low-pressure depressions and thunderstorms to hurricanes, typhoons and tropical cyclones. Storms are commonly associated with fierce winds. In addition, storms are often multi-hazard, including other hydrometeorological phenomena and hazards such as precipitation and storm surges (chapter 7), leading to flooding, lightning and rain-induced landslides (chapter 5).

Early warning systems for storms need capabilities that can detect the potential for storm development and monitor the life cycle of a storm once it develops. Satellite technologies, therefore, play a crucial role in providing Earth observation data, which can be used to detect and forecast storms and then track the storm's progress, behaviour and characteristics to enable warnings to be updated with the latest and most accurate information.

Satellite technology is particularly relevant for the most destructive storms, hurricanes, typhoons and tropical cyclones, which materialize over warm oceans where other ground-based monitoring technologies, such as automatic weather stations and radar, are absent.

In addition, wind scatterometers mounted on a polar-orbiting satellite can derive wind speed and direction close to the ocean's surface, providing valuable observations in the absence of ground-based monitoring.

Scatterometers direct radar pulses towards the Earth's surface and measure the strength of the backscattered return beam. Over the oceans, backscattering is caused by small wind-generated waves rather than larger swell waves.

These smaller waves on the sea surface, typically of wavelength 5–20 cm, tend to lie at right angles to the wind direction. Therefore, by measuring the backscatter at two or more angles of incidence, it is possible to derive the wind speed and direction close to the sea surface.[60]

CASE STUDY

How ECMWF satellite data assimilation improves forecasting hurricane development and tracking [a]

Tropical cyclones are some of the most devastating natural hazards on Earth. In 2017, the Atlantic hurricane season was one of the most active for years, with 17 storms, 10 hurricanes and 6 major hurricanes.[b] Several verification reports acknowledge deterministic and probabilistic tropical cyclone tracks from the European Centre for Medium-Range Weather Forecasts (ECMWF) as world-leading, and their contribution to forecasting the hurricanes of the 2017 season is well noted.

The presence of Irma in the Atlantic, for example, was predicted with high confidence by the extended-range forecast system more than a week before the genesis of the cyclone. Such predictability is increasingly common and based on a large forecast data set covering the past 20 years that is improving. Figure 3.1 presents a satellite image of hurricanes Katia, Irma and Jose in the western Atlantic acquired in September 2017.

One of the main challenges in assimilating tropical cyclones is the need for direct observations in the vicinity of the active environment inside and around these systems. Conventional observations (from buoys, aircraft and ships) are usually limited to scattered surface pressure observations and sometimes drop sondes from reconnaissance flights. However, satellites provide critical observations for forecasting, especially in the early stage of tropical cyclone development.

ECMWF uses satellite observations from various sophisticated sensors flying on more than 25 dedicated meteorological spacecraft. This complementary information from multiple satellite instruments is brought together by the 4D-Var system to build a comprehensive thermodynamic picture of the cyclone and its environment and to provide the best possible initial conditions for predicting its future evolution. For skilful medium-range predictions of tropical storms, not only is the information needed in the vicinity of tropical cyclones, but also in remote regions, seemingly unrelated to the location of tropical cyclone development and tracking, that later can affect the steering winds and other atmospheric characteristics which can have a significant effect on the tropical cyclone.

As with all hydrometeorological hazards, data from satellite technologies is assimilated alongside data from other ground, ocean and air observation technologies. However, the impact of satellite data on Irma has been investigated by retrospectively rerunning the forecasting and assimilation system with satellite observations deliberately withheld to simulate the effect of a significant absence of satellite data.

The skill of hurricane forecasting has continuously improved over the past few decades, and the track errors in the northern Atlantic and north-western Pacific have been halved over two decades. Such improvements originate from various sources, such as resolution upgrades, improved coupling and data assimilation, and are expected to continue. However, producing reliable intensity forecasts is still challenging for the ECMWF global forecasting model, especially regarding maximum wind speed.

[a] L. Magnusson and others, "ECMWF Activities for Improved Hurricane Forecasts", *Bulletin of the American Meteorological Society*, vol. 100, issue 3 (1 March 2019). Available at https://doi.org/10.1175/BAMS-D-18-0044.1

[b] United States, National Oceanic and Atmospheric Administration, "A Season to Remember". Available at www.weather.gov/news/17512_season-to-remember

[60] United Kingdom, Meteorological Office, *Observations from space*. Available at www.metoffice.gov.uk/weather/learn-about/how-forecasts-are-made/observations/observations-from-space

Figure 3.1 Hurricanes Katia, Irma and Jose in the western Atlantic in September 2017

Source: NASA Earth Observatory

CASE STUDY

Detecting and forecasting rapid-onset thunderstorms for warnings and disaster response [a, b, c]

Convective cells originate from the quick, vertical updraft of humid and relatively warm air. The fast cooling of the air with rising height leads to optically thick and icy clouds. This, in turn, is likely to lead to thunderstorms and heavy precipitation resulting in impacts from flash flooding, lightning strikes and fierce winds. Therefore, early and reliable prediction of convective cells is of great importance for weather forecasts and early warnings.

The reliable forecast of convective cells using numerical weather prediction is challenging. Convective cells are relatively small, and model resolutions are not sufficiently fine to capture cell formation and movement well. In addition, convective cells can have a trajectory that does not always follow the atmospheric conditions around the cell.

The thick, cold clouds of convective cells can be monitored by satellites. Mature cells can be well detected and tracked through satellite observations. The cells can also be observed during early development, although the signal is less pronounced. During the development phase, convective cells do not usually produce any precipitation and cannot be observed by weather radars. Thus, satellite sensing is a key for improved detection and short-term forecast of convective cells and heavy thunderstorms.

Meteo-France, in the framework of the EUMETSAT, has developed the Rapidly Developing Thunderstorm-Convection Warning (RDT-CW) nowcasting product.

Using mainly geostationary satellite data, it provides information on clouds related to significant convective systems, from mesoscale (200 to 2,000 km) down to smaller scales (a tenth of a km).

The objectives of RDT-CW are:

- The identification, monitoring and tracking of intense convective system clouds
- The detection of rapidly developing convective cells
- The forecast of the convective cells

The RDT-CW detection method is based on adaptive temperature thresholding of infrared images. The approach underlying the RDT-CW product allows for characterizing convective, spatially consistent entities through various parameters of interest to the forecaster, such as motion vector, cooling and expansion rate, cloud top height and their time series, which adds value to the satellite image.

The object mode of RDT-CW analyses the motion of each cell and computes speed. Then, the forecast scheme uses this speed estimate to forecast the successive position of each cell. This method has proven to be quite efficient in the 1-hour range.

Therefore, the RDT-CW is a helpful nowcasting tool for forecasters monitoring convective cell development for issuing warnings. Still, it is also valuable for aviation, where thunderstorms are a significant hazard. Figure 3.2 presents an example of RDT-CW product visualization using SYNOPSIS.

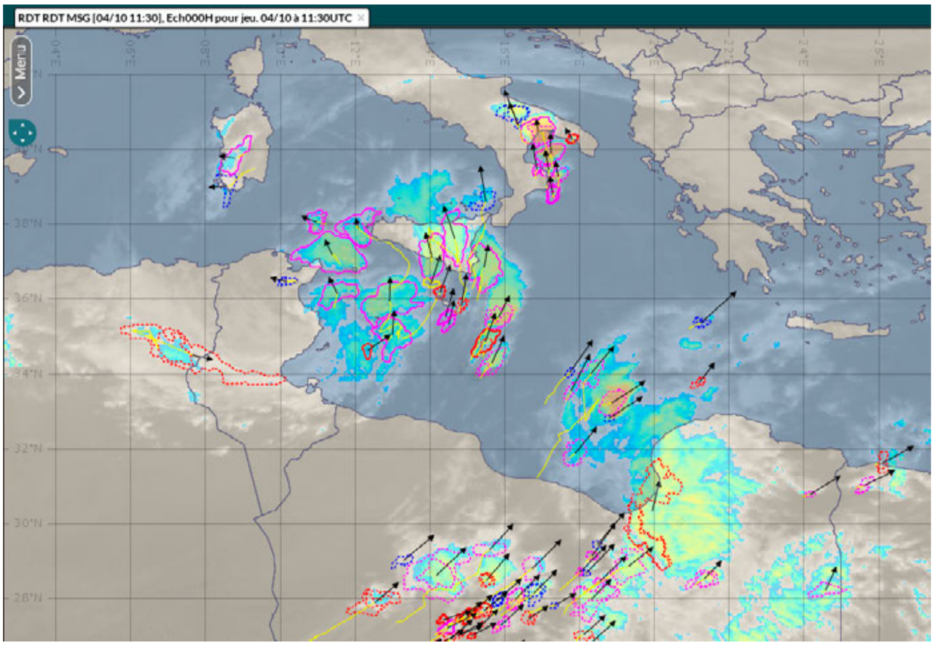
Nowcasting tools such as RDT-CW and KONvektive Entwicklung in RADarprodukten – Deutscher Wetterdienst also provide central tools for disaster management authorities. With convective systems developing quickly, disaster management often has little time to prepare and respond to rapid-onset flooding. Devices that allow emergency response organizations to monitor cell progression enable faster and more reliable decision-making for deploying resources and providing timely responses.

[a] Federal Republic of Germany, Deutscher Wetterdienst, *Detection and forecast of convective cells*. Available at www.dwd.de/EN/research/weatherforecasting/met_applications/satellite_data_applications/convective_cell_detection_node.html

[b] European Organisation for the Exploitation of Meteorological Satellites, *Rapidly Developing Thunderstorm – Convection Warning*. Available at https://www.nwcsaf.org/rdt_description

[c] Federal Republic of Germany, Deutscher Wetterdeinst, *Thunderstorm Detection and Tracking with KONRAD*. Available at www.dwd.de/EN/research/weatherforecasting/met_applications/nowcasting/konrad_en_node.html;jsessionid=61397321B6E4E971011C9B1696B5F7C5.live31094

Figure 3.2 Example of RDT-CW product visualization using SYNOPSIS (Meteo-France workstation)



Source: EUMETSAT 2022

3.2 Floods

Floods are the most common natural hazards affecting people, infrastructure and the natural environment. They can occur in many ways and in many environments. Riverine floods, the most prevalent, are due to heavy, prolonged rainfall, rapid snowmelt in upstream watersheds or the regular spring thaw of snow in river catchments. Other floods are caused by hefty rainfall occurring over a short period, the backup of estuaries due to high tides coinciding with riverine flooding or storm surges, dam failures, dam overtopping due to landslides into a reservoir, and seiche and wind tide effects in large lakes. Occasionally an eruption under a glacier or snow-covered volcanic peak can cause a flood or a mudflow in which the terrain is radically changed and any rural development is destroyed, frequently with much loss of life.[61]

According to the 2021 report of the Centre for Research on the Epidemiology of Disasters and the United Nations Office for Disaster Risk Reduction,[62] the flood was the most frequent type of disaster worldwide and the only one that became increasingly deadly in 2020. Moreover, flood occurrence significantly increased in 2020 compared to the 2000–2019 annual average. Therefore, policy and decision makers need efficient flood monitoring tools to facilitate their work towards increasing disaster resilience, especially in the urban and peri-urban areas, where most of the population and critical infrastructure are located.

Defining the entire flood potential is a challenge. Nevertheless, historical evidence often provides some valuable risk knowledge. Still, as flood plains and catchments are continuously subjected to change through various variables, such as land clearance and construction, geomorphological changes and even floods themselves, historical events become less valuable.

However, satellite Earth observations can identify significant flood potential and assess the associated risk by providing essential data to build disaster risk knowledge for changing and geographically remote river catchments. In addition, satellite-derived data for understanding flood plains, catchments and rivers can be combined with other critical data sets to assess exposure and vulnerability, which can be applied alongside conventional hydrometeorological modelling to forecast flood impacts and issue flood warnings.

In recent years, several national, regional and international organizations have launched services that present information on potential floods on the basis of hydrological models that transform rainfall estimations into potential floods. Two of these services are GLoFAS of the Copernicus Programme and the Group on Earth Observations Global Water and Sustainability Initiative (GeoGLOWS) streamflow model implemented by several partners including Brigham Young University, the National Oceanic and Atmospheric Administration (NOAA), the NASA/USAID SERVIR programme, the private remote-sensing company Esri of the United States and the European Centre for Medium-range Weather Forecasts (ECMWF).

[61] Organisation of American States, "Chapter 4 – Remote Sensing in Natural Hazard Assessments (1991)" in Primer on Natural Hazard Management in Integrated Regional Development Planning. Available at www.oas.org/dsd/publications/Unit/oea66e/ch04.htm

[62] Centre for Research on the Epidemiology of Disasters and United Nations Office for Disaster Risk Reduction. "2020: The Non-Covid year in disasters: Global trends and perspectives". Available at http://hdl.handle.net/2078.1/245181

CASE STUDY

Global Flood Awareness System [a]

The Global Flood Awareness System (GLoFAS) is an operational system of the Copernicus Emergency Management Service of the European Commission. It was established to forecast and monitor floods worldwide. It has been producing daily flood forecasts since 2011 and monthly seasonal streamflow outlooks since November 2017.

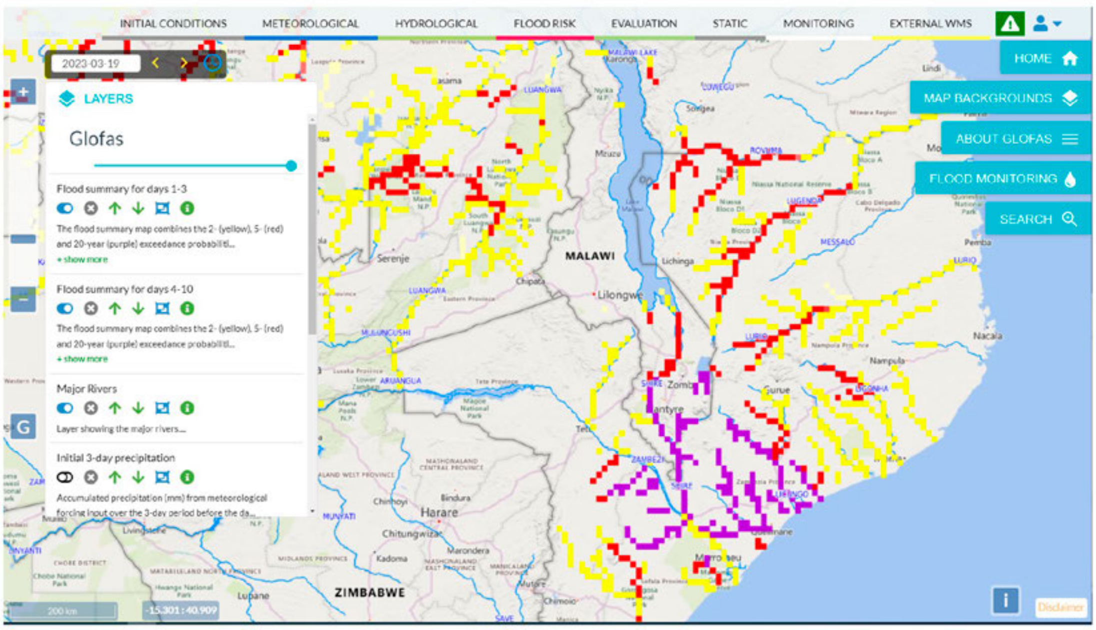
The aim of GLoFAS is to complement relevant national and regional authorities and services and to support international organizations in decision-making and preparatory measures before significant flood events (particularly in large transnational river basins). However, GLoFAS prediction only focuses on rivers and does not provide real-time forecast information on flash flood risk, coastal flooding or inundated areas.

In 2021, a new operational service for the automated, global, satellite-based monitoring of floods in near-real time was integrated into GLoFAS. The new Global Flood Monitoring (GFM) application continuously monitors floods worldwide by immediately processing and analysing all incoming Copernicus Sentinel-1 synthetic aperture radar (SAR) satellite data. Being a fully automated system, one of the strengths of the GFM is the high timeliness of its products. Secondly, implementing three independently developed satellite flood mapping algorithms underpins the robustness and high quality of the derived flood and water extent maps.

The timeliness of satellite data enables GLoFAS to forecast floods in large basins with sufficient time for disaster management organizations to act. GFM regularly computes 11 flood-related products, accessible via the hydrological layer tab of the GLoFAS map viewer. Figure 3.3 presents an example of the GLoFAS map viewer showing potential floods of different levels in southern Africa at the end of March 2022.

[a] European Commission, Copernicus Programme, "Emergency Management Service: Global Flood Awareness System". Available at www.globalfloods.eu

Figure 3.3 GLoFAS map viewer showing potential floods of different levels in southern Africa at the end of March 2022



Source: GLOFAS

CASE STUDY

GEOGloWS streamflow model[a]

The GEOGloWS streamflow model is a hydrologic model designed under the umbrella of the Global Water Sustainability initiative of the Group on Earth Observations (GEOGloWS) in 2017. It has been implemented by several partners including Brigham Young University, the National Oceanic and Atmospheric Administration (NOAA), the NASA/USAID SERVIR programme, the private remote-sensing company Esri of the United States and the European Centre for Medium-range Weather Forecasts (ECMWF). The model forecasts river discharge which can be used for forecasting floods. It uses the run-off data compiled globally by ECMWF which is then transformed into river discharge forecasts for every river of the world. The model benefits from archived simulations covering the last 40 years.

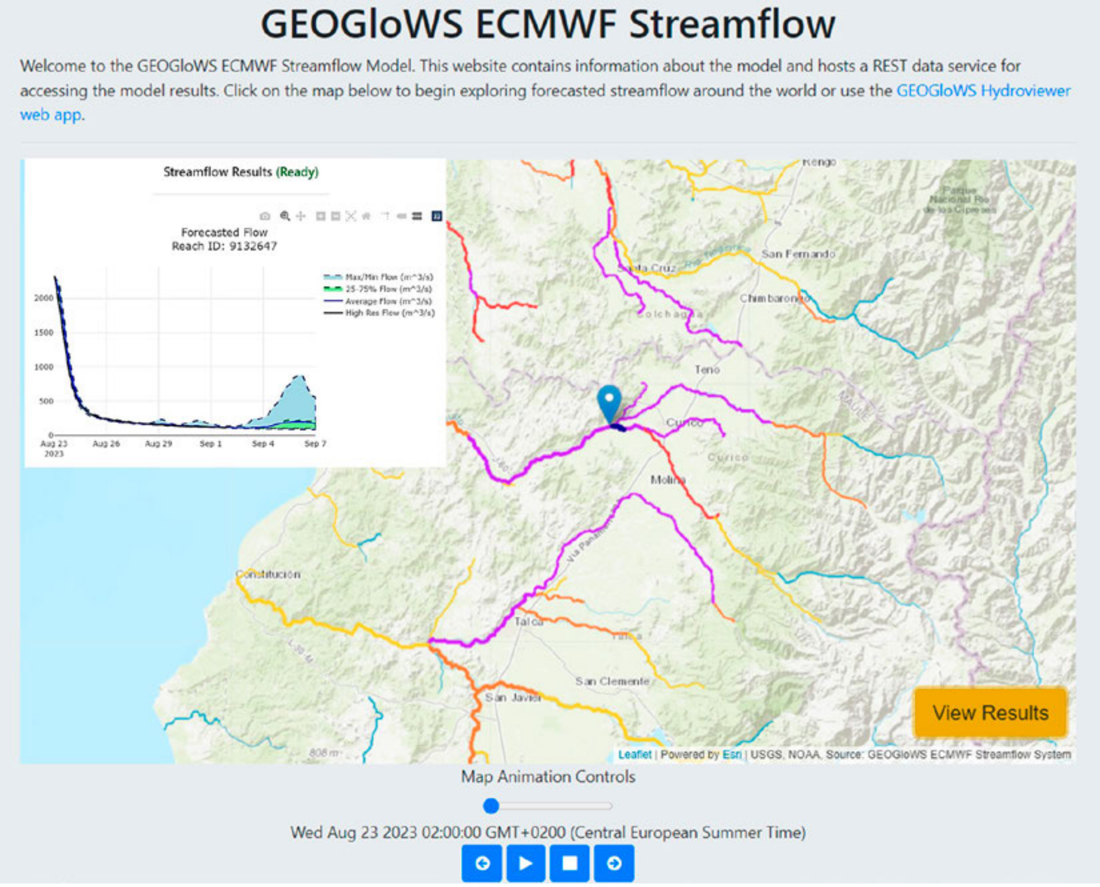
The GEOGloWS ECMWF Streamflow Service uses a Hydrologic Modelling as a Service approach and other components of hydrologic modelling to deliver reliable forecast information as a service.

The GEOGloWS ECMWF Streamflow Hydroviewer offers a free web mapping service produced and hosted by Esri, which is constructed and delivered by an API so that custom web and other applications can be created from HMaaS. Figure 3.4 presents an example of the GEOGloWS ECMWF Streamflow Hydroviewer showing the Mataquito River in the area of Curico Province in Central Chile. The insert in the upper left shows the forecasted flow at the selected point from 23 August to 7 September 2023.

[a] European Centre for Medium-range Weather Forecasts, “GEOGLoWS ECMWF Streamflow”. Available at https://geoglows.ecmwf.int

Figure 3.4 GEOGloWS ECMWF Streamflow Hydroviewer showing the Mataquito River in the area of the town of Sagrada Familia in Curico Province, Central Chile

The insert in the upper left shows the forecasted flow at the selected point from 23 August to 7 September 2023



Source: GEOGloWS ECMWF Streamflow System

As stated in previous chapters, digital elevation models are useful to delineate which areas of the floodplains may experience floods depending on the amount of discharge flowing through the channels of rivers. The use of digital elevation models in hydraulic modelling allows for the elaboration of maps of areas which may be flooded according to parameters such as the period of return of floods (20 years, 50 years, 100 years).

CASE STUDY

Flood hazard modelling using digital elevation models and hydraulic modelling

Flood early warning systems benefit from risk assessment, including the assessment of flood hazard. At the request of the UN-SPIDER programme, experts from the Space Application Center for Response in Emergency and Disasters (SACRED) of the Space and Upper Atmosphere Research Commission (SUPARCO)[a] of Pakistan developed a procedure to assess flood hazard using hydraulic modelling software such as the Hydrologic Engineering Centre's River Analysis System[b] which was developed by the United States Army Corps of Engineers and digital elevation models such as the World DEM™ of Airbus Defence and Space.

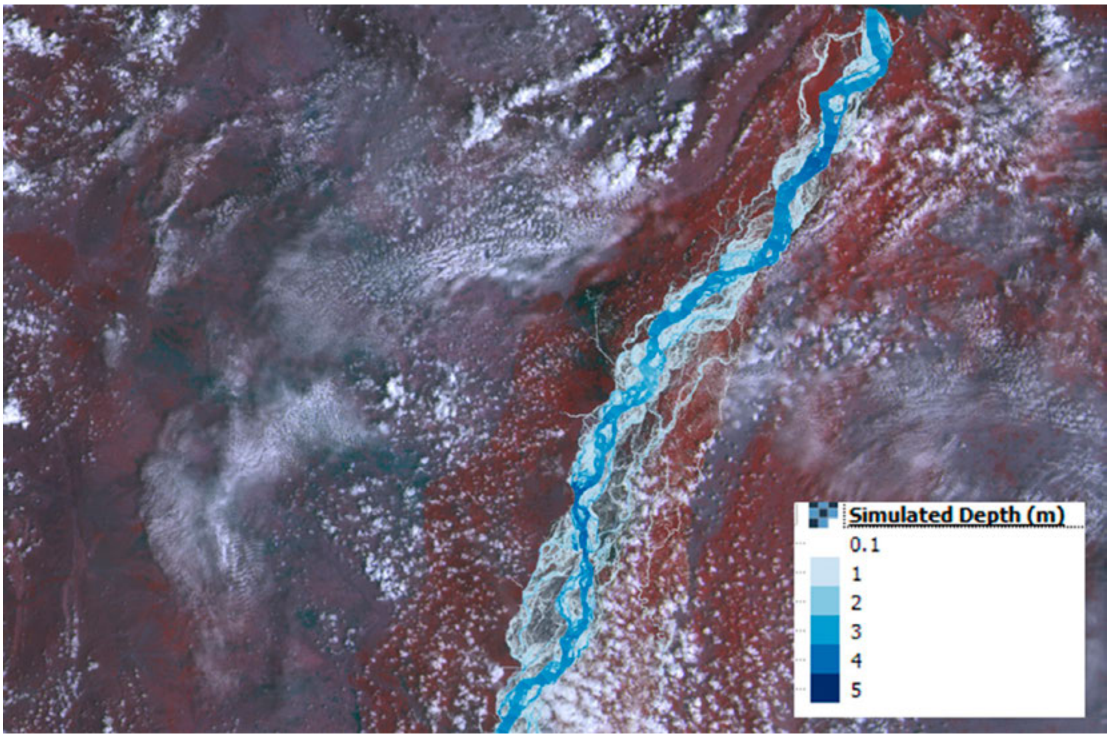
The step-by-step procedure developed by SACRED-SUPARCO is available in the UN-SPIDER Knowledge Portal.[c] Figure 3.5 shows the simulated depth of a flood like the one in 2010 in a segment of the Hindus River obtained with this procedure.

[a] More information on SUPARCO is available at https://suparco.gov.pk.

[b] More information on the HEC-RAS software is available at: www.hec.usace.army.mil/software/hec-ras

[c] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practice Flood Hazard Assessment". Available at www.un-spider.org/advisory-support/recommended-practices/recommended-practice-flood-hazard-assessment

Figure 3.5 Modelling of potential floods in a segment of the Hindus river using the UN-SPIDER Recommended Practice developed by SACRED-SUPARCO



Source: UN-SPIDER

CASE STUDY

Guatemala: Digital elevation models informing preparedness and response [a]

Several decades ago, the former National Emergency Committee, and now the National Coordinating Agency for Disaster Reduction (SE-CONRED), implemented efforts in communities located in the floodplain of the Coyolate river to enhance disaster preparedness, including through the implementation of a community-based flood early warning system in 1997.

At the request of UN-SPIDER, SE-CONRED has since carried out a comparative analysis of the use of digital elevation models (DEM) developed by the United States National Aeronautics and Space Administration (NASA), based on its Shuttle Radar Topography Mission (SRTM) and WorldDEM™, developed by Airbus Defence and Space GmbH. The comparative study into the use of DEMs for flood modelling highlighted opportunities for improving the flood early warning system. The free-at-source IBER[b] and the iRIC[c] software packages were used to model hypothetical floods with periods of return of 50 years.

In addition to identifying strengths and weaknesses in the DEMs capability to model flooding, using the iRIC software and WorldDEM™, it was possible to visualize that one of the communities exposed to floods, called Santa Odilia village, was in a region that is slightly higher than neighbouring areas. Rather than being flooded, the modelling of floods with this software and WorldDEM™ indicates that this village will be cut off in extensive floods. Figure 3.6 presents screenshots of the area near the village of Santa Odilia in the Coyolate floodplains of Guatemala. The figure presents three stages of the flood modelling.

[a] UN-SPIDER Programme, "Flood modelling in Guatemala using different digital elevation models". Available at www.un-spider.org/flood-modelling-guatemala-using-different-digital-elevation-models

[b] Iber is a two-dimensional hydraulic model for the simulation of free surface flow in rivers and estuaries. More information on Iber is available at www.iberaula.es.

[c] iRIC software is a free numerical simulation platform supporting a wide variety of computational solvers for problems in water science and engineering. The software began as a river flow and morphodynamics analysis tool but has now includes predictions of flooding, rainfall run-off generation, tsunami propagation, debris flows, habitat assessment and more. More information on iRIC is available at https://i-ric.org/en.

Figure 3.6 Modelling of floods in the vicinity Santa Odilia village in the Coyolate floodplains of Guatemala

The village may not be flooded, but access to the village by road will not be possible

Source: UN-SPIDER

In some countries, meteorological and hydrological institutes are combining data from satellites, ground stations and other services to elaborate forecasts of floods in near-real time.

CASE STUDY

The FloodHub system for flood early warning and monitoring [a]

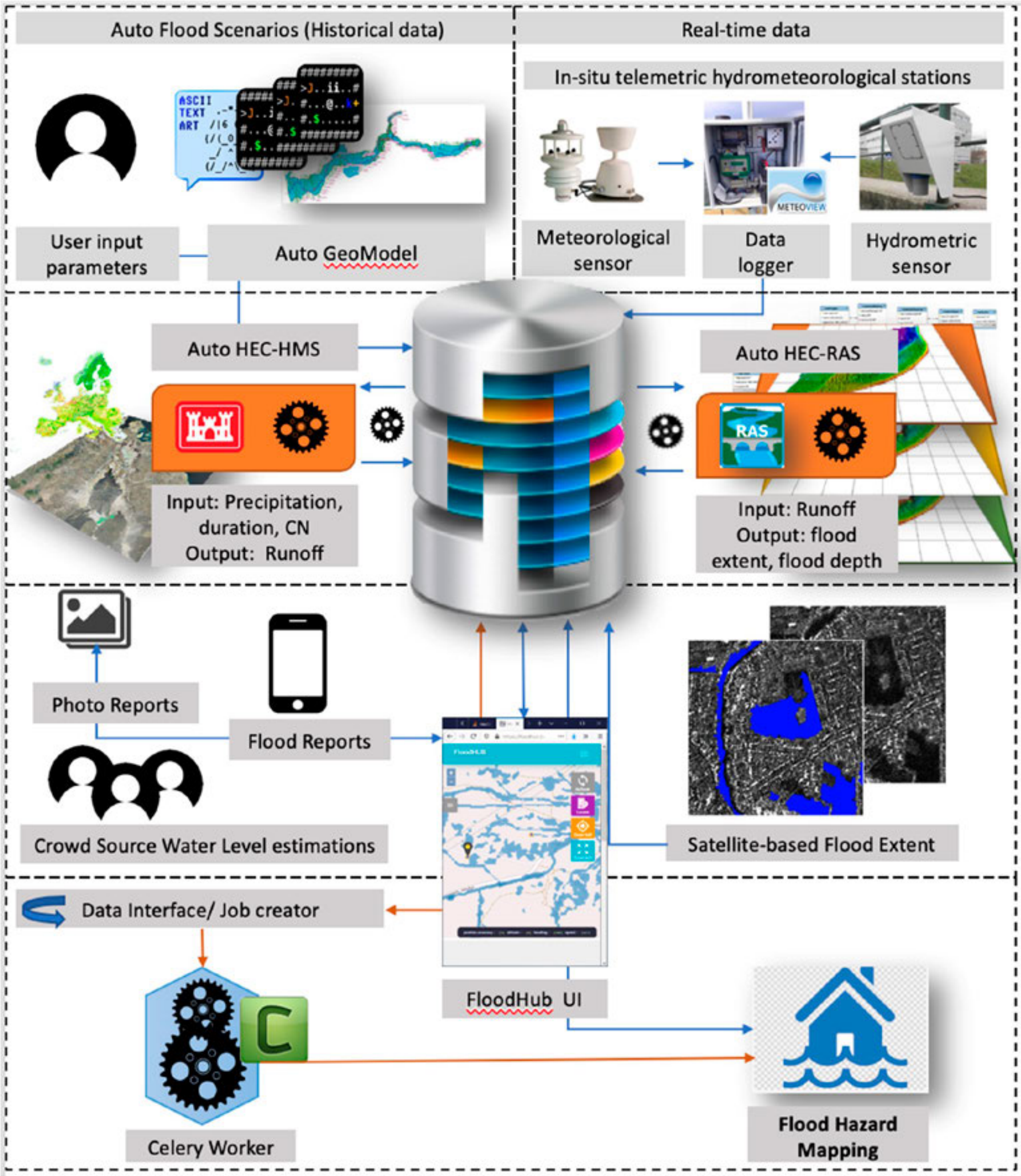
The BEYOND Center of Earth Observation, at the National Observatory of Athens, developed the FloodHub system in the framework of the EuroGEO Disaster Resilience Action Group, supported by ongoing actions (SMURBS/ERA-PLANET and Excelsior H2020 projects and the sponsor Hellenic Petroleum SA). The system's innovation lies in integrating different data sources to deliver a reliable flood forecast. In addition, the flood system provides a crisis situational awareness report every five minutes to the relevant civil protection authorities, such as the municipality, and the regional and national authorities.

FloodHub allows the near-real-time ingestion and assimilation of hydrometeorological measurements from in situ telemetric stations, Sentinel satellite data, and crowdsourced data in a multisource data fusion concept, using sophisticated hydrologic and hydraulic modelling and statistical regression techniques. In addition, it offers increased reliability through continuous validation and optimization of results, automation in assimilating flood modelling in real-time, computational efficiency, openness, flexibility, scalability, transferability and the speed to meet rapid awareness during a crisis. Figure 3.7 presents the architecture of the FloodHUB system.

Therefore, FloodHub is a valuable tool for the relevant authorities and key stakeholders, contributing to effective flood risk and crisis management. This is in line with the requirements for implementing the European Union Floods Directive 2007/60/EC, the Sendai Framework for Disaster Risk Reduction, the United Nations Sustainable Development Goals (SDGs) and the Societal Benefit Areas of the Group on Earth Observations (GEO).

[a] Greece, National Observatory of Athens, BEYOND Centre of Earth Observation and Satellite Remote Sensing, "The FloodHub system for flood early warning and monitoring". Available at http://beyond-eocenter.eu/images/PPT2_S3_3_NOA.pdf

Figure 3.7 Architecture of the FloodHUB system



Source: BEYOND Center of Earth Observation and Satellite Remote Sensing

CASE STUDY

Detecting and monitoring river and sea levels for flood warnings with Iridium systems[a]

The tropical weather in the eThekwini municipality of South Africa, including the city of Durban, often triggers devastating floods. After catastrophic floods in 2017 and 2019 that caused massive economic damage, human displacement and loss of life, the eThekwini municipality initiated a new disaster management strategy to better prepare for future crises. The local government identified the need for real-time environmental observations and forecasts for flood prediction and preparedness.

Initial research into solutions raised several challenges: the existing solutions were too expensive; the available instrumentation was cumbersome and easy to spot, making it vulnerable to theft; available multichannel data loggers with several wired external sensors were not robust enough for a massive disaster management programme; data were hard to gather and analyse without a centralized portal; some flood-prone areas were outside the city or further offshore, making communication between potential data sites and receiving stations challenging. To overcome these challenges, satellite communications became imperative.

Obscape, a Netherlands-based environmental monitoring equipment manufacturer, worked with the Iridium satellite telecommunications company to create affordable, robust solar-powered, wireless turnkey equipment to collect long-term, actionable environmental data. The engineers mounted the systems above the water on bridge decks, walls, trees, and poles near rivers in the flood hazard zones.

One component of the monitoring system is the Iridium 9603 transceiver that serves as a time-lapse camera, rain-level gauge and weather station, forming one monolithic piece without external cables, which makes it inconspicuous but also robust.

Another component of the monitoring system is the Iridium Connected wave buoy, which is equipped with sensors that detect wave height and direction – both important environmental data components. It provides critical, precise data to help water managers monitor flood-prone coastal areas, urban river corridors and wetlands almost in real-time. All data from the various measuring devices flow into a centralized portal, allowing seamless gathering and analysis.

Thanks to the Iridium Connected solution, the eThekwini municipality can receive threshold alerts and predictive environmental markers visualized in downloadable reports. The data allow the municipality to identify potential forecast patterns, which enable targeted responses to protect residents and safely manage port operations.

[a] Iridium, "Iridium Helps Predict Floods in Coastal South Africa". Available at www.iridium.com/case-studies/predicting-floods-south-africa

3.3 Assessing exposure and vulnerability to hydrometeorological hazards

As more hydrometeorological early warning systems evolve into impact-based warning systems,[63] satellite technology is increasingly being used to inform risk knowledge for hydrometeorological early warning systems.

Historically, hydrometeorological warning systems focused on the exposure of locations to specific types and magnitudes of hydrometeorological hazards. In recent years, early warning services have developed and are growing to consider vulnerability to hazards and exposure, enabling impact-based warnings to be issued. The need for a more comprehensive understanding of risk is seeing an even greater application of space technology-derived data in hydrometeorological early warning systems.

Satellite-based Earth observation has long demonstrated the capacity to map elements at risk, and satellite data has supported hazard mapping for some time. However, as early warning systems evolve, mapping other factors that inform a hazardous event's risk picture is becoming increasingly necessary. Earth observation data are also being used to map the distribution of human population, buildings, strategic infrastructure and roads. [64]

Remote-sensing can be a cost-effective alternative for mapping population distribution. While it is expected to result in a different accuracy to a traditional census, it can be a useful surrogate in the absence of up-to-date census data. Two different remote-sensing approaches have been developed for population mapping:

- Top-down approaches using interpolation methods based on land cover maps and other spatial indicators to disaggregate census data to a finer spatial scale (e.g., WorldPop, LandScan, Global Human Settlement Layer-Population, Global Rural-Urban Mapping Project
- Bottom-up approaches aiming at defining a statistical relationship between remote sensing-derived variables (night-time light, number or size of dwelling units, settlement area, type of buildings) and population numbers[65]

[63] World Meteorological Organization, "Impact-based Forecasting and Warning: Weather Ready Nations". Available at https://public.wmo.int/en/resources/bulletin/impact-based-forecasting-and-warning-weather-ready-nations

[64] G. Le Cozannet, M. Kervyn, S. Russo and others, "Space-Based Earth Observations for Disaster Risk Management". *Surveys in Geophysics*, vol. 41, (10 March 2020), pp. 1209–1235. Available at https://doi.org/10.1007/s10712-020-09586-5

[65] United Kingdom, Meteorological Office, *UK weather warnings*. Available at: www.metoffice.gov.uk/weather/warnings-and-advice/uk-warnings

CASE STUDY

High-resolution satellite imagery increases the accuracy of flood exposure assessments in 18 countries[a]

The quality of data being used to produce early warning systems significantly affects the quality of the early warning issued. As more and more countries develop early warning systems and transform them into impact-based early warning systems, this issue becomes even more pronounced. For example, one study has shown how using high-resolution satellite imagery and population data sets can improve exposure risk knowledge that could significantly affect the quality of warnings issued and the efficiency of civil protection measures.

Smith et al. (2019) used the High-Resolution Settlement Layer (HRSL), a new high-resolution (~30 m) population density data set, to map flood exposure for 18 countries including Burkina Faso, Cambodia, Ghana, Haiti, Madagascar, Malawi, Mexico, Mozambique, the Philippines, Puerto Rico, Rwanda, South Africa, Sri Lanka, Uganda and the United Republic of Tanzania.

HRSL is derived from satellite imagery capable of resolving individual buildings. This data was then intersected with flood depth data (resolution of the order of 90 metres) produced by HydroSHED, a global-scale accurate hydrodynamic model, to produce estimates of the population exposed to flooding. The estimates of the populations exposed to flooding derived using HRSL were compared to calculations using two further global population data sets: WorldPop (resolution of the order of 90 metres) and Land-Scan™ (resolution of the order of 900 metres).

Across each of the 18 countries studied, estimates of the population exposed to a one in a hundred year flood (the area of land with a 1 per cent chance of being inundated in any given year) are smaller when HRSL population data are used instead of WorldPop or LandScan™ data: 101, 122 and 134 million respectively.

Looking at the data in more detail, other characteristics are highlighted which have consequences for disaster management. For example, when looking at the exposure totals calculated for Haiti, estimates of a total population exposed to flooding range between 3.14 million and 3.09 million for the WorldPop and HRSL-derived forecasts, respectively. This constitutes a slight change of minus one per cent. However, in the case of the WorldPop data, this exposure is spread over an area of the order of 40,000 square kilometres, compared with an area of roughly 3,700 square kilometres when using HRSL data.

The smaller area of exposure highlighted in the Haiti example was also seen across the other 17 countries, with the HRSL data confining exposed populations to much smaller areas. Moreover, the results suggest that existing population data sets significantly overestimate rural flood exposure, with only a tiny proportion of the total exposed area being urban.

Rapid and intensive urbanization in flood-prone areas is driving dramatic increases in flood exposure across Africa. This largely unplanned encroachment onto floodplain areas creates exposure concentrations, resulting in an amplification of losses when flood events occur. The results from research by Smith et al.[a] suggest that pre-existing demographic data sets need help to represent the significance of these exposure hotspots. This misestimation of exposure concentration would have significant implications for decision makers using these data for adaptation and mitigation. With increasing flood losses primarily attributed to increased urbanization, it seems crucial that these areas are correctly represented.

To move from flood hazard to flood risk estimates, data representing the spatial heterogeneity of people and assets with commensurate resolution and accuracy are also clearly required. Otherwise, as demonstrated here, inaccurate representations of exposure may persist, rendering the output of increasingly complex flood hazard models ineffective as decision-making tools.

[a] Andrew Smith, Paul D. Bates, Oliver Wing and others, "New estimates of flood exposure in developing countries using high-resolution population data". *Nature Communications,* vol. 10, Article Number 1814, (18 April 2019). Available at https://doi.org/10.1038/s41467-019-09282-y

Iberian Peninsula affected by drought in 2023

Image courtesy of NASA

Chapter 4.
Space technologies for slow-onset hydrometeorological hazards

Slow-onset hydrometeorological hazards typically develop and strengthen over weeks, months and seasons. Therefore, the need to be able to issue rapid warnings and have frequent imagery updates is lessened for such slow-onset hazards.

Satellite data collected today that can benefit rapid-onset hazard early warning services are also used to predict the occurrence of hydrometeorological hazards and phenomena that may occur in slower periods.

This chapter will cover two such hazards: droughts and El Niño/La Niña events (El Niño-Southern Oscillations).

4.1 Drought

Droughts are one of the most feared natural phenomena in the world; they devastate farmland, destroy livelihoods and take a toll on sustainability. They occur when an area experiences a shortage of water supply from a lack of rainfall, surface or groundwater. Droughts can last for weeks, months or years, and put livelihoods and ecosystems at risk and, in extreme cases, can trigger famine, displacement and conflict.[66] Sixty per cent of all deaths caused by extreme weather events are caused by droughts, even though they represent only 15 per cent of natural disasters. Between 1998 and 2017, droughts caused US$ 124 billion in economic losses globally.

Drought is described as an extended period (a season, a year or several years) of deficient rainfall relative to the statistical multi-year average for a region. However, dozens of more specific drought definitions are used worldwide according to the lack of rain over various periods or measured impacts such as reservoir levels or crop losses. Because of the several ways drought is measured, an objective definition has yet to be produced upon which everyone can agree.

[66] United Nations Convention to Combat Desertification. "The Drought Initiative". Available at www.unccd.int/land-and-life/drought/drought-initiative

Despite the lack of a definitive definition, drought can be classified according to meteorological, hydrological or agricultural criteria:

- *Meteorological drought* is usually based on long-term precipitation departures from normal. Still, there is no consensus regarding the threshold of the deficit or the minimum duration of the lack of precipitation that makes a dry spell an official drought.
- *Hydrological drought* refers to deficiencies in surface and subsurface water supplies. It is measured using parameters such as stream flow, lake, reservoir and groundwater level.
- *Agricultural drought* occurs when there is insufficient soil moisture to meet the needs of a particular crop at a specific time. Agricultural drought is typically evident after a meteorological drought but before a hydrological drought.[67]

Agriculture is the immediate victim of drought. A deficit of rainfall over cropped areas during critical periods of the growth cycle can result in destroyed or underdeveloped crops with significantly depleted yields. Drought affects the crop growing area, crop production and farm employment, and severely impacts the affected population. However, the impact of a drought is not determined solely by the severity of the drought but by the ability of communities and countries to anticipate and prepare for it. Satellite technologies play a significant role in providing data essential for drought early warning systems (DEWS) and monitoring ongoing drought conditions.

DEWS traditionally rely on rainfall data anomalies and measurements taken from specific sites in the field relating to crop health and ground conditions. Satellite data can be used to generate a range of indices and products that can help decision makers issue drought early warnings and take pre-emptive actions to prepare for and mitigate drought impacts.

The Drought Initiative of the United Nations is one effort to elaborate frameworks to guide long-term objectives in developing technical and institutional capacity to manage drought. This includes data sharing, early warning, monitoring, vulnerability and impact mapping, and drought risk mitigation measures.[68]

A long-term programme funded by the United States Agency for International Development is the Famine Early Warning Systems Network (FEWS NET), which is operated in several regions of the world.

CASE STUDY

The Famine Early Warning Systems Network[a, b]

The Famine Early Warning Systems Network (FEWS NET) monitors markets and prices, nutrition, livelihoods, government policies, conflicts and the agro-climatology conditions of a region before and during the growing season. FEWS NET relies on satellite data, computer models, and local and web-based tools to produce a series of products for monitoring the rainy season and agricultural production.

[67] United States, United States National Aeronautics and Space Administration, *Drought: The Creeping Disaster*. Available at https://earthobservatory.nasa.gov/features/DroughtFacts

Satellite data are beneficial since they are obtained at short intervals and cover the entire analysed territory. Infrared and visible satellite data, coupled with computer models, allow the calculation of rainfall estimates, soil moisture, Normalized Difference Vegetation Index (NDVI), evapotranspiration, snow depth and water stress, among other variables. These data are fundamental for early warning and monitoring and analysis of crops, water resource availability, risk management, and short- and long-term forecasting at local or regional levels.

FEWS NET partners use satellite data to produce a range of products and services to support the monitoring, detection and mitigation of famine. For example, the Climate Hazards Center at the University of California, Santa Barbara, is part of FEWS NET and produces the Climate Hazards InfraRed Precipitation with Stations (CHIRPS).

CHIRPS has developed a rainfall record available from 1981 to the present. CHIRPS consists of a 5x5-km resolution grid with quasi-global coverage (50 to -50 latitude and all longitudes) and updates every five days (pentads).[c] CHIRPS results stem from an algorithm combining satellite and meteorological station data. In addition, the rainfall data allows other variables to be calculated, such as the Standardized Precipitation Index (SPI) or Water Requirement Satisfaction Index, that serve as indicators to detect a reduction in water availability and estimate the level of impact it may have on crops. Figure 4.1 presents information on rainfall data in Uganda extracted from CHIRPS.

To facilitate the analysis of large amounts of data, FEWS NET has developed a series of tools for local or web-based use. These tools and products are used together by FEWS NET analysts, along with information and analyses of markets, trade and nutrition, to develop eight-month food security assumptions and forecasts, which decision makers use to mitigate and prevent food insecurity in the different regions where FEWS NET works.

The United States Geological Survey Earth Resources Observation and Science Center also publishes several products and tools based on satellite data as part of FEWS NET:

- GeoCLIM (Geospatial Climate) calculates summary statistics, among other functions, with time series of rainfall, temperature or evapotranspiration estimates.[d]
- GeoWRSI (Geospatial WRSI) utilizes rainfall estimates, plus crop information, to calculate crop water balance and provide a perspective, at any time during the growing season, of the crop condition at the end of the season.[e]
- The Early Warning eXplorer (EWX) allows the user to visualize and obtain statistics of some variables specific to drought and feminine.[f]
- The Agro-climatology Assumptions for Scenario Development tool facilitates agro-climatic analyses, including climatology, climate modes, seasonal forecasts and seasonal monitoring).[g]

[a] Funk, C., Shukla, S., Mamadou, W. et al, Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. *Bulletin of the American Meteorological Society.* 100 (6). Available at https://doi.org/10.1175/BAMS-D-17-0233.1

[b] Chris Funk, Shraddhanand Shukla, and others, "Chapter 3 – Famine Early Warning Systems" in *Drought Early Warning and Forecasting Theory and Practice.* (Elsevier, Netherlands). Available at https://data.chc.ucsb.edu/people/chris/DroughtEarlyWarningBook/Final_Full_Book_Drought_Early_Warning_and_Forecasting_subset.pdf

[c] Agrometeorological unit of measurement consisting of 5 days' worth of observations. More information available at www.wamis.org/agm/gamp/GAMP_Chap02.pdf

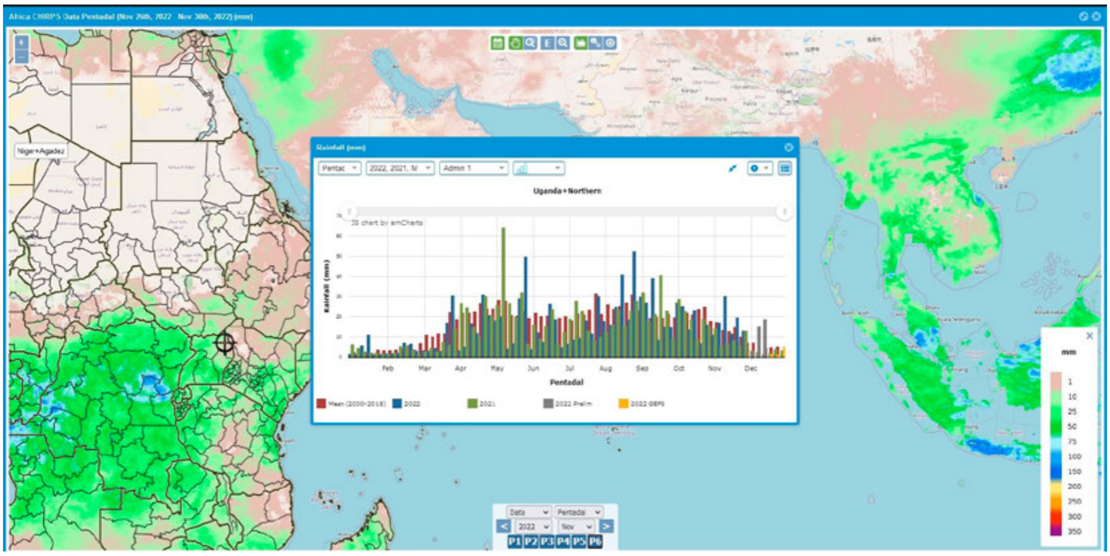
[d] United States Geological Survey, *GeoCLIM Overview.* Available at https://earlywarning.usgs.gov/fews/software-tools/20

[e] United States Geological Survey, *GeoWRSI Overview.* Available at https://earlywarning.usgs.gov/fews/software-tools/4

[f] United States Geological Survey, *Africa CHIRPS.* Available at https://earlywarning.usgs.gov/fews/ewx/index.html?region=ea-af

[g] United States Geological Survey, *Agro-climatology Assumptions for Scenario Development*. Available at https://earlywarning.usgs.gov/fews/climate-workshop

Figure 4.1 CHIRPS rainfall data, Uganda, displayed using the FEWS NET early warning eXplorer tool



Source: FEWS NET

4.1.1 Vegetation indices

Vegetation interacts with solar radiation differently from other natural materials, such as soils and water bodies. The absorption and reflection of solar radiation are the results of many interactions with different plant materials, which vary by wavelength. Water, pigments, nutrients and carbon reflect sunlight with often overlapping, but spectrally distinct, reflectance behaviours. These known signatures contained in the optical spectrum from 400 nm to 2500 nm, allow scientists to combine reflectance measurements at different wavelengths to enhance specific vegetation characteristics by defining vegetation indices (VIs).[68]

VIs are combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation. Each of the VIs is designed to accentuate a particular vegetation property.[69] As vegetation is a vulnerable element to drought, these indices are used to complement rainfall anomaly data for producing early warnings and drought forecasts. One well-known vegetation index is the Normalized Differential Vegetation Index (NDVI). This index compares the reflectance of vegetation to sunlight in the red and near-infrared bands. The chlorophyll in the green leaves absorbs red light strongly, whereas in dry leaves, there is very little chlorophyll, and hence the reflectance in dry leaves is stronger in this red band. In contrast, the reflectance in the near-infrared band is similar in the case of green and dry vegetation. Thus, the comparison of reflectance in the red and near-infrared allows for the detection of dry vegetation. The mathematical formula is:

$$\text{NDVI} = \frac{\text{Near-infrared band reflectance} - \text{Red band reflectance}}{\text{Near-infrared band reflectance} + \text{Red band reflectance}}$$

The NDVI presents a low value when vegetation is dry, and a high value when it is green. When NDVI is near zero, it means that there is hardly any vegetation, such as in urban areas.

[68] L3Harris, "Vegetation and Its Reflectance Properties" Available at www.l3harrisgeospatial.com/docs/understandingvegetation.html

[69] L3Harris, "Vegetation Indices". Available at www.l3harrisgeospatial.com/docs/vegetationindices.html

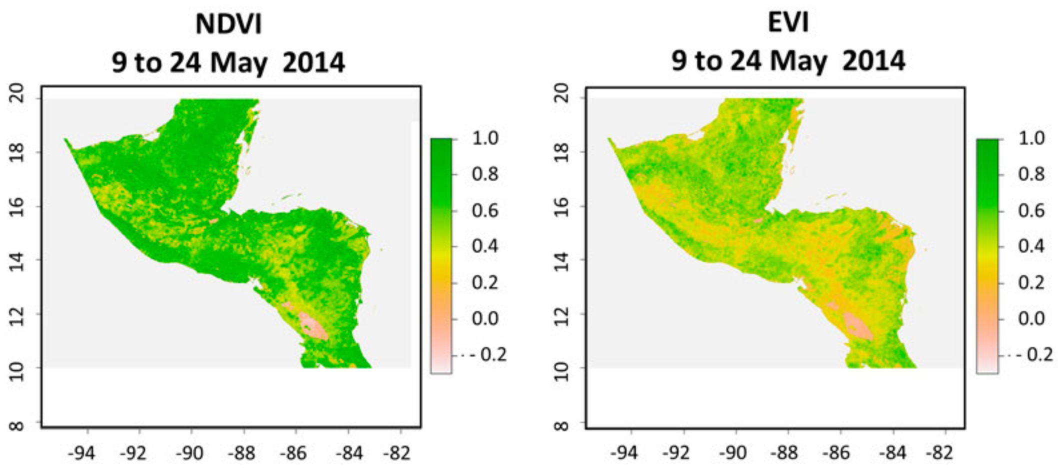
Another index is the Enhanced Vegetation Index (EVI), which includes the blue band to minimize the effect of atmospheric noise such as aerosols. The mathematical formula of EVI is:

$$EVI = G \frac{\text{Near-infrared band reflectance} - \text{Red band reflectance}}{\text{Near-infrared band reflectance} + C_1 \text{ Red band reflectance} - C_2 \text{ Blue band reflectance} + L}$$

Where G is a gain factor and C1 and C2 are atmosphere resistance coefficients in the red and blue bands respectively, and L is the canopy background brightness correction factor.

Figure 4.2 presents a comparison of NDVI and –EVI for the same geographic area in Eastern Mexico and Central America for the period from 9 to 14 May 2014, extracted from MODIS imagery.

Figure 4.2 Comparison of assessments of NDVI and EVI for the same geographic area in Eastern Mexico and Central America for the period from 9 to 14 May 2014, extracted from MODIS imagery



Source: UN-SPIDER

The National Oceanic and Atmospheric Administration (NOAA) of the United States generates NDVI and EVI values for all regions of the world every 10 and every 16 days using the moderate resolution imaging spectroradiometer (MODIS) sensor on board the Aqua and Terra satellites.[70] This periodicity allows professionals engaged in drought early warning to monitor the effects of droughts on vegetation over time. The resolution of images of MODIS is 250 metres.

More than 150 VIs have been published in scientific literature, but only a small subset has a substantial biophysical basis or has been systematically tested.[70]

Taking advantage of the long-time series of NDVI and EVI data acquired using the MODIS sensor, experts have developed composite indices that compare values of either NDVI or EVI in one period of a year to the NDVI or EVI values in the same period, but in other years. Some of the most used composite indices are:

[70] United States, National Aeronautics and Space Administration, *Moderate Resolution Imaging Spectroradiometer* (MODIS). Available at https://modis.gsfc.nasa.gov/about

- Vegetation Condition Index (VCI)
- Standard Vegetation Index (SVI)
- Vegetation Health Index (VHI)

NASA and the National Oceanographic and Atmospheric Administration (NOAA) of the United States and other agencies provide access to several of the VIs.[71]

Agricultural Stress Index

The Agricultural Stress Index (ASIS) was proposed in 2011 as a new index for agricultural drought monitoring and early warning.[72] ASIS is based on the Vegetation Health Index (VHI). This index is integrated by time and space considering only the cropping areas and limiting the temporal analysis during the length of the crop cycle.[73]

CASE STUDY

The Agricultural Stress Index System [a]

The Food and Agriculture Organization of the United Nations (FAO) developed a country-level Agricultural Stress Index System (ASIS) tool to help countries monitor agricultural drought and manage its risks. The tool uses satellite data to detect agricultural areas in which crops might be affected by drought. The country-specific version of the tool is based on the general methodological principles of the global ASIS, which is used at FAO Headquarters to support the Global Information and Early Warning System on Food and Agriculture. Figure 4.3 presents information on ASIS.

The country-level ASIS tool was created to assist countries in strengthening their agricultural drought monitoring and early warning systems. Once the tool is calibrated with field information (current land-use maps, sowing dates, length of the crop cycle and crop coefficients), it offers more precise results regarding the water stress periods for different crops than the global tool.

The surveillance of agricultural drought is a continuous activity throughout the year. It is based on satellite information received from FAO every 10 days, which is an ideal period for monitoring annual crops because it considers the water contribution made by soil water holding capacity. The results are then summed up in maps that are easily interpreted by decision makers that can implement the drought mitigation activities on time.

The country ASIS tool has been implemented in El Salvador, Guatemala, Honduras and Mexico. A regional-level web application has been added to the official website of the Regional Committee on Hydraulic Resources.

Several other countries have expressed their interest in having the country-level ASIS tool installed, including the Dominican Republic, Ecuador, Ethiopia, the Islamic Republic of Iran, Kazakhstan (Kostanay Region), Panama, the Republic of Moldova and Timor-Leste, as it will bridge the gaps in the analysis and distribution of agricultural drought information. Efforts are being made to ensure that the interested countries receive the related training and equipment, where appropriate.

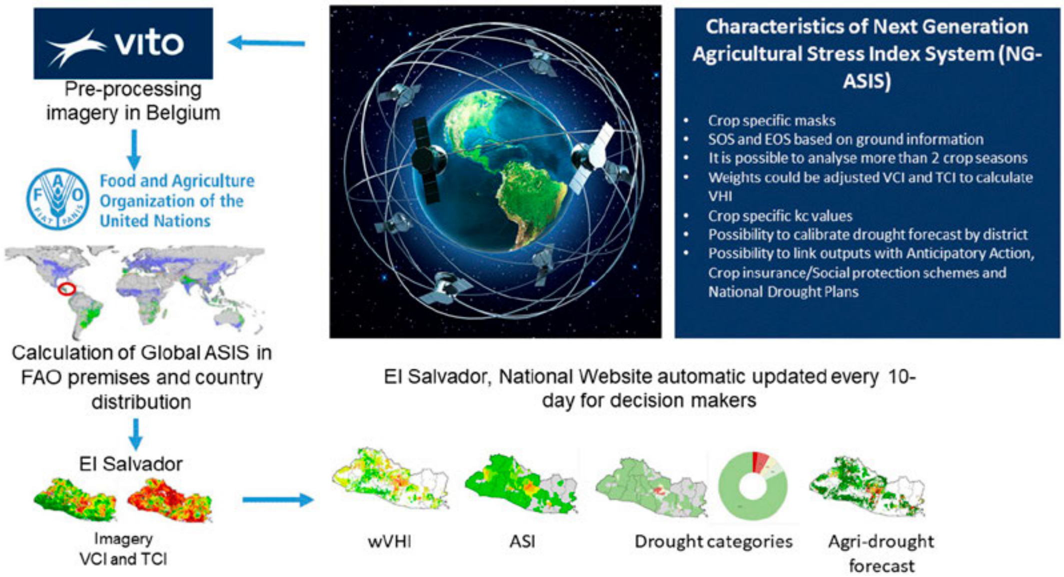
[a] Food and Agricultural Organization, "Earth Observation". Available at.www.fao.org/giews/earthobservation/asistool.jsp?lang=en

[71] See for example: United States National Aeronautics and Space Administration, *MODIS Vegetation Index Products (NDVI and EVI)*. Available at https://modis.gsfc.nasa.gov/data/dataprod/mod13.php and: United States, National Oceanic and Atmospheric Administration, *NOAA STAR - Global Vegetation Health Products: Browse Archived Images*. Available at www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php

[72] Oscar Rojas, A. Vrieling, and Felix Rembold, "Assessing drought probability for agricultural areas in Africa with remote sensing". *Remote Sensing of Environment*, vol. 115, issue number 2, (2011), pp. 343–352. Available at https://research.utwente.nl/en/publications/assessing-drought-probability-for-agricultural-areas-in-africa-wi

[73] R. Van Hoolst, H. Eerens, and others, "FAO's AVHRR-based Agricultural Stress Index System (ASIS) for global drought monitoring", *International Journal of Remote Sensing*, vol. 37, issue number 2, pp. 418–439, DOI: 10.1080/01431161.2015.1126378.

Figure 4.3 FAO process for generating ASIS products for El Salvador



Source: FAO ASIS

CASE STUDY

International Water Management Institute South Asia Drought Monitoring System[a, b]

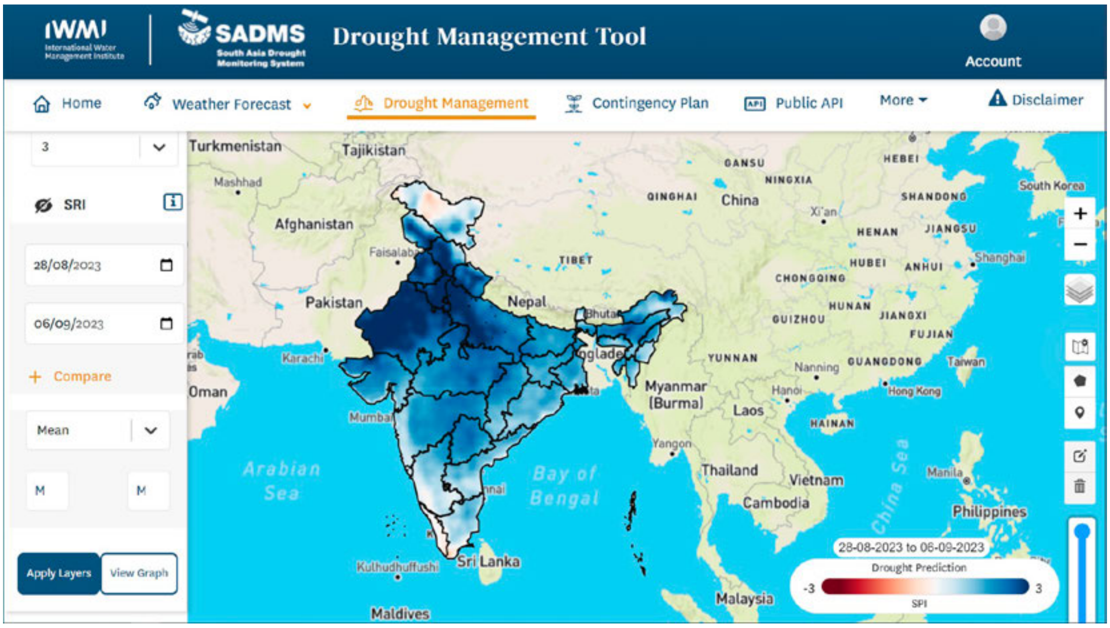
In South Asia, 50 major droughts have been reported since 1990, affecting 750 million people, and triggering losses in the order of US$7 billion. To address this challenge, the International Water Management Institute (IWMI) launched its South Asia Drought Monitoring System (SADMS) in partnership with the Indian Council of Agricultural Research (ICAR). The system covers Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka. The system uses an integrated drought severity index that is calculated combining data on the Vegetation Condition Index (VCI), the Temperature Condition Index (TCI) and the Precipitation Condition Index (PCI).

SADMS incorporates multisource information including open-access satellite data that provides farmers, extension workers, and agriculture and water resources authorities with all the information needed to forecast, monitor and manage drought. Specifically, it provides seasonal, subseasonal and seven-day weather forecasts; monitoring tools to indicate when drought is present and, if so, the level of severity. The system includes a decision support system, information for contingency planners, and a public API to allow users to retrieve indices developed in SADMS for use in other applications. Figure 4.4 presents information as seen in the SADMS website.

[a] International Water Management Institute, "IWMI launches the South Asia Drought Monitoring System (SADMS)". Available at www.iwmi.cgiar.org/2022/09/iwmi-launches-the-south-asia-drought-monitoring-system-sadms

[b] International Water Management Institute (IWMI). "Drought Management Tool". Available at https://dmsdemo.iwmi.org/drought-monitor

Figure 4.4 SADMS Drought Management Tool showing NDVI for Uttarakhand, India from 10 December 2022 to 9 January 2023



Source: IWMI SADMS

Drought indices such as the Vegetation Condition Index (VCI), the Vegetation Health Index (VHI) and the Standard Vegetation Index (SVI) are used in drought early warning systems, as they allow those in charge of droughts to monitor how droughts are progressing over time, and to answer one specific but very important question: how severe is a current drought in comparison to historic droughts? The next examples present information on step-by-step procedures developed at the request of UN-SPIDER to calculate SVI, VCI and VHI.

CASE STUDY

Standard Vegetation Index to monitor the effects of droughts

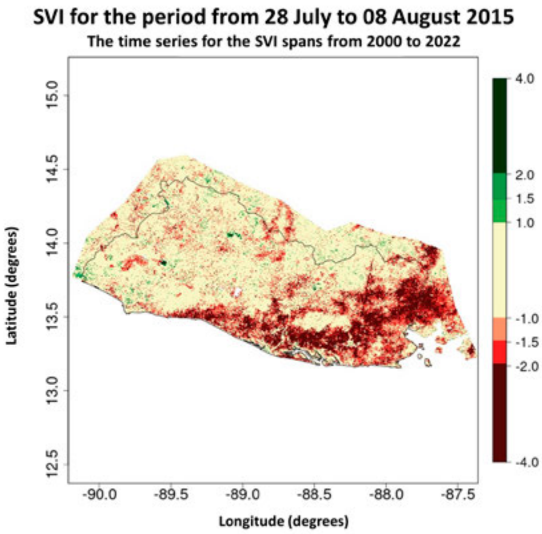
In the last three decades, Central American countries have experienced more frequent and intense droughts. These droughts have manifested themselves in arid areas of this region and have a greater impact on subsistence farmers. The worse effects and impacts have taken place when an international stressor (extreme reduction in the price of an agricultural export crop such as coffee in the world markets; or the substantial increase in the price of oil in the international markets) coincides with a severe drought.

At the request of UN-SPIDER, experts from the Federal University of Santa Maria (UFSM) in Brazil developed a step-by-step procedure to monitor the effect of droughts on vegetation. The procedure, available as an UN-SPIDER Recommended Practice,[a] is based on the Standard Vegetation Index (SVI). SVI is a comparative index that compares the state of vegetation in a specific period of one year to the state of vegetation in the same period, but in other years. The procedure developed by UFSM uses EVI data from the MODIS sensors on board the Aqua and Terra satellites. Since these satellites have been in orbit since the beginning of the year 2000, SVI compares vegetation since that time.

Figure 4.5 presents an example of an SVI for El Salvador and neighbouring areas for the period from 12 to 27 July 2018. At that time the country began to experience a deficit in rainfall the led to dry conditions in many regions of the country. Dark, red-coloured pixels indicate that in this period from 12 to 27 July 2018, the vegetation was the driest when compared with other years (2000 to 2022). Dark green-coloured pixels would indicate that the vegetation in this period in 2018 was greener than in previous years. Beige-coloured pixels indicate that the vegetation was neither too dry, nor too green in comparison to the other years.

[a] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practice "Drought monitoring using the Standard Vegetation Index (SVI)". Available at www.un-spider.org/advisory-support/recommended-practices/recommended-practice-drought-monitoring-using-standard.

Figure 4.5 Map of the Standard Vegetation Index in El Salvador for the period from 28 July to 12 August 2015



Source: UN-SPIDER

CASE STUDY

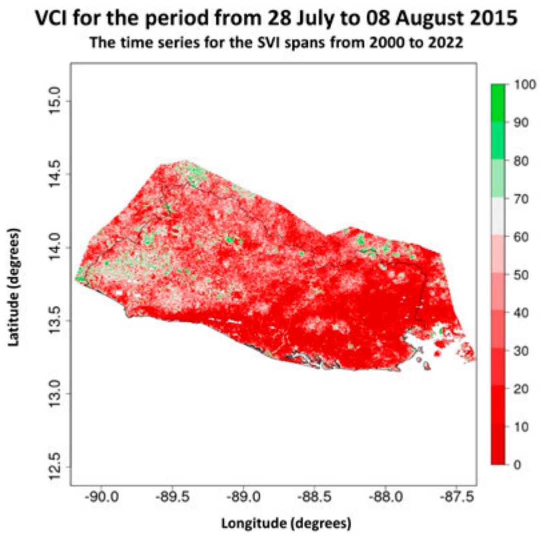
Vegetation Condition Index to monitor the effects of droughts

At the request of UN-SPIDER, experts from the Iranian Space Agency developed a step-by-step procedure to monitor the effect of droughts on vegetation. The procedure, available as an UN-SPIDER Recommended Practice,[a] is based on the Vegetation Condition Index (VCI). As in the case of SVI, VCI is a comparative index that compares the state of vegetation in a specific period of one year to the state of vegetation in the same period, but in other years. The procedure developed by ISA can be used with NDVI or EVI data from the MODIS sensors.

Both SVI and VCI compare the state of vegetation in a specific period of one year to the state of vegetation in the same period, but in other years. VCI compares the status of the vegetation in one year with the greenest and the driest states of vegetation in all the years being compared. In contrast, SVI calculates the average value of greenness or dryness for all years in a series, and then compares the deviation from that average for every year in the series. Figure 4.6 presents an example of VCI for El Salvador for the period from 12 to 27 July 2018. Dark red-coloured pixels indicate that in this period in 2018 vegetation was driest that in the same period but in other years (2000 to 2022).

[a] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practice "Drought monitoring using the Vegetation Condition Index (VCI)". Available at www.un-spider.org/advisory-support/recommended-practices/recommended-practice-drought-monitoring-using-vegetation.

Figure 4.6 Map of the Vegetation Condition Index in El Salvador for the period from 28 July to 12 August 2015



Source: UN-SPIDER

CASE STUDY

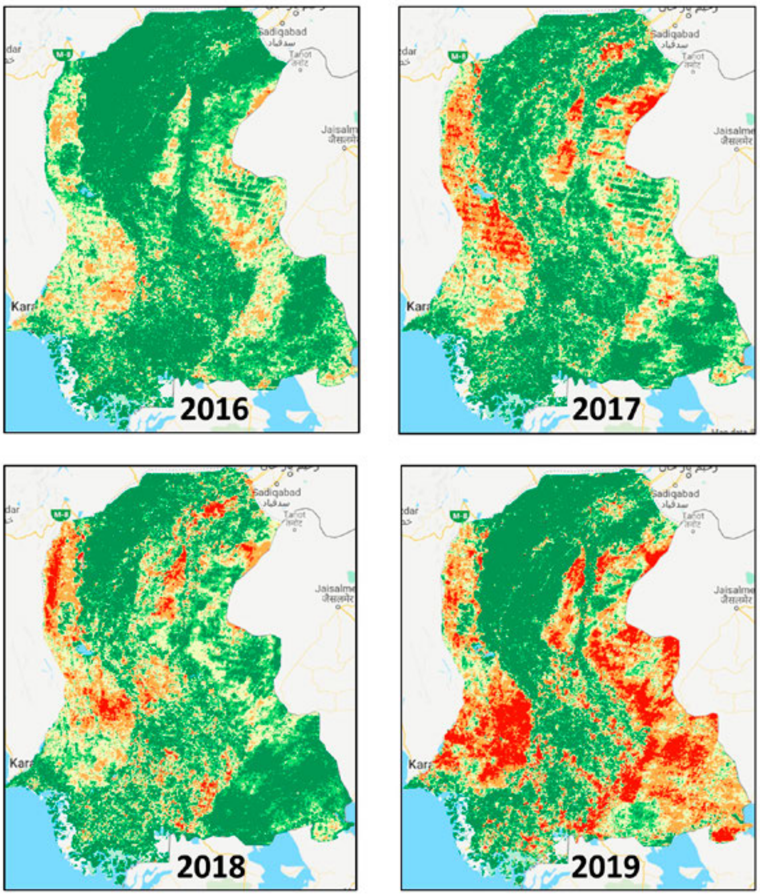
Vegetation Health Index to monitor the effects of droughts

In its role as a Regional Support Office of the UN-SPIDER programme, the Space Application Center for Response in Emergency and Disasters (SACRED) of the Space and Upper Atmosphere Research Commission (SUPARCO) of Pakistan developed a step-by-step procedure to assess the Vegetation Health Index. The procedure, available as an UN-SPIDER Recommended Practice,[a] allows users to generate maps of the Vegetation Health Index (VHI), that combine information on the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI). VCI and TCI are extracted from the data supplied by MODIS on board the Aqua and Terra satellites.

Figure 4.7 presents four maps of VHI for the Sindh province of Pakistan corresponding to March 2016, 2017, 2018 and 2019.

[a] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practice "Agriculture Drought Monitoring and Hazard Assessment using Google Earth Engine". Available at: www.un-spider.org/advisory-support/recommended-practices/recommended-practice-agriculture-drought-monitoring.

Figure 4.7 Maps of the Vegetation Health Index for the Sindh province in Pakistan for March 2016, 2017, 2018 and 2019



Source: UN-SPIDER

4.1.2 Soil moisture

In addition to vegetation indices, soil moisture is another parameter that can be used to indicate the start and duration of agricultural drought conditions. When soil moisture availability to plants drops sufficiently it can adversely affect crop yield and agricultural production.

CASE STUDY

Global Drought Observatory Soil Moisture Anomaly and the risk of drought impacts on agriculture [a]

The Soil Moisture Anomaly (SMA) indicator that is implemented in the Copernicus Global Drought Observatory (GDO) is used for determining the start and duration of agricultural drought conditions, which arise when soil moisture availability to plants drops to such a level that it adversely affects crop yield, and hence, agricultural production.

The SMA indicator in GDO is derived from anomalies of estimated soil moisture (or soil water) content, which are produced as an ensemble of three data sets:

- The daily soil water content produced by the LISFLOOD hydrological model of the Joint Research Centre of the European Commission at 0.1-degree resolution
- The eight-day land surface temperature (LST) as derived from the acquisition of the MODIS satellite sensor at 0.05-degree resolution (MOD11C2, collection 6)
- The dead combined active/passive skin soil moisture product produce within the ESA Climate Change Initiative (CCI) and distributed by C3S at the spatial resolution of 0.25 degrees

The three data sets are spatially interpolated over the same regular global grid of 0.1 degrees, and 30-day anomalies are computed separately three times per month (corresponding to 36 yearly updates). Each data set utilizes its baseline data set, all of which refer to the same climatological period (2001–2017). Figure 4.8 presents an example of soil moisture for South Africa as presented by the Global Drought Observatory for the month of April 2023.

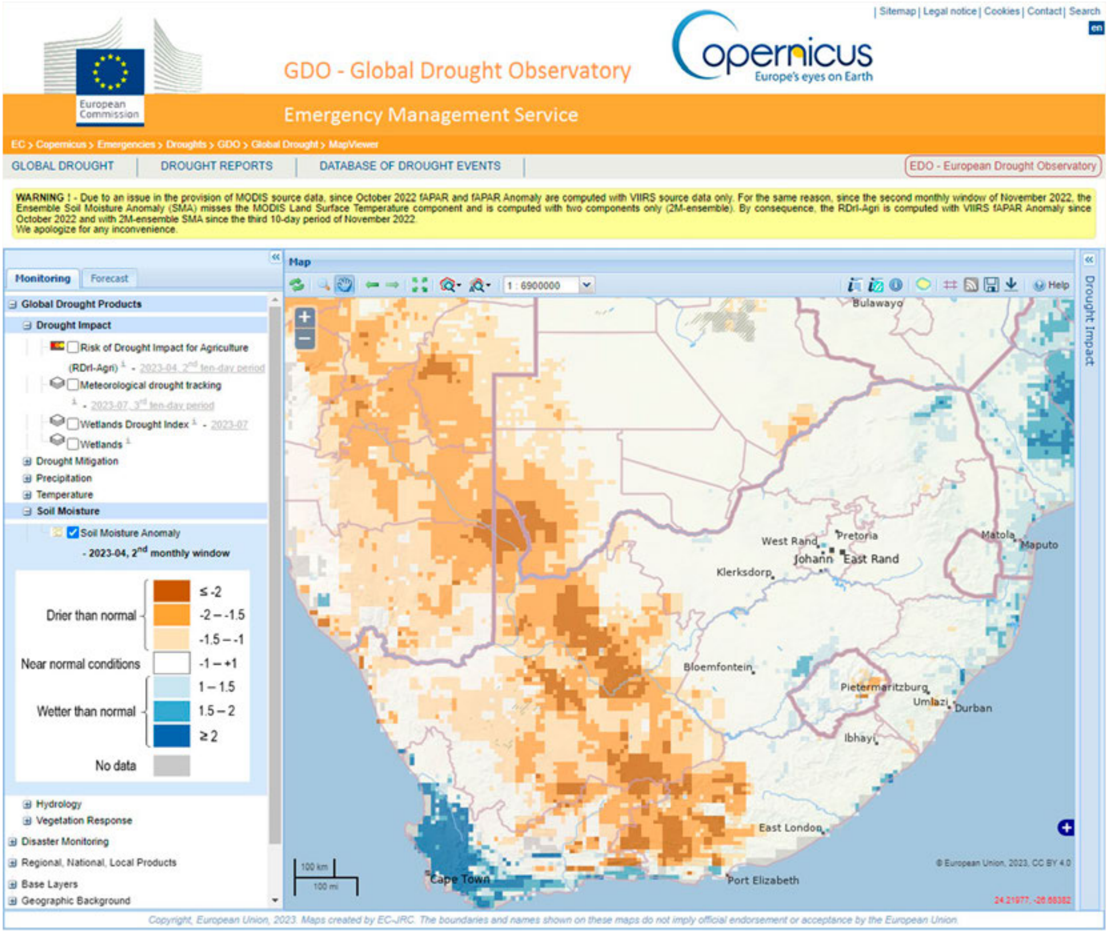
The three anomaly data sets are merged into a specific product using a weighted average. The LST data set is converted into a water available index (i.e., high LST corresponds to low soil moisture), hence negative anomalies represent dry conditions.

The latest available SMA map, as well as the past archive, is visualized in the GDO MapViewer, as well as a range of other drought indices and indicators. These maps provide information on the spatial distribution of soil moisture anomalies and their evolution over time.

Soil moisture content can be used as a direct indicator for determining the start and duration of agricultural drought conditions. The maps of soil moisture anomalies can also be used as a "proxy" for the presence of potential drought conditions which can be used to inform early warnings and pre-emptive decision-making.

[a] European Commission, Copernicus Programme, "Soil Moisture Anomaly (SMA)". Available at https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_soilmoisture_gdo.pdf

Figure 4.8 An example of soil moisture extracted from the Global Drought Observatory for South Africa for the month of April 2023



Source: Copernicus Global Drought Observatory

4.1.3 Tracking the dynamics of lakes, reservoirs and rivers

Just as vegetation and soil moisture indices can be used to assess the potential for drought and issue early warnings, so the monitoring of water levels in lakes, reservoirs and river channels can also be used to supplement indices and inform drought decision-making.

Satellite Earth observations provide the capability for monitoring changes in bodies of water that are indicative of drought.

According to Gao and other researchers, [74] the drying dynamics of river surface extent during droughts remain understudied. However, satellite remote sensing enables surveys and analyses of rivers at fine spatial resolution by providing an alternative to in situ observations. This is particularly useful in regions with complex terrain.

[74] Shang Gao, Zhi Li, and others, "Monitoring Drought through the Lens of Landsat: Drying of Rivers during the California Droughts". *Remote Sensing*, vol. 13, issue number 17, p. 3423. Available at https://doi.org/10.3390/rs13173423

Pham-Duc and other researchers [75] have used satellite remote sensing to monitor lake and reservoir levels, derived from Sentinel-1 observations, and variations of surface water levels derived from Jason-3 altimetry data. The data showed a good correlation with in situ measurements, highlighting that variation of water resources in the upper part of river catchments can be estimated precisely using satellite technologies. This information could be extremely useful for countries in the lower catchments to better manage their water resources and be of use for monitoring sources of water in remote locations.

CASE STUDY

Satellite imagery used for monitoring river levels in Italy due to drought [a]

In August 2022, many areas of central Europe experienced drought conditions. Very high temperatures were experienced across the season and extremely low precipitation was experienced for an extended period leading to significant changes in the broader landscape: lakes and reservoirs with decreased water levels and rivers with a considerable drop in flows.

Cloudeo exploited the high-resolution imagery of Copernicus Sentinel-2 (10 m pixel size) to calculate the changes in water areas and cultivated lands between the Lombardy and Emilia-Romagna regions around the River Po, Italy. With a total study area of 412 km^2, the total area affected by drought is estimated to have affected 236,7 km^2 of croplands and water areas, or approximately 57.4 per cent of the selected study region, compared to data in the same area over the past three years.

For the drought mapping, Sentinel-2 imagery was used. Its sensor includes the Red and Near-Infrared bands, which help in the classification process of extracting vegetated and water areas, and the 10-metre spatial resolution is ideal and cost-effective for event monitoring over large areas,

To estimate the impacts over the cultivated areas of the selected region, satellite imagery covering the period from 2019 to 2022 was retrieved and used for visualization and analytics generation. For each year, the Normalized Difference Vegetation Index (NDVI) was calculated. The comparative analysis or NDVI data allowed researchers to conclude that by 16 August 2022 there was a drop of 43.1 per cent in cultivated areas, which also meant a high loss in crop yield, and a 14.3 per cent reduction in water coverage.

[a] Cloudeo. "How satellite imagery can monitor drought events: river Po, Italy". Available at www.cloudeo.group/blog/cloudeo-blog-space-1/how-satellite-imagery-can-monitor-drought-events-river-po-italy-55

[75] Binh Pham-Duc, Frederick Frappart, and others, "Monitoring Lake Volume Variation from Space Using Satellite Observations—A Case Study in Thac Mo Reservoir (Vietnam)". *Remote Sensing*, vol. 14, issue number 16, p. 4023. Available at https://doi.org/10.3390/rs14164023

CASE STUDY

Using satellite data to monitor Lake Sulunga, United Republic of Tanzania [a]

Like many countries around the world, the United Republic of Tanzania is vulnerable to extreme weather events. Currently, more than 70 per cent of all natural disasters in the country are climate-change-related and are linked to recurrent droughts and floods. Digital Earth Africa (DE Africa) has helped the National Bureau of Statistics (NBS) in the United Republic of Tanzania, to analyse data on issues related to agriculture, deforestation, water access and food security. NBS has been researching how to monitor and report on Sustainable Development Goal (SDG) indicator 6.6.1: change in the extent of water-related ecosystems over time, and more specifically the spatial extent of water-related ecosystems.

Lake Sulunga, also known as Bahi Swamp, is in Central Tanzania and is relied upon by many surrounding settlements for drinking water, fishing, agriculture, livestock farming and salt production. The lake measures about 25 km wide and 42 km long, and lies 45 km west of the capital, Dodoma. The communities which live around the lake depend on fishing and animal husbandry for their livelihoods.

Using DE Africa services, the Tanzanian NBS was able to analyse Lake Sulunga using the Water Observations from Space (WOfS) service, gathering valuable insights to improve policy to protect Lake Sulunga and the communities who depend on it. WOfS covers inland and coastal areas across the African continent to highlight the changes in water availability over time. It enables analysis of individual water bodies, which can help users to analyse flood events or the effect of drought on a single lake. Based on Landsat imagery, WOfS spans decades of data with records dating back to 1984 in some locations. Figure 4.9 presents this overview of the water extent over time in Lake Sulunga.

WOfS can be used to understand the extent of water available on the surface, which can be useful for analysis of flood risk assessment, understanding the change of water extent over time, observing the effect of major weather on a water system, and more. This can inform governance and policy decisions around managing water systems, inform assessment of insurance risk as well as assess the health of a water body or system.

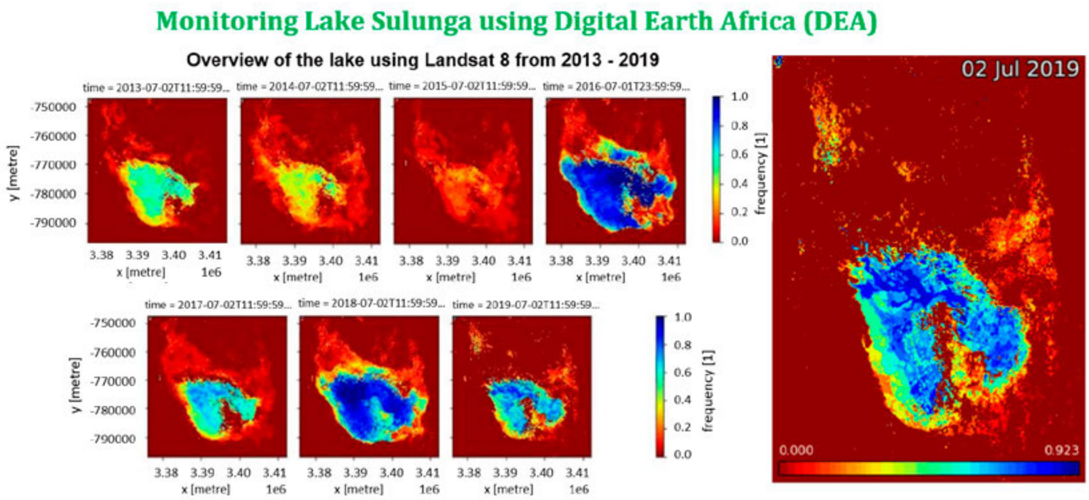
Using Digital Earth Africa's Water Observation from Space (WOfS) algorithm the Tanzanian NBS analysed Lake Sulunga's water extent over five years (January 2014 to January 2018). A comparison of two distinct periods from 2014 to the year 2017 showed a 4 per cent reduction in lake area over this time.

Fieldwork conducted by NBS revealed communities have been resettling on the banks of the lakes as it shrinks, as these areas are more fertile for agriculture. This poses a risk to these communities when floods occur, as their properties and dwellings are destroyed. Using data captured over the five years, NBS has been able to demarcate the actual boundary of the lake from the images supplied by DE Africa to protect citizens from flooding.

The insights gained are already helping the Government improve policy and make informed decisions to contribute to the Sustainable Development Goals, while NBS is also using the DE Africa platform to investigate incidences of land degradation in other regions of the United Republic of Tanzania.

[a] Digital Earth Africa, "Using satellite data to combat drought: Monitoring Lake Sulunga, Tanzania". Available at www.digitalearthafrica.org/why-digital-earth-africa/impact-stories/using-satellite-data-combat-drought-monitoring-lake-sulunga

Figure 4.9 Overview of Lake Sulunga, United Republic of Tanzania, using Landsat 8 imagery from 2013 to 2019



Source: Digital Earth Africa

4.2 El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) is a recurring climate pattern involving changes in the temperature of waters in the central and eastern tropical Pacific Ocean. On periods ranging from about three to seven years, the surface waters across a large swath of the tropical Pacific Ocean warm or cool by anywhere from 1°C to 3°C, compared to normal.[76]

El Niño is the warm phase of ENSO and describes the warming of the region's Pacific surface waters. La Niña, the "cool phase" of ENSO, is a pattern that describes the unusual cooling of the region's surface waters. El Niño and La Niña are considered the ocean part of ENSO, while the Southern Oscillation is its atmospheric changes.[77]

Although not technically classified as a hazard, the oscillating warming and cooling ENSO cycle causes changes in the atmospheric circulation which directly affects hydrometeorological hazards, such as rainfall distribution in the tropics, and can have a strong influence on weather and related hazards across the Pacific and other parts of the world. Figure 4.10 presents information on sea surface anomaly on 7 December 2017, as analysed by NASA scientists. Shades of blue show where sea level and temperatures were lower than average (water contraction). Normal sea level conditions appear in white.

An important feature of the ENSO cycle is that its evolution is predictable several months in advance, so the impacts can be anticipated, and decisions made to mitigate adverse effects or take advantage of favourable effects.[78]

[76] United States, National Weather Service, *What is ENSO*. Available at www.weather.gov/mhx/ensowhat

[77] National Geographic (2022). *El Nino*. Available at https://education.nationalgeographic.org/resource/el-nino

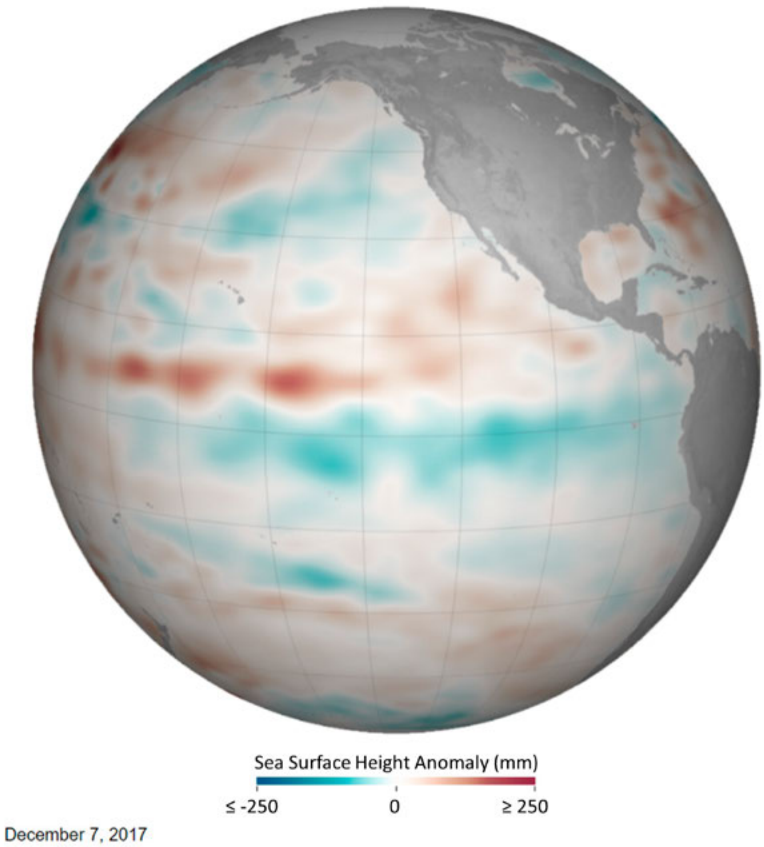
[78] United Kingdom, Meteorological Office. *El Nino, La Nina and the Southern Oscillation*. Available at www.metoffice.gov.uk/research/climate/seasonal-to-decadal/gpc-outlooks/el-nino-la-nina/enso-description

A range of indicators is used to assess the state of ENSO including sea surface temperatures, relative humidity, cirrus clouds, outgoing longwave radiation and sea surface heights, all of which are measured by satellites.

Combined with other data sets, these indicators are used to produce a range of ENSO products, including current conditions, forecasts and advisories for the changing conditions in the central and eastern Pacific, and impact maps. El Niño forecasts and impact maps provide one of the earliest warnings of possible climate-related impacts that government decision makers or managers of climate-sensitive industries might receive in time to act.[79]

Figure 4.10 Pacific Ocean surface height anomalies on 7 December 2017, as analysed by NASA scientists

The measurements were made by altimeters on the Jason-2 and Jason-3 satellites and show averaged sea surface height anomalies. Shades of red indicate areas where the ocean stood higher than the normal sea level; surface height is a good proxy for temperatures because warmer water expands to fill more volume. Shades of blue show where sea level and temperatures were lower than average (water contraction). Normal sea level conditions appear in white



Source: NASA Earth Observatory

[79] El Nino Ready Nations, "El Nino Early Warning Systems (EWSs)". Available at https://elninoreadynations.com/el-nino-early-warning-systems

CASE STUDY

NASA El Niño and La Niña observations[a]

In 2016, a significant El Niño developed in the Pacific Ocean. The impacts across the United States and the world were anticipated to be substantial, and the interest in this El Niño event was high. The Jet Propulsion Laboratory of NASA and partner agencies produced a series of images of key spaceborne observations of the ocean and atmosphere. The data for the 2016 conditions were compared with the largest El Niño on record in 1997–1998 or with a "normal" year for measurements that do not extend back to 1997. Images produced included:

- *Sea surface temperature (SST) anomaly*: derived from the advanced very high-resolution radiometer (AVHRR) instruments that have been in orbit on board the operational polar-orbiting satellites of NOAA since 1981 beginning with NOAA-7 and continuing to present with NOAA-19.
- *Rainfall:* These images are produced from the Integrated Multi-Satellite Retrievals for Global Precipitation Measurement mission, which assembles multiple orbits of GPM and partner satellite data into a common grid every 30 minutes. GPM is a collaboration between NASA and the Japanese Aerospace Exploration Agency (JAXA).
- *Sea surface height (SSH) anomaly:* Satellites Jason-2 and Jason-3 used space-based radar altimetry to collect sea surface height data of all the world's oceans. These images are processed to highlight the inter-annual signal of sea surface height:
  - *Relative humidity (RH):* relative humidity images are captured by the Atmospheric Infrared Sounder (AIRS) instrument on the Aqua satellite.
  - *Wind:* The images show the near-surface winds observed over the global oceans by the NASA RapidScat. The ISS-RapidScat was launched aboard the International Space Station (ISS) on 21 September, 2014, and began providing high-quality data just a couple of weeks later.
  - *Outgoing longwave radiation:* is a measure of how much infrared energy is leaving the Earth's surface and atmosphere. These images are from the AIRS instrument on the Aqua satellite.

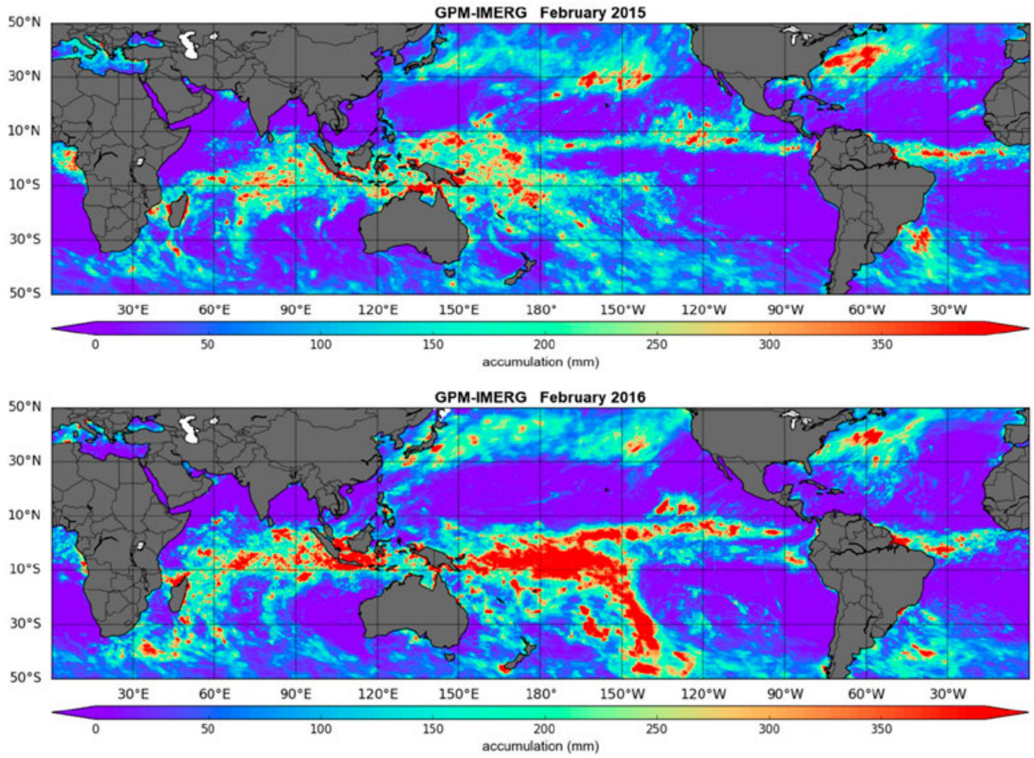
Many of the images showed a data "anomaly", revealing when data was outside of normal measurement ranges. The colour bar indicates how far from normal the measurements were.

Together, the images enable practitioners to anticipate the potential influence of ENSO on atmospheric processes and hazards and the severity of impacts that may occur. Early warnings within the seasonal ENSO forecasts alert authorities to the potential need for disaster management interventions to minimize the impact of ENSO on those at risk.

Figure 4.11 presents a comparison of monthly oceanic precipitation totals (in millimetres) for February 2015 and February 2016.

[a] United States, National Aeronautics and Space Administration, Jet Propulsion Laboratory, *El Nino/La Nina Observations*. Available at https://climatesciences.jpl.nasa.gov/projects/enso

Figure 4.11. Monthly oceanic precipitation totals (in millimetres) February 2015 and February 2016



Source: NASA JPL

CASE STUDY

The International Research Centre on El Niño[a, b, c]

The International Research Centre on El Niño Phenomena (CIIFEN) was established in 2003 and supported by the Government of Ecuador, WMO and UNDRR. The vision of CIIFEN is to carry out applied research to provide innovative solutions for the benefit of the most vulnerable communities, ecosystems, and livelihoods to confront the challenges posed by the El Niño phenomena (ENSO), climate variability and global change. CIIFEN covers the countries in the north west of South America.

The strategic objectives of CIIFEN include:

- Enhancing the use of climate services and services to contribute to disaster risk reduction and adaptation
- Strengthening regional and global coordination mechanisms to improve climate services, disaster risk reduction and adaptation
- Contributing to awareness-raising regarding scientific knowledge on the weather, vulnerability and impacts in Latin America
- Contributing to the regional, national and local initiatives to strengthen climate resilience and sustainable development

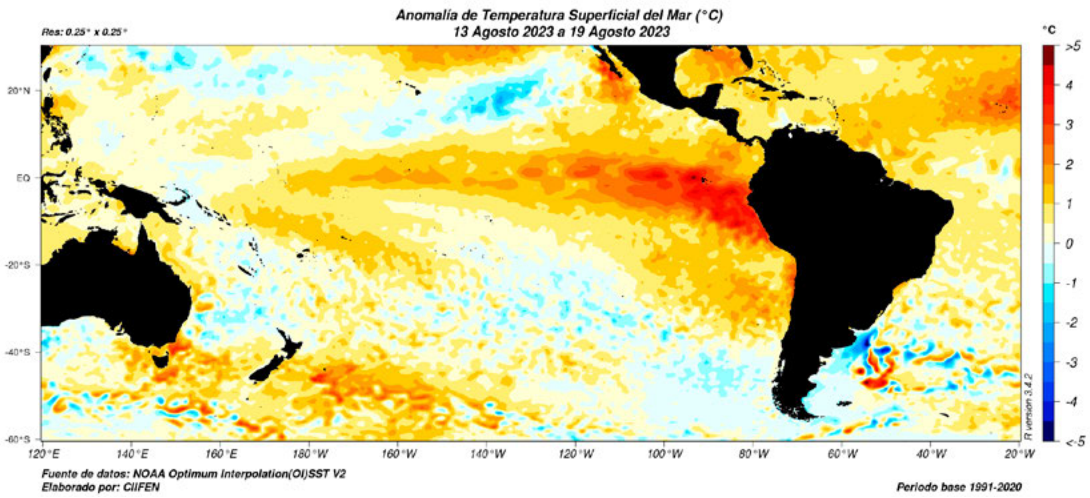
CIIFEN provides relevant and timely information on El Niño phenomena (ENSO), seasonal forecasts and other relevant climate products, such as a mapping tool to show the surface temperature of the ocean. Many of these are derived from satellite observations. In 2015, CIIFEN was chosen by WMO to operate its Centre for the Western Region of South America. It operates within Region III (South America) of WMO and aims to strengthen the capacity of national meteorological and hydrological services in the western region of South America. Figure 4.12 presents a forecast sea surface temperature anomaly presented by CIIFEN.

[a] International Research Centre on El Niño Phenomena. "Plan Estrategico". Available at https://ciifen.org/plan-estrategico

[b] International Research Centre on El Niño Phenomena, "Historia". Available at https://ciifen.org/historia

[c] Centro Regional del Clima para el Oeste de Sudamerica. "Que es el Centro Regional del Clima?" Available at https://crc-osa.ciifen.org/que-es-el-crc

Figure 4.12 Sea surface temperature anomaly map for the period from 13 to 19 August 2023



Source: CIIFEN

CASE STUDY

IFRC forecast-based financing Peru – El Niño disaster management pre-emptive actions

In Peru, the El Niño phenomenon leads to particularly disruptive and damaging weather patterns. Heavy rain leads to flooding in the normally rainless coastal regions and the highlands can suffer from crippling droughts.[a]

Space technologies that are used to monitor and forecast the potential for ENSO are contributing to the successful implementation of the International Federation of Red Cross and Red Crescent Societies forecast-based financing (FbF) in Peru, enabling preparedness for El Niño impacts. When the forecast reaches a specific threshold, FbF funds are released to enable pre-emptive actions that will contribute towards the mitigation of impacts from hydrometeorological hazards, influenced by El Niño.

The forecasts thresholds that trigger FbF use a range of forecast models and tools, including the Precipitation Flexible Seasonal Forecast, the EUROSP multi-model seasonal forecast of ECMWF, the Climate and Global Forecast Systems of NOAA and GLoFAS, [b] all of which use satellite data to inform and verify their forecast tools.

[a] German Red Cross. "Peru". Available at www.forecast-based-financing.org/projects/peru

[b] Juan Bazo, Elisabeth Stephens, and others, "Implementing Forecast based Financing Mechanism in Peru to Enable Preparedness for El Niño Impacts". Available at https://iri.columbia.edu/wp-content/uploads/2015/11/RED_CROSS_-ELNI%C3%91OCONFERENCE_BAZO.pdf

Popocatepetl volcano in Mexico as seen by the Landsat 8 satellite on 2 January 2021

Image courtesy of NASA

Chapter 5.

Space technologies for geological hazards

A geological hazard is an extreme natural event in the crust of the Earth that poses a threat to life and property.[80] Natural geohazards such as earthquakes, tsunamis, volcanic eruptions, landslides and sink holes can occur without warning and cause damage to health, infrastructure and livelihoods. The Earth's surface is constantly shifting and moving, sometimes slowly, but sometimes swiftly and violently with catastrophic and immediate results.[81]

Collectively, geohazards make up a relatively small proportion of the total disasters that occur around the world, just 15 per cent in the last 20 years (2000–2019).[82] However, the potential impacts, leading to significant loss of life and financial cost, make the potential to warn for geohazards a key ambition for disaster management organizations worldwide.

Sudden-onset geohazards are a particular challenge for early warning systems. Often the most impactful geohazards occur with very little, or no notice, and there is often very limited time to take actions that could save lives.

While considerable progress has been made in recent decades in the field of early warning, early warning systems are generally less developed for geohazards and significant challenges remain in advancing the development of these systems for specific hazards, particularly for sudden-onset hazards such as earthquakes.[83]

Traditionally, geohazard researchers monitor ground deformation with ground-based sensors and global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) of the United States. Furthermore, satellite technologies, such as interferometric synthetic aperture radar (InSAR), that compliment ground-based sensors, have revolutionized how earthquakes and volcanoes are monitored and understood.[84]

[80] Organisation for Economic Co-operation and Development, "Glossary of Statistical Terms". Available at https://stats.oecd.org/glossary/detail.asp?ID=1112

[81] United Kingdom, British Geological Survey, *Earth Hazards*. Available at www.bgs.ac.uk/discovering-geology/earth-hazards

[82] United Nations Office for Disaster Risk Reduction, "The human cost of disasters: an overview of the last 20 years (2000–2019)". Available at www.undrr.org/media/48008/download

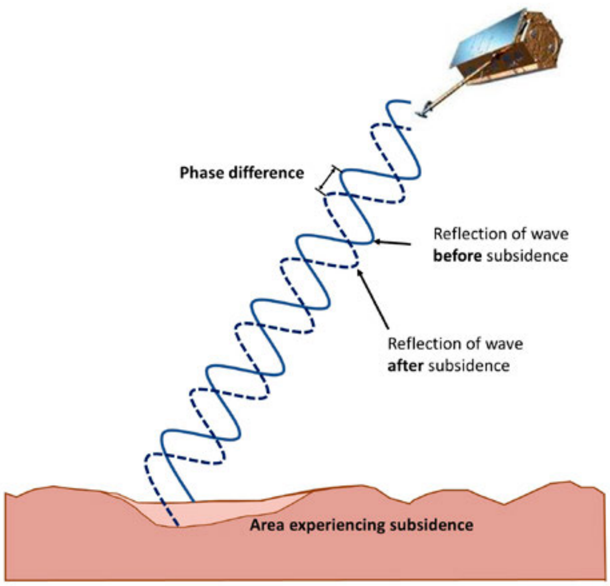
[83] United Nations Educational, Scientific and Cultural Organization, "International Platform on Earthquake Early Warning Systems (IP-EEWS)". Available at https://en.unesco.org/disaster-risk-reduction/early-warning-systems/IP-EEWS

[84] United States, National Aeronautics and Space Administration, *New Radar to Monitor Volcanoes and Earthquakes from Space*. Available at https://science.nasa.gov/technology/technology-highlights/new-radar-to-monitor-volcanoes-and-earthquakes-from-space

Another methodology used to assess deformations of the ground is differential interferometry synthetic aperture radar (DInSAR). Figure 5.1 presents a schematic diagram of the process of satellite imagery acquisition of ground surface for detection of ground deformation using DInSAR. The process involves the comparison of reflected waves from the satellite before and after the motion, in terms of the phase difference. This phase difference is then compared with the wavelength of the wave to estimate the magnitude of the displacement.

Figure 5.1. The DInSAR technique used to detect the ground deformation

The phase difference between the reflected waves before and after the deformation of the ground is used to determine the amount of the deformation and its average speed



Source: UN-SPIDER

The synthetic aperture radar instruments on board the Sentinel 1 satellites offer the capability to regularly monitor ground deformation with millimetre accuracy, for timely forecasting of impending natural hazards such as landslides. However, the main limitation is its incapacity to monitor active areas covered in dense vegetation such as forests.

CASE STUDY

Interferometric synthetic aperture radar and geological hazards [a]

Interferometric synthetic aperture radar (InSAR) is ideally suited to measure the spatial extent and magnitude of surface deformation associated with geohazards such as earthquakes, volcanoes and landslides. It is often less expensive than obtaining sparse point measurements from labour-intensive spirit-levelling and GNSS surveys, and can provide millions of data points in an area of about 10,000 square kilometres.

By identifying specific areas of deformation within broader regions of interest, InSAR imagery can also be used to better position specialized instrumentation (such as extensometers, GPS networks and levelling lines) designed to precisely measure and monitor surface deformation over limited areas.

Interferograms are maps of relative ground-surface change that are constructed from InSAR data to help scientists understand how tectonic or human activities cause the land surface to uplift or subside. Interferograms require two images taken at intervals in time to determine if there has been any shift in land surface levels. If the ground has moved away from (subsidence) or towards (uplift) the satellite between the times of the two SAR images, a slightly different portion of the wavelength is reflected back to the satellite resulting in a measurable phase shift that is proportional to displacement. The map of phase shifts, or interferogram, is depicted with a repeating colour scale that shows relative displacement between the first and the second acquisitions. The direction of displacement – subsidence or uplift – is indicated by the sequence of the colour progression of the fringe(s) towards the centre of a deforming feature.

Monitoring ground deformation is a key tool in understanding tectonic and ground motion which could be indicative of the potential for earthquakes, volcanic eruptions, landslides and subsidence.

[a] United States Geological Survey, "Interferometric Synthetic Aperture Radar (InSAR)". Available at www.usgs.gov/centers/land-subsidence-in-california/science/interferometric-synthetic-aperture-radar-insar

5.1 Volcanic activity

Volcanic eruptions are typically multi-hazard affairs that include the emission of hot, dangerous gases, ash, lava, boulders and pyroclastic clouds, all having the potential to cause significant loss of life, health impacts, destruction of property and critical infrastructure.

All over the world, volcano alert level systems (VALS) are used to provide warnings and scientific information related to volcanic unrest and eruptive activity, typically based upon forecasts arising from observation, monitoring and data analysis,[85] to provide sufficient time and advice to prevent and mitigate the impacts of a volcanic eruption. VALS are the communicational component of an early warning system, accounting for warnings both prior to and during a hazard event. Observation of eruption phenomena and integration of monitoring of precursory signals such as geodetic, seismic and gas flux as well as the detection and interpretation of magma migration are important to issue timely warnings to local people and governments and thus mitigate risks from volcanic phenomena.

Indicators of an impending volcanic eruption include:

- Changes in the amount and composition of the gases being ejected
- Changing fumarole temperatures
- Deformation of the volcanic edifice
- Small earthquakes[86]

A variety of instruments is employed for monitoring volcanoes: released gases can be sampled directly, through ground-based stations and hand-held devices, and some of them may also be determined by satellite remote-sensing

[85] Earth System Knowledge Platform, "Volcanic Alert Systems". Available at www.eskp.de/en/natural-hazards/volcanic-alert-systems-935705

[86] Earth System Knowledge Platform, "Assessing volcanic hazards". Available at www.eskp.de/en/natural-hazards/assessing-volcanic-hazards-935307

techniques. Seismic networks record earthquakes and GPS networks and satellites are available for the detection of deformation of the volcanic edifices.[88]

Satellites play a key role, as they can monitor thermal and gas emissions, as well as movements in vertical and horizontal motions, thus witnessing all the steps that lead to an eruption. With the launch of the Sentinel 1 satellites, the field of volcanology received a large boost, as spacecraft can monitor volcano movements at unparalleled resolution and at regular time intervals. Being equipped with InSAR sensors, the satellites can observe subcentimetre deformations, thus allowing scientists to observe the entire swelling process of a volcano[87] and provide key information paramount to issuing early warnings.

5.1.1 Monitoring hotspots and deformation from space

Ground deformation in volcanic areas often occur as a precursor of eruptions or are indicative of an increase in volcanic activity. Under the pressure of the magma present beneath volcanoes, the volcano tends to "inflate" its walls and deform until the magma finds a way out. However, even in association with massive phenomena, the deformation may be relatively small: in the order of a few centimetres or tens of centimetres.[88]

The use of the techniques of differential interferometry synthetic aperture radar (DInSAR) is essential in this case. Analysis of two InSAR images of a particular object in different time periods can create the differential InSAR (DInSAR) image which reflects the pattern of the deformation.[89] This technique is used to detect ground deformation in the case of landslides or land subsistence.

In particular, the technique SBAS (which stands for Small Baseline Subset), developed at the Institute of Electromagnetic Sensing of the Environment of the National Research Council of Italy in Naples, allows the temporal evolution of deformation to be followed over a period of several months.[90]

CASE STUDY

Monitoring ground deformation in volcanic and seismic regions to support civil protection activities[a]

In the last decades, differential interferometry synthetic aperture radar (DInSAR) has demonstrated that it is an effective tool for detecting and following Earth surface deformations with a centimetre to millimetre accuracy in different hazard scenarios. In particular, DInSAR techniques now play an important role in the study of ground deformation phenomena, such as volcanic eruptions and seismic events, thanks to their ability to provide dense measurements over wide areas and at relatively low cost.

[87] Skyrora, "Volcanoes from Space". Available at www.skyrora.com/volcanoes-from-space

[88] Italy, National Research Council, "Measurement of volcanic deformation". Available at www.irea.cnr.it/en/index.php?option=com_k2&view=item&id=78:misura-delle-deformazioni-di-vulcani&Itemid=91

[89] UN-SPIDER Programme, "Knowledge Portal. Data Application of the Month: Land Deformation Mapping Using DInSAR". Available at www.un-spider.org/links-and-resources/data-sources/daotm-land-deformation

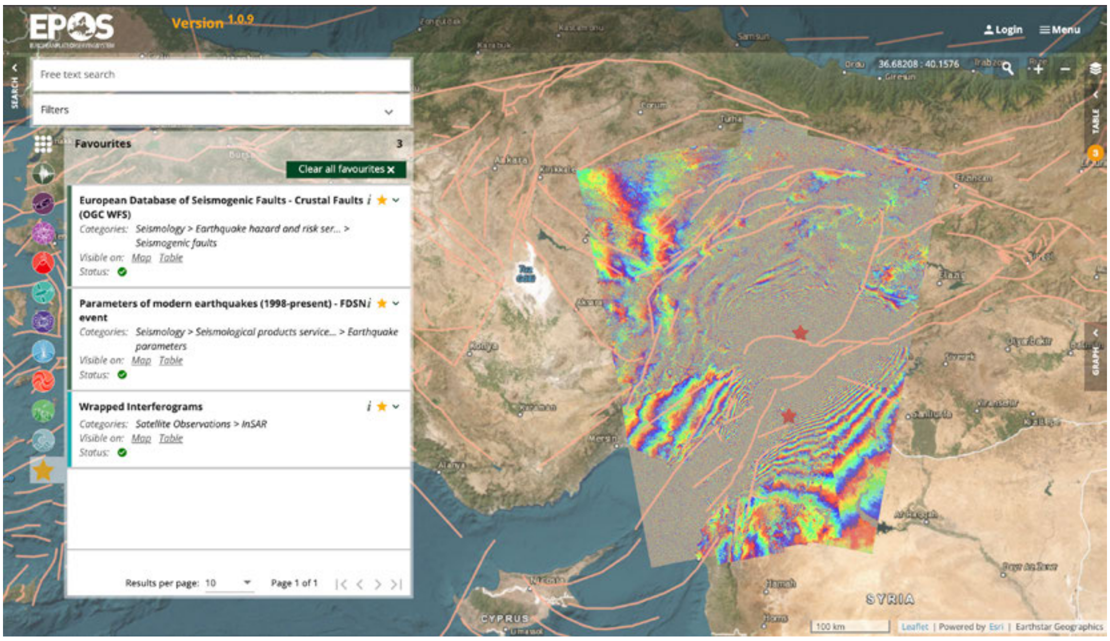
The increasingly widespread use of DInSAR is also the result of access to huge, easily accessible SAR data archives, such as those acquired, since late 2014, by the Copernicus Sentinel-1 constellation. This routinely provides C-band SAR data with a defined repeat-pass frequency at a global scale. Therefore, this constant and reliable availability of data has allowed us to move from single event analysis to monitoring tasks, particularly in natural hazard-prone areas.

The Institute of Electromagnetic Sensing of the Environment of the National Research Council of Italy (CNR-IREA) acts as a centre of competence of the Italian Department of Civil Protection for ground deformation monitoring in volcanoes and seismic areas using DInSAR techniques. Figure 5.2 presents an interferogram of the area near the epicentre of the recent February 2023 earthquake in Türkiye generated by CNR-IREA.

[a] This work is supported by the 2022-2024 CNR-IREA and Italian DPC agreement and the H2020 EPOS-SP Project (GA 871121).

Figure 5.2 EPOS portal view of the Sentinel-1 co-seismic differential interferograms relevant to the Mw 7.8 and Mw 7.5 earthquakes that struck south-eastern Türkiye on 6 February 2023

Each colour cycle corresponds to about 2.8 cm of displacement. Exploited satellite data were acquired on 17 January 2023 and 10 February 2023 from descending passes (Track 21) and 16 January 2023 and 9 February 2023 from ascending passes (Track 14). Epicentres of the main shocks (red stars) and the location of main seismogenic faults (lines) are also available within EPOS and are provided by the European-Mediterranean Seismological Centre (EMSC) and National Institute of Geophysics and Volcanology (INGV), respectively



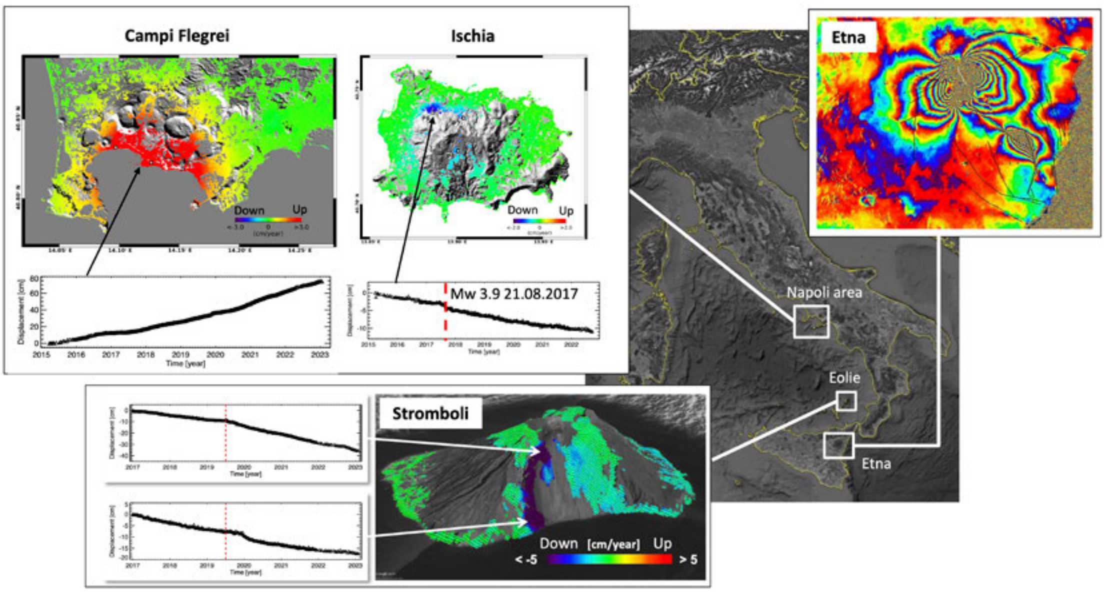
Source: CNR-IREA

First, by exploiting the Sentinel-1 data archives and the publicly accessible earthquake catalogues, CNR-IREA implemented an automatic service that generates DInSAR co-seismic displacement maps, once an earthquake that is likely to cause ground deformation occurs. Originally developed to monitor the Italian territory, the service has been extended to operate at global scale and the generated products are made freely available to the scientific community through the European Plate Observing System Research Infrastructure. Although earthquakes cannot be forecasted, the service can be useful during disaster response and management.

Furthermore, by also exploiting Sentinel-1 data, CNR-IREA developed a second service which is devoted to volcano ground displacement monitoring. The designed system is fully automatic and the process is triggered by the availability of new SAR data in the Sentinel-1 catalogues acquired from both ascending and descending passes, for every monitored volcano site. The data, per each orbit, are automatically ingested and then processed through the well-known Parallel Small BAseline Subset DInSAR technique that allows the generation of the displacement time series and the corresponding mean displacement velocity maps relevant to the overall observation period. The line of sight measurements retrieved in this way are then combined to compute the vertical and East-West components of the retrieved deformation, which are clearly understandable to most end users. This service is currently operative for the main active Italian volcanoes (Campi Flegrei caldera, Mt. Vesuvius, Ischia, Mt. Etna, Stromboli and Vulcano), but it can be easily extended to include other volcanic areas on Earth. Figure 5.3 presents examples of the result of interferometric analysis of the deformation of volcanic domes generated by CNR-IREA.

Figure 5.3 CNR-IREA DInSAR ground deformation monitoring service for Italian volcanoes

Mean deformation velocity maps and displacement time series of relevant points for some of the monitored volcanoes are presented



Source: CNR-IREA

CASE STUDY

Monitoring volcanoes: MIROVA[a] and MOUNTS[b]

MIROVA (Middle InfraRed Observation of Volcanic Activity), a collaborative project between the Universities of Turin and Florence (Italy), is an automatic hotspot detection system developed to detect, locate and measure the heat radiation generated by volcanic activity.

The main goals of MIROVA are to support volcano observatories in evaluating the state of activity and in maintaining situational awareness during an eruptive crisis, detect thermal unrest signals in potentially active volcanoes, and update a multi-year database of infrared satellite data of the most active volcanoes.

MIROVA is developed to work in near-real time by providing infrared images and thermal flux time series within a few hours from satellite overpasses. It was originally based on the analysis of middle infrared radiation (MIR) provided by the MODIS sensor. Currently, the system integrates infrared data acquired from multiple sensors and elaborated by different algorithms, including:

- MODIS (moderate resolution imaging spectroradiometer): On board the satellites Terra (March 2000) and Aqua (May 2002), it acquires data in the middle infrared (MIR) and thermal infrared (TIR) regions, with a resolution of about 1 km. Image cadence: approximately every 12 hours.
- VIIRS (visible infrared imaging radiometer suite): On board the Suomi-NPP (October 2011) and JPSS-1 (November 2017) satellites, it acquires data in the middle infrared (MIR) and thermal infrared (TIR) regions, with a resolution of about 750 m (375 m for the imaging bands). Image cadence: approximately every 12 hours.
- MSI (multispectral instrument): On board the Sentinel 2A (June 2015) and Sentinel 2B (March 2017) satellites, it acquires data in the near infrared (NIR) and short wave infrared (SWIR) regions, with a resolution of about 20 m. Image cadence: approximately every five days.
- OLI (Operational Land Imager): On board the Landsat 8 satellite (Feb 2013), it acquires data in near infrared (NIR) short wave infrared (SWIR) regions, with a resolution of about 30 m. Image cadence: approximately every 16 days.

The main features of MIROVA are:

- Automated detection of high-temperature volcanic activity in near-real time (within few hours from the satellite overpass)
- Multi-sensor approach using data with different spatial, temporal and spectral features
- Quick overview of the latest thermal images
- Updated volcanic radiative power time series in logarithmic and normal scale
- Last thermal map image of each volcano available for Google Earth overlapping
- Possibility to add any new target volcanoes in near-real-time observation, in any area of the globe (on request in few hours)

The MOUNTS project was initiated in April 2017 and aims to develop a worldwide operational monitoring system for volcanoes using satellite imagery. It currently focuses on processing Sentinel-1 (SAR), Sentinel-2 (SWIR) and Sentinel-5P data. Artificial intelligence plugins are developed and implemented in the processing chain to assist monitoring tasks.

CASE STUDY *(continued)*

The Monitoring Unrest from Space project (MOUNTS) is currently led by the Institute of Geophysics at Universidad Nacional Autónoma de Mexico, and is strongly inspired by the MIROVA operating system, with which close collaborations are ongoing. The products are available on the website of the project.

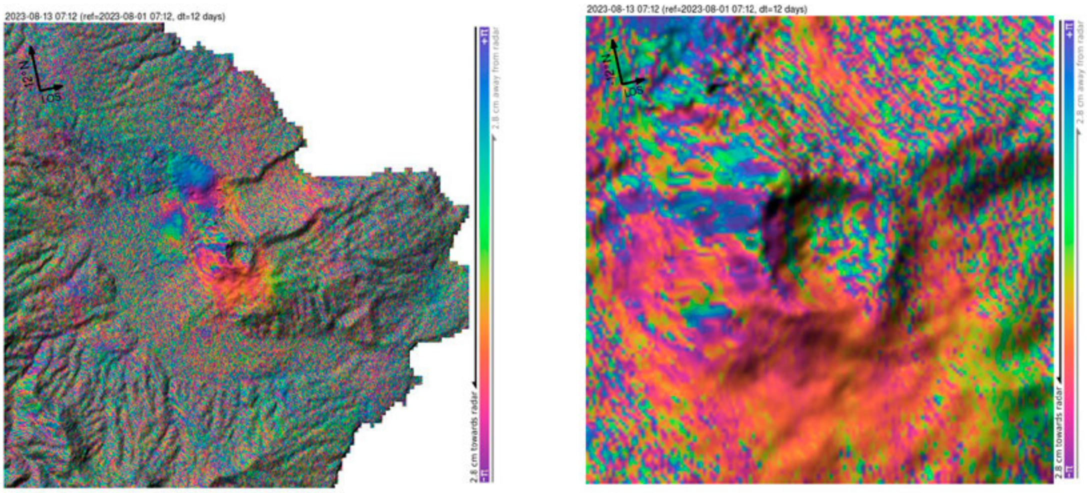
Figure 5.4 presents a map of ground deformation in the Yasur volcano in Vanuatu as of 21 December 2022, generated by researchers engaged in the MOUNTS project. The ground deformation was detected using radar interferometry.

[a] Middle Infrared Observations of Volcanic Activity, "MIROVA". Available at www.mirovaweb.it/?action=about

[b] Monitoring Unrest from Space, "Monitoring Unrest from Space". Available at www.mounts-project.com/about

Figure 5.4 Images displayed on MOUNTS showing ground deformation of the Yasur crater, Vanuatu 21 December 2022

The image on the right is a zoomed in shot of the Yasur crater



Source: MOUNTS/ESA

CASE STUDY

Testing of multitemporal radar interferometry in active volcanoes in Asia and Latin America

A visiting scientist from the National Autonomous University of the State of Mexico at UN-SPIDER carried out research to test the feasibility of the use of the "Short Baseline Subset (SBAS)" technique[a] to detect deformations of volcanic domes prior to eruptions.

The analysis was carried out using satellite imagery acquired by the Sentinel-1 satellite in both the ascending and descending orbits in three volcanoes: Anak Krakatoa in Indonesia,[b] the Taal volcano in the Philippines[c] and the Nevado del Chillán volcano in Chile.[d] In each case, Sentinel 1 imagery was acquired for a period covering from six months before an eruption up to the time of the eruption.

In all cases, the procedure allowed for the detection of inflation processes in areas of the cone of the active volcano before the eruption. However, it was not possible to detect any deformation in those areas covered with dense vegetation. In addition, there were some slight differences in the results obtained when assessing deformation with imagery acquired in ascending and descending orbits.

Nevertheless, in the case of the Anak Krakatoa volcano, interesting results showed the expected uplift in one flank of the active cone and an unexpected deflation in the other flank of the cone during the months that preceded the eruption. This result can be confirmed by the fact that the lateral eruption of the volcano on 23 December 2018 triggered a tsunami that impacted communities and resulted in fatalities and injuries. The deflation detected with the interferometric technique coincided with the lateral eruption that triggered the mass movement into the sea that subsequently provoked the tsunami. Figure 5.5 presents the result of a multitemporal radar interferometric analysis of the cone of the Anak Krakatoa volcano covering the period from June to December 2018. The analysis was carried out processing 14 Sentinel 1 images acquired between 27 July and 7 December 2018. The results indicate an uplift of the eastern region of the volcanic cone (depicted in blue-coloured pixels) and subsidence in the western side of the cone, more noticeable towards the south-west of the cone.

[a] P. Berardino, G. Fornaro, R. Lanari, and E. Sansosti, "A new algorithm for surface deformation monitoring based on small baseline differential interferograms". *IEEE Transactions on Geoscience and Remote Sensing*, vol. 40, No. 11, p. 2375.

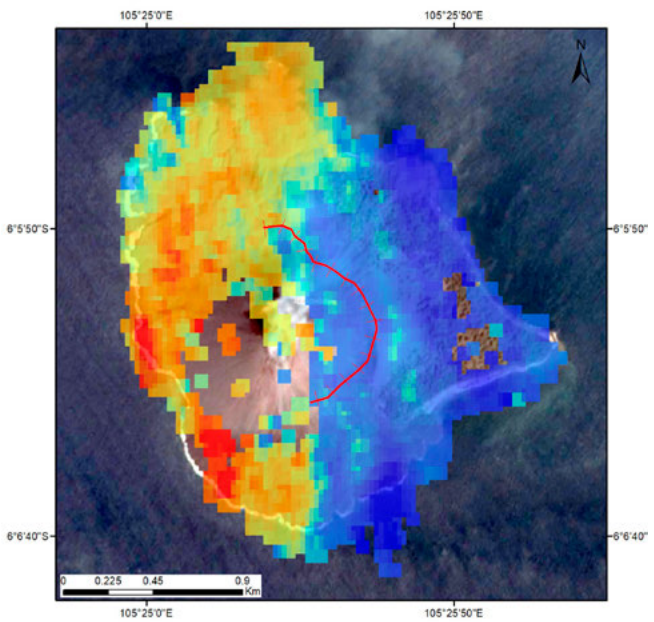
[b] UN-SPIDER Programme, "Knowledge Portal: Use of SBAS to monitor activity of the Anak Krakatoa volcano". Available at https://un-spider.org/use-sbas-monitor-activity-anak-krakatoa-volcano

[c] UN-SPIDER Programme, "Knowledge Portal: User Stories, Use of DinSAR and SBAS to monitor activity of the Taal volcano". Available at www.un-spider.org/use-dinsar-and-sbas-monitor-activity-taal-volcano

[d] UN-SPIDER Programme, "Knowledge Portal: Use of SBAS to monitor activity of the Nevados de Chillan volcano". Available at https://un-spider.org/use-sbas-monitor-activity-nevados-de-chillan-volcano

Figure 5.5 Multitemporal analysis of the Anak Krakatoa volcano in the period between June and December 2018 (27 September–7 December 2018) using Sentinel 1 imagery acquired in ascending orbit

Pixels in blue display uplift, while those in orange and red display subsidence



Source: UN-SPIDER

5.1.2 Tracking volcanic ash clouds

Explosive volcanic eruptions can release huge amounts of ash into the atmosphere that can spread over large distances, turning daylight into darkness and drastically reducing visibility.

Volcanic ash is made of tiny fragments of jagged rock, minerals and volcanic glass. Unlike the soft ash created by burning wood, volcanic ash is hard, abrasive and does not dissolve in water. Generally, particles of volcanic ash are 2 millimetres (0.08 inches) across or smaller.[90]

Atmospheric processes can carry small volcanic ash particles to great heights and across great distances. For example, the 2008 eruption of Chaiten volcano in Chile produced an ash cloud that blew 1,000 km (620 miles) across Patagonia to Argentina, reaching both the Atlantic and Pacific coasts.[92]

As a result of these characteristics, volcanic ash is a significant health, aviation, infrastructure and economic hazard. The 2010 eruption of Eyjafjallajökull, Iceland, produced an ash cloud that forced the cancellation of roughly 100,000 flights and affected 7 million passengers, costing the aviation industry an estimated $2.6 billion.[92] The ability to warn of the presence of volcanic ash is therefore imperative to help pre-emptive actions that can reduce the socioeconomic impact of volcanic ash.

Satellites are used to detect and track the movement and extent of volcanic ash clouds and to cross-check predictions from numerical models of the spread of the ash. The geostationary Meteosat satellites can detect ash in the atmosphere and play an important role in following its movement and dispersion in European airspace, in near-real time. The Meteosat satellites, with the aid of the IASI, GOME-2 and AVHRR instruments, can collect more detailed data about volcanic ash clouds, including sulphur dioxide, ash and ice content, but with less frequency as they only pass over the same area roughly twice a day.[91]

Newer-generation geostationary satellites, such as HIMAWARI-8, which was launched in October 2014, with coverage over the Western and Central Pacific, have image resolution down to 500 m for visible and 2 km for infrared imagery, and refresh frequencies up to 2.5 min, enabling detection of much smaller volcanic clouds than earlier counterparts.

GOES-16 and GOES-17 satellites (GOES-R Program) with refresh frequencies of between 30 seconds and 1 minute were launched respectively in November 2016 and March 2018 and cover the Americas, Eastern and Central Atlantic and Eastern Pacific. These satellites use the thermal infrared brightness temperature difference method, or "true colour" satellite techniques, to detect volcanic ash, with increased resolution and refresh frequencies, enabling better distinction from meteorological cloud.

The increased detection capability of these newer-generation satellites is supplemented by algorithms, such as the VOLcanic Cloud Analysis Toolkit (VOLCAT)[92] and the Support to Aviation Control Service[93] system that scan satellite data and automatically detect emergent eruptive activity and notify of volcanic ash and SO_2 in the atmosphere.

[90] National Geographic, "Human and Environmental Impacts of Volcanic Ash". Available at https://education.nationalgeographic.org/resource/human-environmental-impact-volcanic-ash

[91] European Commission, Copernicus Programme, "Topic4c – Part 1: Monitoring volcanic emissions- Overview". Available at:https://content.atmospheremooc.org/monitoring-atmospheric-composition/week-4-long-range-pollution-transport/topic-4c-applications-case-study-1-monitoring-volcanic-emissions

[92] More information on VOLCAT is available in this link: https://volcano.ssec.wisc.edu/blog/category/volcat

[93] More information on SACS is available in this link: https://sacs.aeronomie.be

Despite these improvements, there remain areas without satellite coverage on the frequency required to actively monitor volcanic activity globally. In addition, volcanic clouds are still often obscured by meteorological clouds making ground observations essential.[94]

CASE STUDY

GOES-R capability improves the detection of volcanic ash[a]

New spectral channels, improved resolution and faster scanning from the GOES-16 and GOES-17 Advanced Baseline Imager (ABI) allow for sophisticated new data products and better detection of volcanic ash. GOES-16 and GOES-17 observe a significant fraction of the most volcanically active region on Earth, known as the "Pacific Ring of Fire," which includes the western portions of North and South America, East Asia, Indonesia, Micronesia and New Zealand.

Information from the ABI flying aboard GOES-16 and GOES-17 is used by volcanic ash advisory centres (VAACs) which are responsible for issuing volcanic ash advisories 24/7. VAAC forecasters use the data to monitor clouds whose location, evolution and/or spectral properties are consistent with volcanic activity.

The ABI can also be used to estimate the height of ash clouds, determine the extent of ash and estimate the amount of ash present in each satellite pixel. Visible and infrared ABI channels can be combined to create RGB (red-green-blue) products that allow for better discernment of features such as ash and hotspots. ABI is also sensitive to sulphur dioxide (SO_2), a noxious gas often produced by volcanic eruptions. SO_2 detection is a new capability offered by the GOES-R Series ABI, due to new infrared channels that previous GOES imagers lacked. Figure 5.6 presents the geographic extent of the ash cloud triggered by the eruption of the Hunga Tonga-Hunga Ha'apai volcano in mid-January 2022.

[a] United States, National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration, *GOES R. New tools for monitoring hazardous volcanic ash*. Available at www.goes-r.gov/featureStories/volcanicAsh.html

Figure 5.6 GOES image of the Hunga Tonga-Hunga Ha'apai volcano eruption on 18 January 2022

Source: NOAA/NESDIS

[94] S. Engwell, L. Mastin, and others, "Near-real-time volcanic cloud monitoring: insights into global explosive volcanic eruptive activity through analysis of Volcanic Ash Advisories". *Bulletin of Volcanology*, vol. 83, article number 9 (2021). Available at https://link.springer.com/article/10.1007/s00445-020-01419-y

CASE STUDY

VOLcanic Cloud Analysis Toolkit

The large volumes of satellite data now available to geohazard monitoring and detection make manual examination impractical. The need to distil large volumes of GOES-R data into actionable information and for timely volcanic eruption detection led to the development of the VOLcanic Cloud Analysis Toolkit (VOLCAT).[a]

VOLCAT is an automated detection tool that uses a collection of software developed by NOAA, in partnership with the University of Wisconsin-Madison. VOLCAT is an artificial intelligence software suite that ingests satellite observations and other data to detect, characterize and track volcanic clouds and provide timely alerts to research partners (e.g., volcanic ash advisory centres, airlines, etc.) of new volcanic activity. The VOLCAT system provided many alerts for the explosions from Soufrière St. Vincent in Saint Vincent and the Grenadines in 2021.[b]

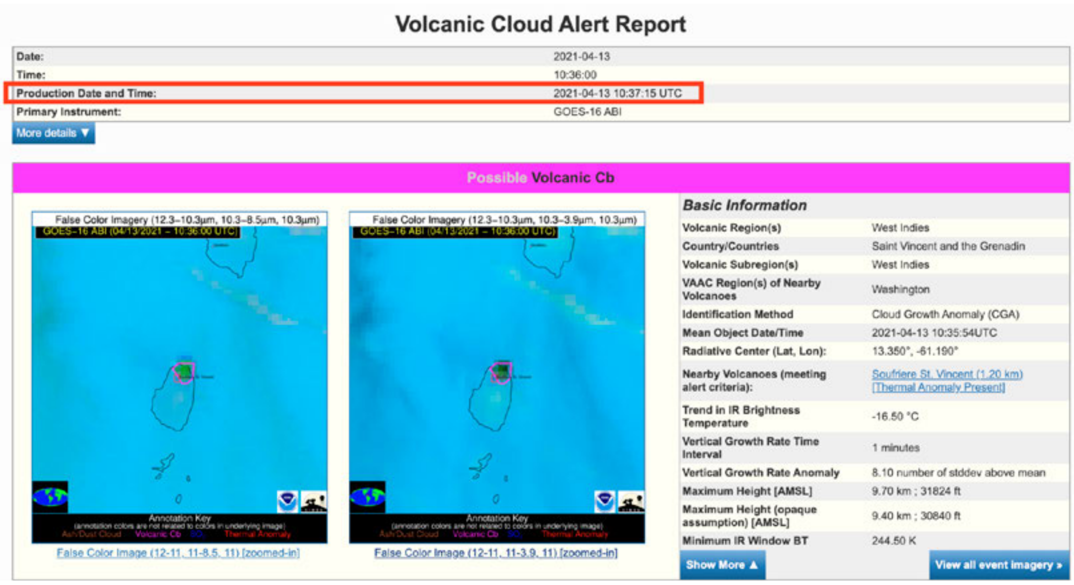
VOLCAT generates alerts when volcanic unrest or an eruption is detected and automatically tracks and characterizes volcanic clouds. The alerts are in the form of a hyperlink, distributable via email or short message service. The hyperlink points to a web-based alert report that includes information on the cloud growth anomaly, a list of the most likely source volcanoes and relevant satellite imagery. VOLCAT alerts are currently distributed to expert users at volcanic ash advisory centres and volcano observatories in an experimental manner. Work is underway to include SO_2 alerts and GLM lightning information in the VOLCAT tool.

Figure 5.7 presents an example of the Volcanic Cloud Alert Report related to the eruption of the Soufrière volcano in St. Vincent in April 2021.

[a] More information on VOLCAT is available in this link: https://volcano.ssec.wisc.edu/blog/category/volcat

[b] United States, University of Wisconsin. *NOAA/CIMSS Volcanic Cloud Monitoring VOLCAT* (8 April 2020). Available at https://volcano.ssec.wisc.edu/blog/category/volcat

Figure 5.7 Mesoscale based VOLCAT vCb alert issued at 10:37:15 UTC for an explosion of Soufrière St. Vincent, April 2021



Source: VOLCAT

5.2 Mass movements

Mass movement is the downhill movement of material under the influence of gravity. Rock falls, mud slides, debris flows and landslides are all examples of mass movement and can be triggered by a range of processes, such as earthquakes, tectonic activity, hydrometeorological hazards and erosion and weathering.

Satellite technology has already provided valuable data for the early warning systems supporting volcanic eruptions and hydrometeorological hazards. The very same space capabilities can also be harnessed to provide valuable services in the case of mass movement, particularly landslides.

5.2.1 Landslides

A landslide is defined as the movement of a mass of rock, debris or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity. The term "landslide" encompasses five modes of slope movement: falls, topples, slides, spreads and flows. These are further subdivided by the type of geological material (bedrock, debris or earth). Debris flows (commonly referred to as mudflows or mudslides) and rock falls are examples of common landslide types.[95]

Landslides are a serious geological hazard and can be triggered by a variety of geological, morphological and human causes. As a result, they are often strongly correlated with other types of natural hazard and are often involved in cascading events of multi-hazard disasters.[96]

Landslides are affecting urban and rural communities in mountainous regions around the world. According to the Centre for Research on the Epidemiology of Disasters, between the years 2000 and 2019, there were 376 landslides, nearly 50 per cent more than in the period from 1980 to 1999.

According to USGS,[97] there are three types of triggers that are responsible for the most damaging landslides around the world. These are:

- *Water*: Saturation from intense rainfall, snow melt, changing water levels in groundwater, dams, lakes, rivers and coastlines can trigger landslides.
- *Seismic activity*: Earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, which allows rapid infiltration of water.
- *Volcanic activity*: Volcanic lava may melt snow at a rapid rate, causing a deluge of rock, soil, ash and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars) reach great distances, once they leave the flanks of the volcano, and can damage structures in flat areas surrounding the volcanoes.

[95] United States Geological Survey, *What is a landslide and what causes one?* Available at www.usgs.gov/faqs/what-landslide-and-what-causes-one

[96] N. Casagli, F. Guzzetti, and others, "Chapter 3 Section II - Hydrological risk: landslides". In: Poljanšek, K., Marin Ferrer, M., De Groeve, T. and Clark, I., eds. *Science for disaster risk management 2017: knowing better and losing less*. Publications Office of the European Union, Luxembourg , pp. 209–218. Available at https://drmkc.jrc.ec.europa.eu/portals/0/Knowledge/ScienceforDRM/ch03_s02/ch03_s02_subch0305.pdf

[97] United States Geological Service, *Landslide Types and Processes*. Available at https://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Satellite radar images have been used to predict and capture the early warning signs of impending natural disasters, including landslides. However, a significant challenge for landslide monitoring and detection are the enormous areas of high-risk slopes to monitor.[98] The challenge for tracking satellite data has been where to focus the analysis to be able to spot potential landslides before they occur.

Various satellites are available to detect current and past landslides at diverse modes of resolutions and radar bands while time series data analysis is useful for predicting future potential landslides. Table 5.1 provides a list of several satellites which can be used for landslide monitoring and early warning.

Table 5.1 Examples of synthetic aperture radar which can be used for landslide monitoring and early warning

Country	*Agency*	*Satellite*	*Band*	*Link for additional information*
Argentina	CONAE	SAOCOM	L	https://saocom.veng.com.ar/brochure-EN.pdf
Canada	CSA	Radarsat	C	www.asc-csa.gc.ca/eng/satellites/radarsat/technical-features/characteristics.asp
Europe	Copernicus	Sentinel 1	C	https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar
Germany	DLR	TerraSAR-X	X	www.intelligence-airbusds.com/en/8694-terrasar-x-tandem-x
India	ISRO	RISAT 1	C	www.isro.gov.in/RISAT_1.html
Italy	ASI	COSMO-SkyMed	X	www.asi.it/wp-content/uploads/2021/03/CSG-Mission-and-Products-Description-defpdf-1.pdf
Japan	JAXA	ALOS-2	L	www.eorc.jaxa.jp/ALOS-2/en/about/palsar2.htm
Republic of Korea	KARI	KOMPSAT 5	X	www.eoportal.org/satellite-missions/kompsat-5#spacecraft
Spain	Hisdesat	PAZ	X	www.hisdesat.es/en/satelites_observ-paz/
United States	Capella (private)	Capella	X	www.capellaspace.com/data/sar-imagery-products/

Source: UN-SPIDER

[98] Alessandro Cesare Mondini, Fausto Guzzetti, and others, "Landslide failures detection and mapping using Synthetic Aperture Radar: Past, present and future". *Earth-Science Reviews,* vol. 216 (May 2021). Available at https://doi.org/10.1016/j.earscirev.2021.103574.

The InSAR methods used to detect landslides are the same used to assess deformation caused by volcanic activity. Analysis of two InSAR images of a particular object in different time periods can create the differential InSAR (DInSAR) image which displays the deformation. This technique is used to detect ground deformation by landslide or land subsistence.

CASE STUDY

Satellite data from the Maoxian landslide, China, informs landslide early warning systems [a, b]

The 24 June 2017 landslide of Xinmo Village, Maoxian County, Sichuan Province in China, was triggered by heavy rain and destroyed 63 homes, buried a 1.6 km stretch of road and blocked 2 km of the river. Three days later a second landslide hit Xinmo Village and, almost simultaneously, another landslide occurred in Shidaguan Town, 20 km away from Xinmo Village.

The University of Newcastle in the United Kingdom and the Chengdu University of Technology, Tongji University, the China Academy of Space Technology and Wuhan University of the People's Republic of China have proposed a potential landslide early warning system using InSAR techniques.

The joint team combined imagery from the European Sentinel-1 satellite, the Chinese Gaofen-2/3 with field observations.

Sentinel-1 acquired a post-event image 13.5 hours after the Xinmo event and was used to elaborate the first interferogram for the Xinmo landslide. The Sentinel-1 interferogram, together with its corresponding coherence and amplitude maps, helped the research team identify the source area of the landslide and map the landslide boundary.

More importantly, through the analysis of the archived Sentinel-1 data, the team found that pre-event movements could be detected in the source area during the period from 14 May to 19 June 2017 for the Xinmo event. Pre-event signals were even clearer for the Shidaguan landslide, suggesting it had been sliding for a while.

This study demonstrates that InSAR can be used to detect and map active landslides, with encouraging implications for landslide early warning systems.

[a] Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics, "Sentinel-1 satellites reveal pre-event movements and source areas of the Maoxian Landslide, China". Available at https://comet.nerc.ac.uk/sentinel-1-satellites-reveal-pre-event-movements-source-areas-maoxian-landslides-china

[b] United Kingdom, Newcastle University. *Can satellites be used as an early warning system for landslides*. Available at www.ncl.ac.uk/press/articles/archive/2017/07/maoxianlandslides

CASE STUDY

Regional landslide monitoring system: Tuscany Region, Italy[a]

A regional landslide monitoring system, founded and supported by the regional government of Tuscany, is employing systematic processing of Sentinel 1 imagery to detect and issue landslide warnings at the local level. The system automatically downloads and generates ground deformation data using a surface displacement detection software called SqueeSAR that can identify deformation in millimetres from time series SAR data.

When the new satellite acquisition is completed, the new image is processed and updates all deformation points identified in the project. Time series are then automatically analysed through a post-processing procedure, highlighting any anomalous trends and/or acceleration affecting the area of interest and providing possible alerts. The monitoring system provides dynamic streaming of the deformation at regional scale. The deformation is dynamically updated with the latest acquisition and identifies the anomaly.

The anomaly is further analysed with the optical images and thematic information to generate a possible warning. The areas with the persistent anomaly are delivered to the regional authorities in the form of monitoring bulletins. Further investigation is conducted to study the cases at field level and identify potential severity for local authorities to take actions necessary to mitigate the risk.

[a] Emanuele Intrieri, Giulia Dotta and others, "Early Warning Systems in Italy: State-of-the-Art and Future Trends". In Sassa, K., Mikoš, M., Sassa, S., Bobrowsky, P.T., Takara, K., Dang, K. eds, *Understanding and Reducing Landslide Disaster Risk*. World Landslide Forum 2020. ICL Contribution to Landslide Disaster Risk Reduction. Springer, Cham. https://doi.org/10.1007/978-3-030-60196-6_45

CASE STUDY

The Landslide Hazard Assessment for Situational Awareness of NASA[a, b, c]

Recognizing the need to enhance the use of space technologies to address the challenges posed by landslides, NASA started to develop a procedure to identify where and when landslides triggered by intense rainfall may be likely. The Landslide Hazard Assessment for Situational Awareness (LHASA) combines information on the susceptibility of slopes to landslides and satellite rainfall data from the Global Precipitation Measurement (GPM) missions.

NASA scientists have developed a global map of landslide susceptibility[d] combining data from different satellites on slope, vegetation, road networks, geology and forest cover loss.

The newer version 2 of LHASA incorporates the use of machine learning models to double the accuracy of global landslide nowcasts.[e] LHASA 2 incorporates data on potential exposure of population and roads and forecasted precipitation data from the GEOS Forward Processing system of the Global Modeling and Assimilation Office (NASA-GMAO) at NASA. It also includes data from Global Landslide Catalogue.

LHASA 2 provides "nowcasting" information on potential landslides and is updated every 30 minutes. Figure 5.8 presents an example of the LHASA 2.0 landslide nowcast in South and Central America.

[a] United States, National Aeronautics and Space Administration, *New NASA Model Finds Landslide Threats in Near Real-Time During Heavy Rains*. Available at www.nasa.gov/feature/goddard/2018/new-from-nasa-tracking-landslide-hazards-new-nasa-model-finds-landslide-threats-in-near-real

[b] United States, National Aeronautics and Space Administration, *Landslide Hazard Assessment for Situational Awareness (LHASA) Model*. Available at https://gpm.nasa.gov/landslides/projects.html#LHASA

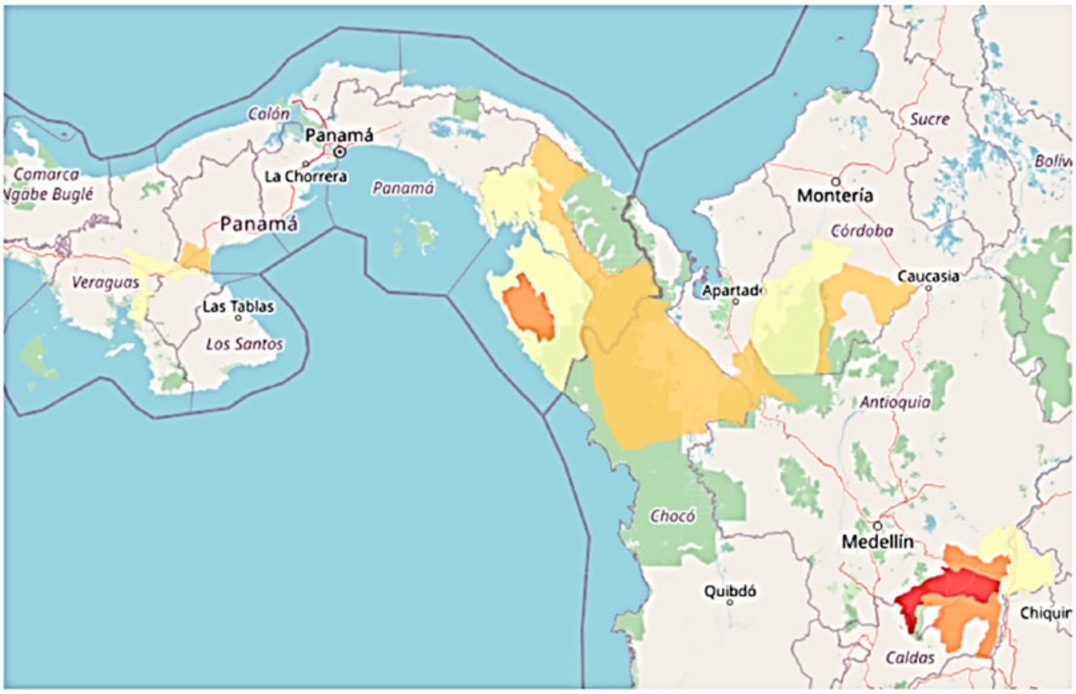
[c] United States, National Aeronautics and Space Administration, *Global Landslide Hazard Assessment Model (LHASA) with Global Landslide Catalogue (GLC) data*. Available at https://svs.gsfc.nasa.gov/4631

[d] United States, National Aeronautics and Space Administration, *A Global View of Landslide Susceptibility*. Available at https://earthobservatory.nasa.gov/images/89937/a-global-view-of-landslide-susceptibility

[e] United States, National Aeronautics and Space Administration, *Weather Analysis and Prediction*. Available at https://gmao.gsfc.nasa.gov/weather_prediction/

Figure 5.8 Example of the LHASA 2.0 landslide nowcast in South and Central America

Red indicates larger populations exposed to landslide hazard. Orange and yellow indicate lesser population exposure



Source: NASA

CASE STUDY

Locating potential land failures to protect at-risk communities[a, b]

Researchers at the University of Melbourne have developed a data-driven prediction method that provides better forecasting when it comes to the location and geometry of impending landslides. Using machine learning to identify the most common and unique characteristics of landslides captured from satellite data, the team has built a new prediction model that can accurately identify the location of impending failures well before they occur.

The researchers addressed this problem by learning the most unique characteristics related to the landslide source area directly from the displacement data captured by Sentinel-1 satellites and building a new prediction method to find the temporally persistent outlying areas over multiple spatial scales as the final prediction. The results from two case studies, the 2017 Xinmo landslide and Stromboli volcano rockfalls in 2015–2016, show that the location of the impending failure can be accurately identified well before the time of failure, by tracking the abnormality in a simple feature: the third quartile in the ground displacement of small regions. This approach provides an important advance for timely risk assessment from satellite data, especially for remote areas that are difficult, if not impossible, to access.

[a] University of Melbourne, Australia. *Forecasting Landslides from Space.* Available at https://pursuit.unimelb.edu.au/articles/forecasting-landslides-from-space

[b] Shuo Zhou, Antoinette Tordesillas, and others, "Pinpointing Early Signs of Impending Slope Failures from Space", *Journal of Geophysical Research: Solid Earth*, vol. 127, issue number 2 (18 January 2022). Available at https://doi.org/10.1029/2021JB022957

CASE STUDY

Using satellite-derived rainfall data to build early warning systems for landslides in Indonesia [a]

In Indonesia, rainfall-induced landslides are a widespread and persistent hazard due to landslide conditioning factors such as steep slopes, susceptible soils and high levels of precipitation.

Chikalamo et al (2020) developed satellite-based precipitation thresholds that can be applied for regional landslide EWS, at the Bogowonto catchment: a data-scarce landslide-prone area. Local conditions such as land cover and geology were considered, as well as analysis of the antecedent rain and the temporal and spatial variability of the thresholds in the study area.

Using the products of the Tropical Rainfall Measuring Mission (TRMM), landslides in Bogowonto catchment have been empirically correlated with weighted antecedent rainfall conditions by taking daily rainfall as a dependent variable and different periods of antecedent rainfall as an independent variable. Following the analysis, at least 15 days antecedent rainfall conditions and daily rainfall on the landslide event day has been found to be correlated to the occurrence of landslides in the study area.

For the study area, the results indicated that it is possible to use TRMM data to determine rainfall thresholds that can be used in a landslide EWS, considering daily and antecedent rainfall.

[a] Elias E. Chikalamo, Olga C. Mavrouli, Janekke Ettema, and others, "Satellite-derived rainfall thresholds for landslide early warning in Bogowonto Catchment, Central Java, Indonesia". *International Journal of Applied Earth Observation and Geoinformation, vol. 89*. (July 2020). Available at https://doi.org/10.1016/j.jag.2020.102093

CASE STUDY

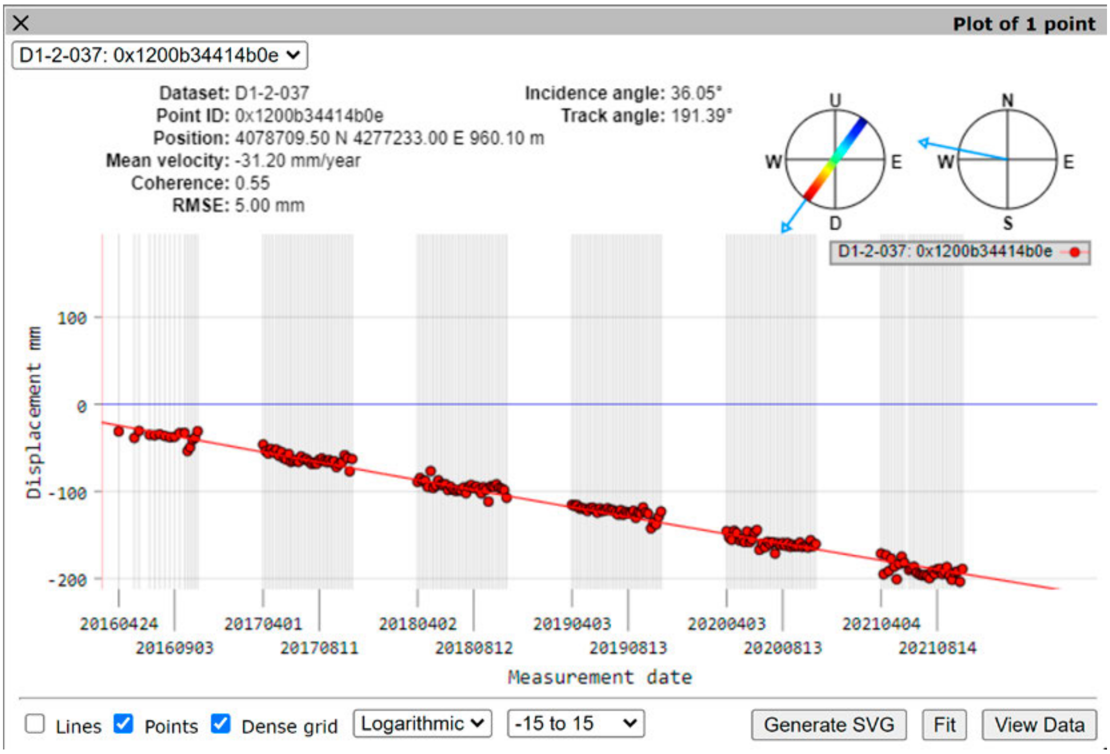
Sentinel-1 monitors ground movement in Norway at national scale

Norway has launched a project to continuously monitor ground movements at national scale using Sentinel-1 InSAR data processing. The project is implemented jointly by the Geological Survey of Norway, the Norwegian Water Resources and Energy Directorate and the Norwegian Space Centre. The monitoring service captures 4,000 images over Norway from Sentinel-1 constellation from ascending and descending passes.

The main goal of this project is to monitor ground deformation across Norway using the InSAR technique and facilitate access for public and commercial users. The InSAR subsidence data is free and open to the public via the InSAR Norway portal[a]. The time series data is loaded to the system and monitors ground deformation from 2016 onwards. Figure 5.9 presents an example of the detection of ground deformation for one point spanning the period from 2016 to 2021.

[a] Norwegian Ground Motion Service (InSAR Norway). Available at https://insar.ngu.no

Figure 5.9 Sample point from 2016 to 2021 showing ground deformation



Source: InSAR Norway

5.2.2 Mining waste spoil

Mining for minerals and resources can result in large amounts of aster material or spoil. The topography of some mining areas restricts the space available for depositing spoil materials and so waste has been dumped on hillsides and in large piles, which themselves have very steep slopes.[99] In addition, some mining operations are in high-altitude, cold environments, which introduces additional slope stability challenges.[100]

The number of Earth observation satellites with radar capabilities is ever increasing, expanding the opportunities to remotely monitor both historic and ongoing motion associated with known and unknown slope hazards and failures on mine sites across the world.

Satellite-based InSAR mapping can be used to detect and survey the different types of mining-induced motion that can occur. The extensive coverage of InSAR, provides a dense, wide-area monitoring approach which reduces the risk in mine design and operation by detecting and highlighting motion in areas where it may otherwise be overlooked.

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[99] Ground Engineering, *Managing Spoil Tip Risks*. Available at www.geplus.co.uk/opinion/managing-spoil-tip-risks-10-02-2022

[100] Ruiching Zhang, Shiwei Wu, and others, "Risk Monitoring Level of Stope Slopes and Landslides in High-Altitude and Cold Mines". *Sustainability*, vol. 14, issue number 13 (22 June 2022). Available at https://doi.org/10.3390/su14137581

Furthermore, InSAR monitoring assists geotechnical engineers in understanding the rock mass response to mining, with the potential for using high-precision InSAR data to calibrate stability models.[101]

CASE STUDY

Monitoring disused coal tips in the United Kingdom [a]

In 1966, the Aberfan spoil tip disaster saw 144 lives lost, most of whom were children, when a colliery waster pile failed and engulfed 19 homes and the Pantglas school.[b] Since that year, other near-miss slope failures on mining tips have occurred, and in September 2021, the Satellite Applications Catapult, a centre of the Catapult Network in the United Kingdom,[c] began working with the Coal Authority, on behalf of the Welsh Government, on using Earth observation data to monitor and assess disused coal tips in South Wales.

The pilot project is aiming to create an evidence base to enable informed decision-making on long-term satellite-enabled services for monitoring of disused coal tips.

The purpose of the pilot project is to evaluate whether synthetic aperture radar (SAR) data can be used to monitor potential ground movement on disused coal tips. Sensors from the Sentinel-1 Copernicus mission can measure millimetre movements on Earth within a small surface area. Although this data has been available since 2014, it is only recently that it has begun to be used for landslip monitoring.

Catapult has selected three companies with expertise in using SAR data – CGG, Terra Motion and SatSense – to analyse and interpret satellite data on disused coal tips using different technical approaches. The results will be compared, combined and selected by Catapult based on the effectiveness and potential to pre-empt any potential environmental hazards.

The pilot will analyse disused coal tips identified by the Welsh Government and the Coal Authority across three phases.

In phase one, soil subsidence (sinking) or uplift (rising) will be monitored as crucial indicators for potential risks at the tip sites, using three years of surface displacement estimation data.

Phase two will draw on experience from previous Catapult projects using corner reflectors (essentially concrete blocks which improve the accuracy of the satellite sensor measurements) to determine whether monitoring can be improved. Up to 20 corner reflectors will be installed on a disused coal tip and the satellite data will be analysed 8–10 months later to understand the impact of installing the reflectors.

Finally, in phase three, Catapult will research and evaluate the use of commercial space data at disused coal tips to understand the benefits this could bring in relation to public safety and coal tip management.

[a] Catapult Satellite Applications, "Using Satellite Technology to Monitor Disused Coal Tips". Available at https://sa.catapult.org.uk/blogs/using-satellite-technology-to-monitor-disused-coal-tips

[b] WalesOnline, "Aberfan. This clock stopped ticking at 9.13 on the morning of October 21, 1966". Available at https://aberfan.walesonline.co.uk

[c] More information on the Catapult Network is available at https://catapult.org.uk

[101] Tom Styles, Harry McCormack, and others, "Using satellite InSAR to detect pit wall failure". Proceedings of the 19th Extractive Industry Geology Conference 2016 and technical meeting 2017, EIG Conferences Ltd. Available at www.researchgate.net/publication/308171258_Using_satellite_InSAR_to_detect_pit_wall_failure

5.3 Earthquakes

Earthquakes, and their associated tsunami (chapter 7), are by far the costliest geohazard, accounting for US$636 billion in economic losses between 2000 and 2019. The top six deadliest earthquakes saw the loss of over 650,000 lives (2000–2019).[102]

Unlike early warning systems for hydrometeorological hazards, earthquake warning systems rely on historical risk knowledge of which regions are prone to earthquakes, and the ability to detect and alert the start of an earthquake rapidly. At best, current earthquake warning systems can provide a few vital seconds notice, sufficient to allow people to take immediate action to protect themselves from potential impacts and to trigger automized emergency measures.

In recent years, earthquake early warning systems (EEWS) have been developed independently in a few countries. EEWS have been operational in Japan and Mexico, while other areas such as Canada, China, Italy, Republic of Korea, Türkiye and California (United States) are in development stages or under restricted applications.

The International Platform on EEWS also recognizes that many other countries, such as those in the Indian subcontinent, South-East Asia, Central Asia, the Middle East, Eastern Africa, South-East Africa, as well as Central America, South America and the Caribbean, are situated in some of the largest and most seismically active regions of the world, or with moderate seismicity but with high vulnerability, and would strongly benefit from the development of an operational EEWS.[103]

Satellites have been unquestionably beneficial in providing data and capability to support the immediate response to earthquakes and provide data essential to the assessment of risk from earthquakes, a vital component to any developing earthquake early warning system.

Remote sensing is employed to assemble databases on building stock and land usage in seismically active regions, which is in turn used for risk assessment and for disaster preparedness.

In the aftermath of an earthquake, remote sensing provides images of the disaster region that help identify the areas most impacted and in need of assistance. Synthetic aperture radar (SAR) image processing techniques exist to subtract post-disaster images from stock images of the same region prior to the disaster, enabling identification of the most heavily afflicted areas.

GPS is used in seismic research, as minute movements in the Earth's crust (in the order of centimetres or less) can be deduced using large numbers of receiver stations mounted close to known fault lines.

[102] United Nations Office for Disaster Risk Reduction, "The human cost of disasters: an overview of the last 20 years (2000–2019)". Available at www.undrr.org/media/48008/download

[103] United Nations Educational, Scientific and Cultural Organization, "International Platform on Earthquake Early Warning Systems (IP-EEWS)". Available at https://en.unesco.org/disaster-risk-reduction/early-warning-systems/IP-EEWS

CASE STUDY

Testing smartphones for advance earthquake warning [a]

Smartphones and other personal electronic devices could, in regions where they are in widespread use, function as early warning systems for large earthquakes. This technology could serve regions of the world that cannot afford higher-quality, more expensive earthquake early warning systems.

A study led by scientists at the United States Geological Survey (USGS), with participation from the Jet Propulsion Laboratory of NASA, found that the sensors in smartphones and similar devices could be used to build earthquake warning systems. Despite being less accurate than scientific-grade equipment, the GPS receivers in a smartphone can detect the permanent ground movement (displacement) caused by fault motion in a large earthquake.

Using crowdsourced observations from participating users' smartphones, scientists could detect and analyse earthquakes, and transmit customized earthquake warnings back to them and other users.

Earthquake early warning systems detect the start of an earthquake and rapidly transmit warnings to people and automated systems before they experience shaking at their location. While much of the world's population is susceptible to damaging earthquakes, the systems are currently operating in only a few regions around the globe, including Japan and Mexico.

Researchers tested the feasibility of crowd-sourced earthquake early warning and accuracy of the GPS data. The stations then send the information to Scripps Institution of Oceanography with a simulation of a hypothetical magnitude 7 quake, and with real data from the 2011 magnitude 9 Tohoku-oki, Japan, earthquake.

The results show that crowdsourced warning systems could be achieved with only a tiny percentage of people in each area contributing information from their smartphones. For example, if phones from fewer than 5,000 people in a large metropolitan area responded, the earthquake could be detected and analysed fast enough to issue a warning to areas further away before the onset of strong shaking, as the speed of an electronic warning travels faster than the earthquake shaking does.

Crowdsourced data are less precise, but for larger earthquakes that cause large shifts in the ground surface, they contain enough information to detect that an earthquake has occurred – information necessary for early warning. The study found that the sensors in smartphones and similar devices could be used to issue warnings for earthquakes of approximately magnitude 7 or larger, but not for smaller, yet still potentially damaging earthquakes.

[a] Tech Briefs, "NASA Monitoring Technologies Shake Up Earthquake Prediction". Available at www.techbriefs.com/component/content/article/tb/supplements/tmtb/features/articles/24432

CASE STUDY

ShakeAlert: An earthquake early warning system for the West Coast of the United States[a]

ShakeAlert® is an earthquake early warning (EEW) system that detects significant earthquakes so quickly that alerts can reach many people before shaking arrives. ShakeAlert does not forecast earthquakes but is rather a ShakeAlert Message that indicates that an earthquake has begun, and shaking is imminent.

By using a combination of ground-based seismic stations, GNSS stations and a very small aperture terminal telemetry system, the ShakeAlert system is able to identify and characterize an earthquake a few seconds after it begins, calculate the likely intensity of ground shaking that will result, and make alerts available for delivery to people and infrastructure in harm's way.

This is done by detecting the primary wave information. ShakeAlert first estimates the location and the magnitude of the earthquake. The anticipated ground shaking across the region to be affected is then estimated and an alert is made available for delivery to devices that will initiate automated actions and prompt other actions such as Drop, Cover and Hold On. The method can provide warning before the secondary wave arrives, bringing the strong shaking that usually causes most of the damage.

Studies in Washington, Oregon and California have shown that the warning time would range from seconds to tens of seconds. ShakeAlert-powered alerts delivered by alert distribution partners could therefore give enough time to slow trains and taxiing planes, to prevent cars from entering bridges and tunnels, to move away from dangerous machines or chemicals in work environments and to take cover under a desk, or to automatically shut down and isolate industrial systems.

For every earthquake, there is a region near the epicentre where alerts will not arrive before shaking begins because the ShakeAlert system needs time to detect the earthquake, issue an alert, and for USGS partners to distribute the alert.

ShakeAlert warnings are available through a number of free app providers, including the MyShake™ app[b] (California, Oregon and Washington), the QuakeAlertUSA app[c] (California and Oregon), ShakeReadySD[d] (California) and Google, providing a ShakeAlert-powered earthquake alert feature that is integrated into the Android Operating System. (California, Oregon and Washington).

[a] ShakeAlert, "An Earthquake Early Warning System for the West Coast of the United States". Available at www.shakealert.org/

[b] MyShake, "Earthquake Early Warning now available publicly in California, Oregon, and Washington". Available at https://myshake.berkeley.edu/

[c] Early Warning Labs, "Now Live in California and Oregon". Available at https://earlywarninglabs.com/mobile-app/

[d] ReadySanDiego. "SD Emergency App". Available at www.readysandiego.org/SDEmergencyApp/

5.3.1 Ionospheric anomalies

Anomalies in the ionosphere, detected by satellite technologies, have been found to be associated with seismic activity, including earthquakes and tsunamis, and have been highlighted as a potential detection method for earthquake early warning systems.

The ionosphere is a layer in the upper atmosphere which is ionized by solar radiation and its characteristics are changed by various factors, including seismic activities. The energy released from an earthquake can cause perturbations in the ionosphere and create anomalies. These can be detected by GNSS and radar techniques and research has shown that ionospheric disturbances can occur prior to an earthquake, hence these anomalies can be detected by satellite to generate potential early warnings.

There has been rapid advancement in detecting earthquake anomalies in the ionosphere using GNSS, the satellite called Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER), and other remotely-sensed satellites.[104]

For example, advances in data processing capabilities of the Global Positioning System (GPS) of the United States are allowing for the detection of perturbations in the total electron content (TEC) of the ionosphere that may be generated by earthquakes. Komjathy et al[105] noted that GPS data can also be used to detect ionospheric disturbances prior to an earthquake. The Tohoku case study demonstrated capabilities to monitor TEC fluctuations using Jet Propulsion Laboratory's real-time Global Assimilative Ionospheric Model system. The study showed that a real-time global TEC monitoring network can detect the acoustic and gravity waves generated by earthquakes and tsunamis. With additional real-time stations deployed, this capability has the potential to provide real-time monitoring of TEC perturbations that could potentially serve as a plug-in to enhance existing early warning systems.

Other studies, such as Liu et al[106] and Park et al,[107] have commented on TEC perturbations in the ionosphere on the days leading up to an earthquake. These examples suggest that ionospheric anomalies can be used as a precursor indicator for earthquakes and could be used to trigger earthquake early warning systems with further study. However, more scientific research is needed to confirm the reliability of this technique.

[104] Munawar Shah, "Chapter 28 - Earthquake ionospheric and atmospheric anomalies from GNSS TEC and other satellites", in Pourghasemi, H, R., *Computers in Earth and Environmental Sciences*, Elsevier, pp. 387-399. Available at https://doi.org/10.1016/B978-0-323-89861-4.00009-9

[105] A. Komjathy, D.A. Galvan, and others, "Detecting ionospheric TEC perturbations caused by natural hazards using a global network of GPS receivers: The Tohoku case study". *Earth Planets and Space*, vol. 64 (28 January 0213), pp. 1287–1294. https://doi.org/10.5047/eps.2012.08.003

[106] J. Y. Liu, Y. I. Chen, and others, "Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 M_w7.9 Wenchuan earthquake". *Journal of Geophysical Research: Space Physics*, vol. 114, issue A4 (30 April 2009). Available at https://doi.org/10.1029/2008JA013698

[107] Sun Mie Park, Kwangsun Ryu, and Kyoungwook Min, "Ionospheric anomalies related to strong earthquakes in North America as observed by TEC". *Advances in Space Research*, vol. 68, issue number 10 (15 November 2021), pp. 4137–4154. Available at https://doi.org/10.1016/j.asr.2021.07.026.

CASE STUDY

Ionospheric disturbances monitored from the satellite before the Wenchuan earthquake, 12 May 2008

On 12 May 2008, a magnitude 8.0 earthquake hit Wenchuan, in the Sichuan province of the People's Republic of China, that unfortunately killed more than 87,000 people.

Several researchers have studied the earthquake and suggest that satellite technology can detect perturbations in the ionosphere which can be used to monitor, detect and issue early warning prior to earthquakes[a]. Liu, et al. (2009)[b] studied the Global Ionospheric Map (GIM), derived from GPS receivers, and identified anomalies in the total electron content (TEC) prior to the event. GIM is routinely published every day by NASA. The research used 10 years of earthquake data analysed against GIM for possible correlation. The statistical analysis shows a decrease of TEC during three to six days prior to most major earthquakes and increased TEC content three days prior to the event.

The study examined the Wenchuan earthquake for TEC from the GPS network. The corresponding GIM around the epicentre clearly shows the ionosphere anomaly.

[a] B. Zhao, M. Wang, and others, "Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake?" *Journal of Geophysical Research*, vol. 113. Available at https://doi.org/10.1029/2008JA013613

[b] J. Y. Liu, Y. I. Chen, and others, "Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 M_w7.9 Wenchuan earthquake". *Journal of Geophysical Research: Space Physics*, vol. 114, issue A4 (30 April 2009). Available at https://doi.org/10.1029/2008JA013698

CASE STUDY

Strong earthquakes in North America observed by total electron content measurements

A number of research studies have illustrated a plausible relationship between seismic activity and ionospheric disturbances. Park et al[a] further investigated seismo-ionospheric disturbances and analysed the temporal and spatial characteristics of ionospheric disturbances associated with large earthquakes that occurred in North America.

Two strong events with $M \geq 6.5$ that took place in 2009 and 2010 during the solar minimum were investigated. The total electron content (TEC) measurements in the United States were used as a main data set, and the changes in the TEC were compared with the variations in the plasma density detected by the DEMETER satellite.

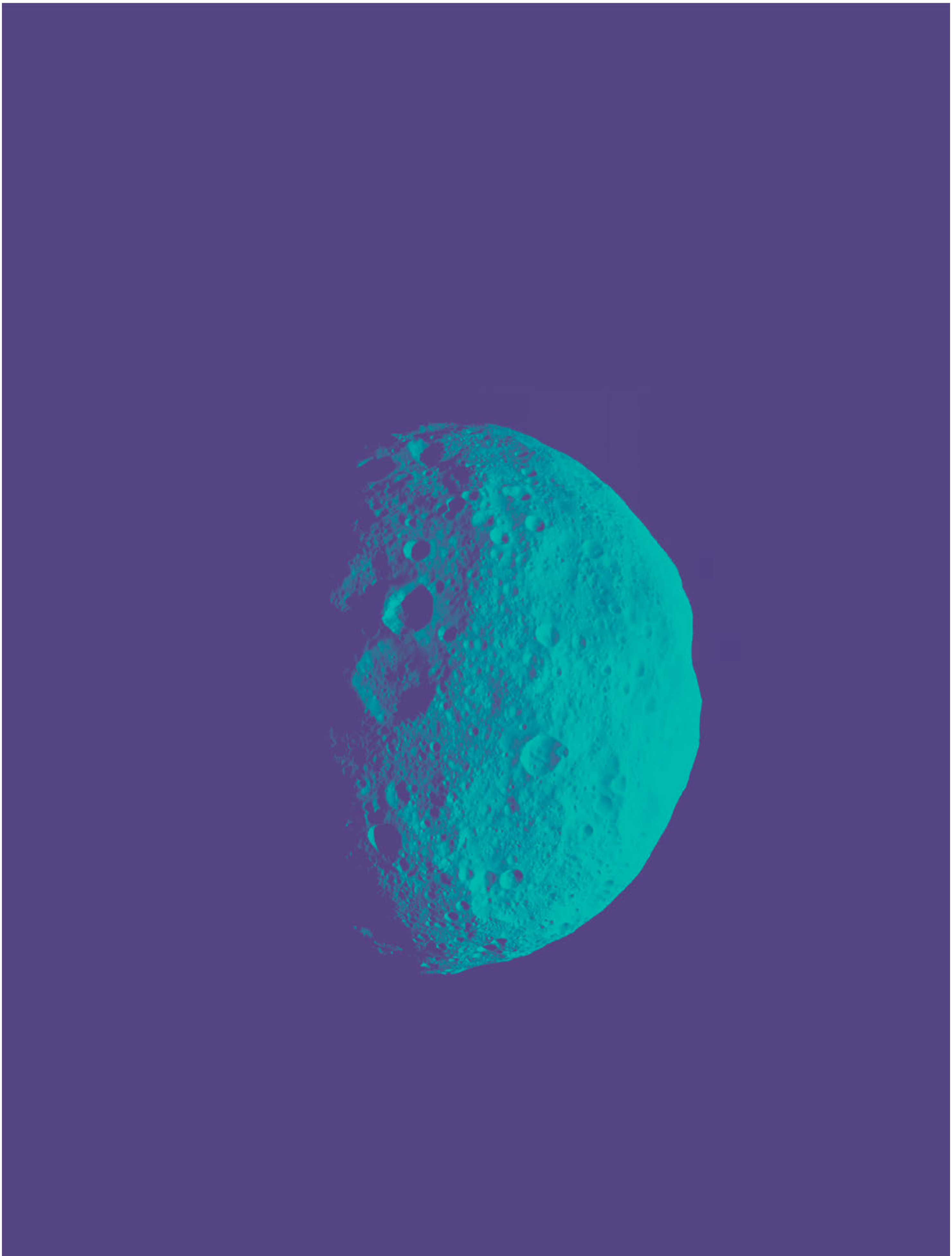
Positive or negative TEC anomalies were observed before and after the earthquakes and the study found that positive anomalies occurred more frequently than negative ones.

Seismic activity-related TEC anomalies were typically limited to the region of the epicentre of earthquake, whereas geomagnetic activity-related TEC anomalies were detected further away. Furthermore, local TEC anomalies were detected up to three weeks before earthquakes and also three weeks after earthquakes.

In addition, TEC anomalies coincided with increases in the electron density obtained by the DEMETER satellite over the seismic zone. Thus, the variations observed in TEC and electron density before and after these two earthquakes suggest that these ionospheric disturbances are related to seismic activities.

[a] Sun Mie Park, Kwangsun Ryu, and Kyoungwook Min, "Ionospheric anomalies related to strong earthquakes in North America as observed by TEC". *Advances in Space Research*, vol. 68, issue number 10 (15 November 2021), pp. 4137–4154. Available at https://doi.org/10.1016/j.asr.2021.07.026

As stated earlier, more scientific research is needed to confirm the reliability of this technique for use in earthquake forecasting.



Vesta asteroid as seen by the Dawn spacecraft of NASA

Image courtesy of NASA

Chapter 6.
Space technologies for extraterrestrial hazards

Extraterrestrial hazards originate in outer space and can impact the planet. Hazards of this type include near-Earth objects, such as meteors, comets and asteroids, and space weather.

Space weather represents the influence of solar activity in terms of substantial electromagnetic waves and highly energetic solar particles that can impact satellite constellations and electric power lines on Earth.

6.1 Near-Earth objects

On 30 June 1908, a prominent asteroid impacted the Tunguska region in the Russian Federation. The asteroid's calculated diameter was 60 metres, and the impact's energy was between 10 and 15 megatons of TNT. More recently, another asteroid impacted the Chelyabinsk region on 15 February 2013, injuring more than one thousand two hundred people and damaging several buildings. The asteroid broke up in the atmosphere nearly 30 km above the city and had an energy release of 30 kilotons TNT equivalent. As a result, the General Assembly declared 30 June as International Asteroid Day to raise awareness regarding asteroids.

At the international level, the more institutionalized efforts to establish a near-Earth object (NEO) early warning system started to take shape in the last two decades under the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). The Committee established in 2001 Action Team 14 to improve the international coordination of activities related to near-Earth objects.[108] According to this Action Team, a NEO is "an asteroid or comet whose orbit brings it within 1.3 astronomical units of the Sun and hence within 0.3 astronomical units, or approximately 45 million km, of the Earth's orbit".[109] The NEO category contains objects that will come close to the Earth at some point in their future orbital evolution. NEOs generally result from objects that have experienced gravitational perturbations from nearby planets, moving them into orbits that allow them to come near the Earth.

[108] General Assembly, "Report of the Committee on the Peaceful Uses of Outer Space". Fifty-sixth Session, Supplement No. 20 (A/56/20). Available at www.unoosa.org/pdf/gadocs/A_56_20E.pdf

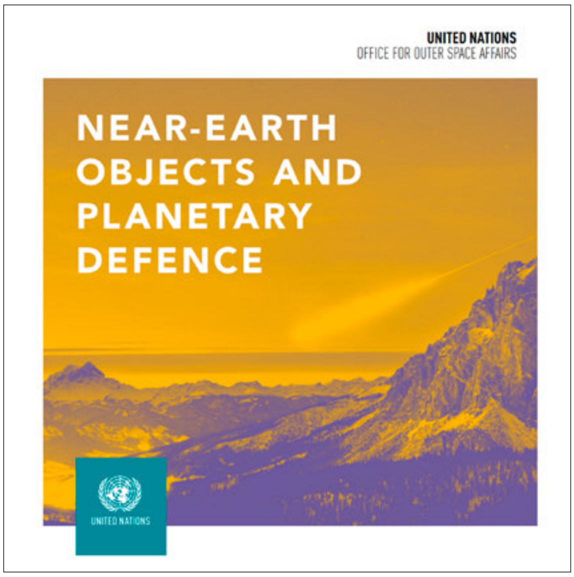
[109] Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, "Draft Recommendations for Near-Earth Objects Threat Mitigation". (Conference Room Paper A/AC.105/C.1/2009/CRP.13). Available at www.unoosa.org/pdf/limited/c1/AC105_C1_2009_CRP13E.pdf.

The NEO early warning system has been designed and implemented through international cooperation. It includes a monitoring and forecasting component operated by the International Asteroid Warning Network (IAWN) and anticipated response efforts headed by the Space Mission Planning Advisory Group (SMPAG). In addition, it includes preparedness activities, including simulations of NEOs that may approach Earth.

IAWN and SMPAG were established in 2014, following a series of recommendations agreed upon by the Member States of the Committee for an international response to the risk of impact of a NEO.[110] IAWN and SMPAG act as global entities to strengthen preparedness in case of a potential NEO-impact hazard.

If a credible impact threat is discovered, IAWN will disseminate the best available information to all Member States through the Office of Outer Space Affairs (UNOOSA). Subsequently, SMPAG will start to assess mitigation options and implementation plans for consideration by the Member States. Figure 6.1 presents the front cover of the UNOOSA publication entitled *Near-Earth Objects and Planetary Defence*.

Figure 6.1 UNOOSA focus on near-Earth objects and planetary defence



Source: UNOOSA

The goal of the NEO early warning system is the global protection of the ecosystem, human beings and their property on Earth, and the civilisation of humankind from the effects of a devastating asteroid impact.

[110] General Assembly resolution, "International cooperation in the peaceful uses of outer space" (A/RES/68/75). Available at www.unoosa.org/res/oosadoc/data/documents/2018/aac_105c_12018crp/aac_105c_12018crp_11_0_html/AC105_C1_2018_CRP11E.pdf

6.1.1 Risk knowledge

The hazard associated with a NEO can be expressed via its size and the probability of impact within the next 50 years. But considering the very low frequency of NEOs impacting Earth and triggering damage, risk assessments have yet to be made at a comparable level to other natural hazards. Nevertheless, several scales have been developed to assess the risk of NEOs of various sizes.

The Torino scale represents an effort to convey to the public a risk assessment and the likely impact of a potential NEO collision with Earth.[111] The scale has been structured in 10 levels of impact. It spans from level 1, referring to a NEO with a doubtful probability of collision with Earth, to level 10, which refers to a collision of a NEO that can cause a global climatic catastrophe and may threaten the future of civilization and life on Earth.

The Broomfield hazard scale[112] has been structured into six classes. It is based on the dimension and kinetic energy potential of the NEO, expressed in tons of TNT equivalency. Class 1 refers to NEOs with a size of fewer than 10 metres that would not threaten society and manifest as visible fireballs. Class 6 refers to NEOs with a diameter size greater than 600 metres and capable of global destruction.

6.1.2 Monitoring and warning service

International cooperation provides an excellent possibility to monitor NEOs facilitating observations by many astronomical observatories around the Earth and exchanging data on such NEOs. This collaboration is crucial to elaborate forecasts, plan strategies and strengthen NEO-impact emergency procedures and action protocols related to the manifestation of potentially catastrophic meteors, comets and asteroids that may impact the planet.

IAWN is operated by a partnership of scientific institutions, observatories and other interested parties that are constantly monitoring outer space to detect, track and physically characterize NEOs and determine those that are potential collision threats to Earth.

IAWN members also perform orbit computation, modelling and other scientific research related to the impact potential and effects of asteroids, and develop a database of potential impact consequences, depending on geography, geology, population distribution and other related factors. IAWN serves as the international focal point for accurate and validated information on NEOs.

[111] United States, National Aeronautics and Space Administration, Jet Propulsion Laboratory, "Torino Impact Hazard Scale – cneos". Available at https://cneos.jpl.nasa.gov/sentry/torino_scale.html

[112] International Asteroid Warning Network, "IAWN Communication workshop, September 2014". Available at https://iawn.net/documents/201610_4th_Pasadena/IAWN-charts.LB_.rev_.10.13.16.pdf

CASE STUDY

The International Asteroid Warning Network

The International Asteroid Warning Network (IAWN) is a virtual network of institutions that carry out activities such as detecting, monitoring and characterizing the potentially hazardous NEOs and designing potential deflection techniques.

IAWN aims to maintain and enhance the international cooperation of NEO observations by proposing criteria for emerging threats and suggesting accurate procedures and communication plans for governments to consider in case of impacts.[a]

IAWN was established in February 2013 by the Action Team's recommendations of the Committee on the Peaceful Uses of Outer Space. More than 30 official signatories to the IAWN Statement of Intent include members from Europe, Asia, and South and North America.

The primary functions of IAWN are to:

- Conduct and coordinate the search for NEOs that may pose a hazard to the Earth
- Make follow-up observations and characterization of NEOs
- Communicate the risks and benefits of NEOs to the public
- Maintain a clearing house for NEOs data
- Maintain a database of impact consequences and, ultimately
- Serve as the principal trusted source of information on NEOs

So far, the activities of this network include report elaboration, observation campaigns and mitigation response planning.[b]

Through its international network of astronomical observatories based in over 40 countries, IAWN continually discovers new NEOs. As of 8 February 2022, the number of known NEOs is 28,340, of which a record number of 3,097 was discovered in 2021. Of these asteroids, 2,263 are now catalogued with orbits that may bring them within 8 million km of Earth's orbit and with diameters larger than about 140 metres. Despite these numbers, it is estimated that only about 41 per cent of NEOs of that size range have been found.

[a] UN-SPIDER Programme, "UN-SPIDER Knowledge Portal: International Asteroid Warning Network". Available at www.un-spider.org/space-application/international-asteroid-warning-network

[b] International Asteroid Warning Network. "About - iawn.". Available at https://iawn.net/about.shtml

6.1.3 Response capability

CASE STUDY

Space Mission Planning Advisory Group

The Space Mission Planning Advisory Group (SMPAG) includes several space agencies and other relevant entities. Its responsibilities include proposing options and implementation plans for initiating and executing space missions for near-Earth object deflection. SMPAG addresses the following main areas:[a]

- Reference missions, technology road maps and collaborative research
- Communication and exchange of information
- International treaty and policy aspects – identifying issues for possible detailed reviews within appropriate forums
- Mitigation campaign planning activities

In 2015, SMPAG started developing its workplan, initially comprising 11 workplan items, each of which is the responsibility of one or more members of SMPAG. The workplan is a road map for planetary defence at the global level, including agreements on initial criteria and thresholds for response actions to the threat of impacts, the consideration of types and technologies which could be used to mitigate the impact of NEOs and the mapping of threats, as well as developing a plan of action in the event of the discovery of a credible threat.

[a] Gerhard Drolshagen and others, "Scope and Objectives of the Space Mission Planning Advisory Group." Available at https://ui.adsabs.harvard.edu/abs/2021plde.confE..83D/abstract

IAWN and SMPAG perform campaigns and exercises to test their capabilities. For example, in 2021, IAWN carried out a coordinated campaign to observe a well-known near-Earth asteroid, 2019 XS, to evaluate the quality of the technical capabilities of this worldwide observation network and to identify areas for improvement. The observation campaign was coordinated with the International Astronomical Union Minor Planet Center, with the participation of 69 observatories across the globe. Similarly, SMPAG is currently performing a hypothetical impact threat exercise to test its capabilities and inter-agency procedures.

In a complementary fashion, the International Academy of Astronautics has been organizing Planetary Defense Conferences since 2009. These conferences include simulation exercises to raise awareness regarding addressing the NEO hazard. The simulation exercises include all phases of the early warning system, including the detection of the simulated NEO, the estimation of its potential impacts on Earth, and the discussion of potential mitigation measures.

Links between planetary defence and disaster preparedness communities have also been initiated during these conferences. (See www.unoosa.org/oosa/en/ourwork/topics/neos/2021/IAAPDC/index.html)

CASE STUDY

NASA Double Asteroid Redirection Test mission

The National Aeronautics and Space Administration (NASA) successfully tested the procedure to deflect the orbit and speed of a small object called Didymos orbiting the Dimorphos asteroid using what is termed a " kinetic impactor".[a] The Double Asteroid Redirection Test (DART) mission aimed to assess the efficacy of asteroid deflection missions and evaluate the orbit change resulting in preparation for future planetary defence scenarios. NASA successfully tested the procedure to deflect the orbit of a small object called Didymos orbiting the Dimorphos asteroid using what is termed a "kinetic impactor".

To confirm the deviation of the small object, the DART mission monitored changes in the reflection of sunlight from the asteroid and the object before and after the impact. The change in the periodicity of the reflection confirmed the change in the orbit of the object around the asteroid after it was impacted.

The DART mission started in 2021 with the launch of the impactor on 23 November 2021. However, the impact occurred nearly a year later, on 26 September 2022. Weeks after the impact, astronomers measured changes in the small moon's orbit, and they confirmed that the typical orbit of the moon had been shortened from 11 hours and 55 minutes to 11 hours and 23 minutes.[b] Figure 6.2 presents two images of the DART mission as it approached the asteroid Dimorphos on 26 September 2022.

The DART mission has been an astonishing achievement because it was the first time humans purposely changed the motion of a celestial object. Other satellite images and ground-based telescope observations could be worthwhile for astronomers to assess future spacecraft impact deflection to prevent potential Earth impact.

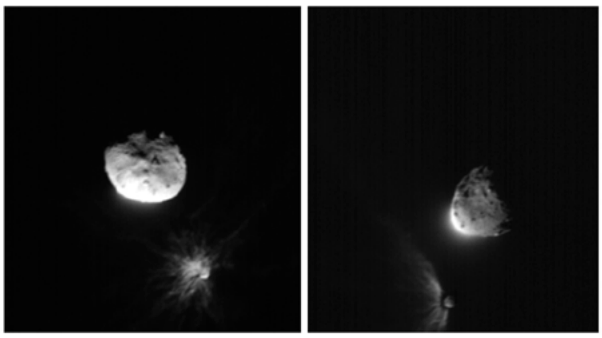
The DART mission was initially conceived by ESA nearly decades earlier. ESA scientists proposed testing the procedure to deflect NEOs in 2005. The ESA mission, called *Don Quijote*, included two spacecraft in different interplanetary trajectories. First, an impactor, *Hidalgo,* would collide with an asteroid at a very high relative speed. Meanwhile, the other spacecraft, *Sancho,* would examine the orbit of the asteroid before and after the impact to assess any variation in its orbital parameters. [c]

[a] United States, National Aeronautics and Space Administration, "Planetary Defense Coordination Office (PDCO) - NASA". Available at www.nasa.gov/specials/pdco/index.html

[b] United States, National Aeronautics and Space Administration, "NASA DART Imagery Shows Changed Orbit of Target Asteroid." Available at www.nasa.gov/feature/nasa-dart-imagery-shows-changed-orbit-of-target-asteroid

[c] European Space Agency, "ESA selects targets for asteroid-deflecting mission Don Quijote". Available at www.esa.int/Newsroom/Press_Releases/ESA_selects_targets_for_asteroid-deflecting_mission_Don_Quijote

Figure 6.2 Two images of the impact of the DART mission on asteroid Dimorphos on 26 September 2022



Source: NASA

6.2 Space weather

Space weather, triggered by intense solar variability, poses a potential threat to satellites and international space stations, human space flight, aviation and ground infrastructure upon which society is increasingly dependent. For example, on 13 March 1989, several regions of Canada experienced a major electrical blackout due to a major solar storm. In October 2003, some areas of Sweden also experienced a blackout triggered by a solar storm.

According to the International Space Weather Initiative (ISWI), severe solar storms affect the magnetosphere of the planet and can trigger what is known as geomagnetic storms. These changes in the magnetosphere can lead to the degradation of the altitude of satellites in low-Earth orbit. In a complementary fashion, highly energetic solar particles can damage electronic components essential for the routine operation of all satellites.[113]

Severe changes in the Earth's magnetic field triggered by intense solar storms can impact the electric power grid. Changes in magnetic fields will induce electric currents in long transmission lines, which may damage or destroy transformers due to the saturation of their limits to operate as expected. In addition, solar storms may generate currents in frequencies that are different to the typical 50 Hz or 60 Hz frequencies used in many regions of the world.

Recognizing the exposure of the entire planet to space weather and the vulnerability of satellite systems, telecommunications and electrical networks around the world, many countries have acknowledged that space weather needs to be addressed globally. Through international cooperation and coordination, the ability to predict potentially severe space weather events has been developing, enabling mitigation of the impact of space weather so that the long-term sustainability of outer space activities and Earth-based vulnerable infrastructure is maintained.

In July 1999, the United Nations organized the third Vienna Conference of the Exploration and Peaceful Uses of Outer Space. At that conference, Member States of the United Nations agreed to cooperate to protect the Earth's environment by developing a worldwide strategy for long-term global observations of space weather.[114]

Since then, UNOOSA has addressed this topic. In 2014, the Committee endorsed the establishment of the Expert Group on Space Weather "with a mandate to promote awareness, provide guidance and enable communication and cooperation in space weather-related activities among States members of the Committee and related national and international organizations. Its workplan included efforts to support increased and expanded involvement of Member States in providing space weather monitoring, from the ground and in space, and in developing, advancing, sharing, and delivering space weather services."[115]

There are several international efforts addressing space weather:

- The International Space Weather Initiative (ISWI) was launched in 2009. According to the website of ISWI, its goal is "to develop the scientific insight necessary to understand the science and to reconstruct and forecast near-Earth space weather. It includes instrumentation, data analysis, modelling, education, training, and public outreach."

[113] International Space Weather Initiative. Available at www.iswi-secretariat.org/.

[114] General Assembly, "Report of the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space" (18 October 1999), pp 21-27. Available at www.unoosa.org/pdf/reports/unispace/ACONF184_6E.pdf

[115] European Space Agency, "Weather services". Available at www.esa.int/Space_Safety/ESA_expands_space_weather_services

- ISWI has a steering committee, a secretariat and national coordinators. It carries out scientific projects as well as training activities. By the end of 2022, ISWI included 90 national coordinators.
- The World Meteorological Organization established in the year 2010 the Interprogramme Coordination Team on Space Weather with a mandate to support Space Weather observation, data exchange, product and service delivery, and operational applications.[116]

Space weather includes several types of hazards generated by the sun. The main hazards include geomagnetic storms and solar radiation storms. These can be triggered when the sun is more active, ejecting more solar flares and coronal mass ejections (CME).

Solar flares currently need more time to predict and reach the surface of the Earth within 8.5 minutes.[117] In contrast, ejections of highly energetic solar particles may reach the planet within a period that ranges from 10 minutes up to a day. In contrast, CMEs can take days to get to the Earth, allowing for early warning efforts.

The magnitude of solar storms is measured using magnetometers on Earth. The K index was introduced in 1949 by Julius Bartels to characterize the magnitude of storms. The parameter represents the maximum fluctuation of the horizontal component of the magnetic field measured with a magnetometer in comparison to the values of the magnetic field on a quiet day. Measurements span three hours.

A planetary Kp index has been introduced based on data compiled from magnetometers in selected observatories worldwide. The German Geo Sciences Research Centre (GFZ) uses data from 13 geomagnetic observatories to monitor the Kp.[118] The Kp index uses a ten-digit scale (0 to 9). Geomagnetic storms with Kp values higher than five can provoke damage to power systems, spacecraft operations and other systems.

Solar radiation storms are measured in terms of the flux level of highly energetic particles.

6.2.1 Vulnerability to space weather

The increasing reliance of advanced societies on electricity for all application types and on telecommunications devices that operate using sophisticated electronic circuits, makes such organizations more vulnerable to the impacts of space weather.

Geomagnetic storms can damage or destroy transformers used in electrical networks due to induced high-voltage overloads. Similarly, such storms can disrupt high-frequency telecommunications and radar systems used in commercial and military aviation. In addition, geomagnetic storms may affect the routine operation of GNSS. Furthermore, such storms may also affect the orbits of other satellites in the low-Earth orbit.

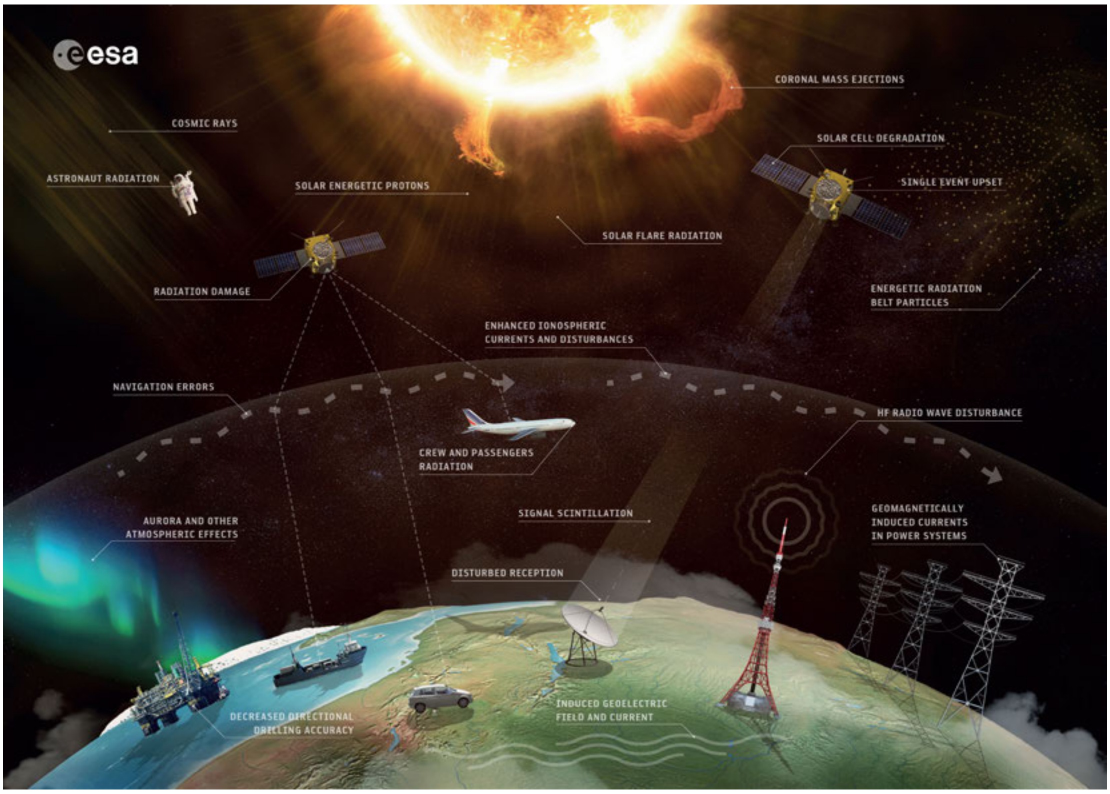
In contrast, highly energetic particles and intense highly energetic electromagnetic radiation may impact and damage or destroy electronic components in satellites and pose a severe risk to astronauts. Figure 6.3 presents a schematic diagram of potential impacts of space weather on land, in the atmosphere and in outer space.

[116] World Meteorological Office, "Space Weather". Available at https://community.wmo.int/activity-areas/wmo-space-programme-wsp/space-weather-introduction

[117] United Kingdom, Meteorological Office, *Space Weather*. Available at www.metoffice.gov.uk/weather/specialist-forecasts/space-weather

[118] Federal Republic of Germany, German Research Centre for Geosciences, *Geomagnetic Kp Index*. Available at https://dataservices.gfz-potsdam.de/pan-metaworks/showshort.php?id=escidoc:5216888

Figure 6.3 Space weather effects



Source: ESA

6.2.2 Detection, monitoring and forecasting

Several astronomical observatories and space agencies are contributing to monitoring solar activity. In addition, several space agencies have launched dedicated satellites to monitor solar activity. Among them are the Deep Space Climate Observatory satellite and the GOES-R satellites operated by the of the National Oceanic and Atmospheric Administration of the United States.

Several meteorological institutes worldwide have established Space Weather Monitoring and Forecasting Centres, including NOAA in the United States, the Meteorological Office in the United Kingdom and the Bureau of Meteorology in Australia. In other countries, space weather monitoring and forecasting are done by national space agencies, as in the case of the South African National Space Agency (SANSA), or dedicated observatories carry out these tasks. For example, in the Russian Federation, the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation Russian Academy of Sciences has been established since 1939.

Many of these institutions provide near-real-time data, some of which provide forecasts of space weather events such as geomagnetic and solar storms. The Space Weather Unit at the German Geosciences Research Centre (GFZ) provides both nowcast and forecast information on the Kp index and other parameters.

CASE STUDY

European Space Agency space weather missions

The European Space Agency (ESA) began its efforts to understand the sun and space weather in 1990 through its Ulysses mission, a joint effort with NASA. The satellite was put in orbit above and below the poles of the Sun. Since then, ESA has deployed additional missions to observe the Sun, including:

- Solar orbiter (2020–present)
- Proba 2 (2009–present)
- Soho (1995–present)
- Ulysses (1990–2009)

The ESA Space Weather Office provides information on potentially harmful space weather events in a timely way to enable the mitigation of impacts to the extent possible. The Office is implementing a Space Weather Service Network to compile relevant data and information from various institutes. For example, the Royal Observatory of Belgium, the Royal Belgian Institute for Space Aeronomy, the Rutherford Appleton Laboratory of the Science and Technology Facilities Council, the Ionosphere Monitoring and Prediction Center of the German Aerospace Centre and the Tromsø Geophysical Observatory of the Faculty of Science and Technology for the Arctic University of Norway. [a]

The Network aims to detect and forecast space weather events and their effects on European space assets and ground-based infrastructure.

The Office provides information on the following:

- High-quality scientific observations, results and models in the domain of space weather
- Long-term solar cycle forecasts for future missions
- Solar weather conditions
- Solar activity
- Radiation environment at low-Earth orbit
- Ionospheric and geomagnetic activity

[a] European Space Agency, "Space Weather Office". Available at www.esa.int/Space_Safety/Space_Weather_Office

CASE STUDY

Space Weather Prediction Center of the National Oceanic and Atmospheric Administration

The Space Weather Prediction Center (SWPC) is part of the National Oceanic and Atmospheric Administration (NOAA) of the United States. Its headquarters is in Colorado and was instituted in 2007. It produces real-time space weather information on solar and geophysical forecasts, research in solar-terrestrial physics, alerts and warnings, modelling, and observations useful to customers, academics and for military and civil purposes.[a] SWPC produces reports based on solar geophysical alerts, models referring to the geomagnetic and solar radiation storms, and summaries of solar and geophysical activity and space weather observations.[b] Figure 6.4 presents a view of the SWPC Dashboard on 25 August 2023.

Throughout its activities and missions, SWPC also provides regular bulletins and communications to indicate the solar activity severity level that can threaten the Earth's climate, electric power transmission, satellite communication and high-frequency radio communication.

The SWPC cooperates with space weather partners and stakeholders, such as:

- Commercial service providers
- Federal agencies
- International organizations
- International service providers
- Space weather research

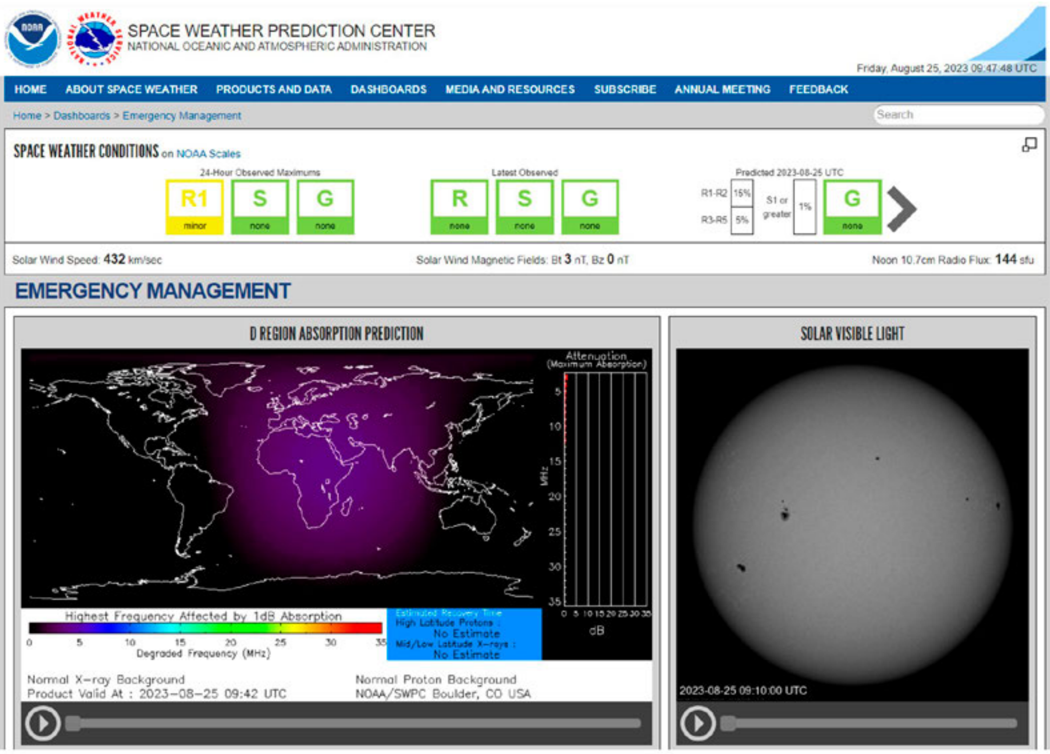
Finally, SWCP arranges a Space Weather conference annually to encourage public debate on space weather impacts, modern technologies and new research within government agencies, academia and industry. [c]

[a] United States, National Oceanic and Atmospheric Administration, *Aurora Forecasts*. Available at www.swpc.noaa.gov/products/aurora-30-minute-forecast

[b] United States, National Oceanic and Atmospheric Administration. *Current Space Weather Conditions*. Available at www.swpc.noaa.gov/forecasts

[c] United States, National Oceanic and Atmospheric Administration (NOAA), *Emergency Management*. Available at www.swpc.noaa.gov/communities/emergency-management

Figure 6.4 NOAA Space Weather Prediction Centre Dashboard on 25 August 2023



Source: NOAA

CASE STUDY

The United Kingdom Meteorological Office

The United Kingdom Meteorological Office issues information on space weather and alerts and warnings when needed.[a] Its forecast overview covers solar activity, geomagnetic activity and solar wind, and highly energetic particles. In addition, it provides near-real-time imagery of the sun and its corona. The Meteorological Office provides a four-day space weather forecast as well.

[a] United Kingdom, Meteorological Office. *Space Weather*. Available at www.metoffice.gov.uk/weather/specialist-forecasts/space-weather

CASE STUDY

Australian Space Weather Forecasting Centre

Like other meteorological departments or offices, the Australian Bureau of Meteorology operates a Space Weather Forecasting Centre.[a] The Centre provides information and forecasts on space weather conditions, including information on solar wind, potential geomagnetic storms, solar auroras and potential impacts on high-frequency radio communications.

The Centre operates the Australia Space Weather Alert System and uses the NOAA scales for geomagnetic storms (G scale), solar radiation storms (S scale) and radio blackouts (R scale). The Centre adapted the NOAA scales to the Australian context. Figure 6.5 presents an image of the cover of the document that contains information on the Australian Space Weather System.

[a] Australia, Bureau of Meteorology, "Australian Space Weather Forecasting Centre". Available at www.sws.bom.gov.au/

Figure 6.5 Australian Space Weather System

Source: ASWFC

6.2.3 Dissemination and communication

As space weather is a very novel topic, it is rarely reported in the news. However, international news networks are beginning to present warning information.

Numerous space weather organizations are steadily improving their research on solar variability activities, which could hit critical economic assets, such as communication networks, satellites and power grids. Some regularly publish space weather alerts for hazardous space weather events with detailed documentation services, exhaustive archives, graphs, official forecasts, real-time photos and statistics on their web portals to disseminate information on solar radiation and geomagnetic storms to users, researchers and customers free of charge.

Space agencies are significantly increasing their efforts to assess the impact of space weather on the use of technology on Earth to anticipate and reduce the severity of space weather events and to envisage potential outcomes on human property and health.

For example, the South African National Space Agency has examined the impact of geomagnetic storms on aircraft crews and passengers during long-haul flights. Indeed, geomagnetic storms could trigger flight deviations from designated routes and expose customers to higher radiation levels.[119]

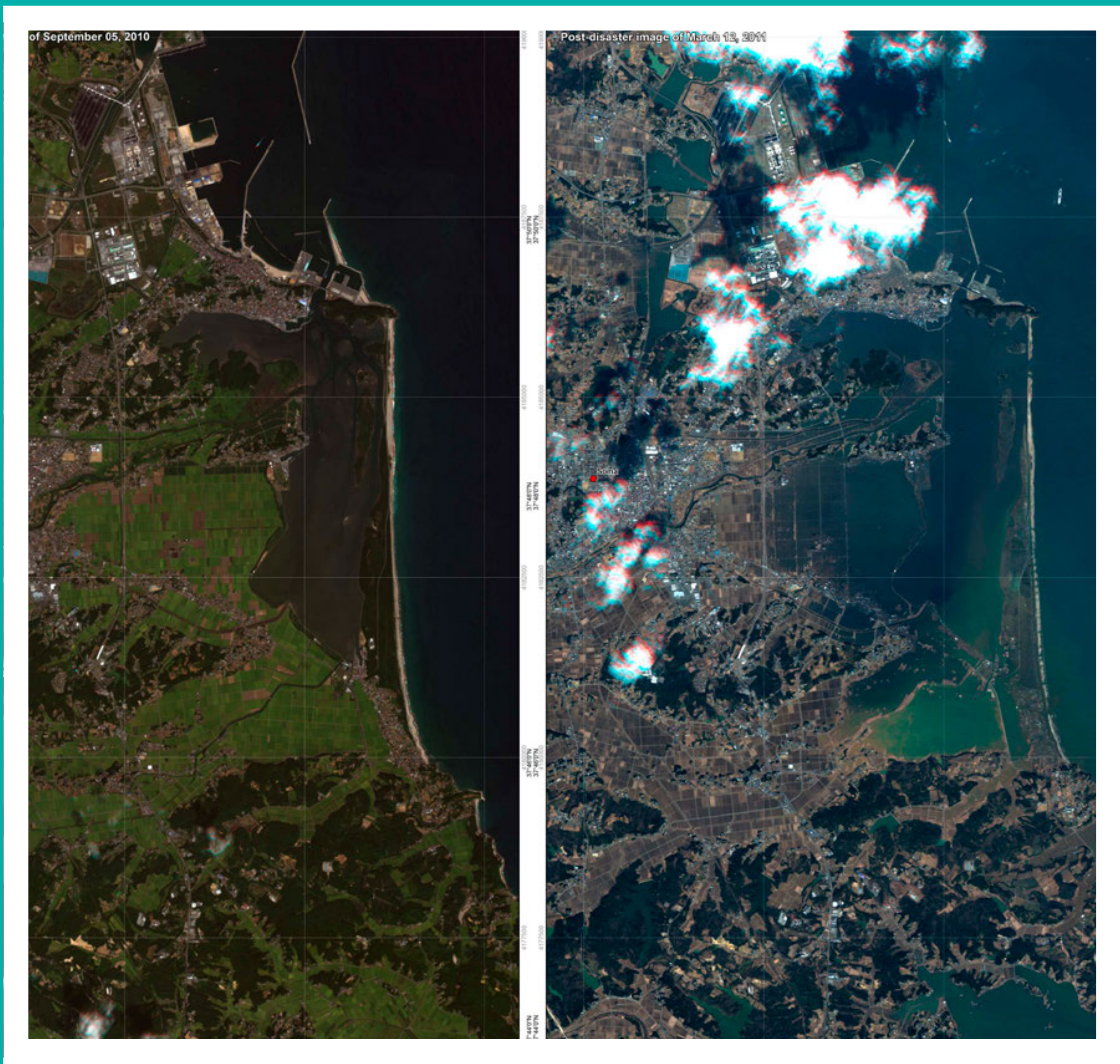
The latest ESA research demonstrated that the impacts of a severe space weather case could raise damage costs to over €15 billion. However, several agencies believe this value could be even higher in future decades due to the rising reliance on satellite navigation systems in transportation and aviation.[120]

Finally, national organizations, academics and working groups play a crucial role in ensuring prompt communications with people by elaborating strategies and action plans to address space weather threats. The interdisciplinary methods adopted by different agencies and departments have strengthened space weather monitoring activities and mitigation procedures for space at the international and national levels. For instance, the National Science and Technology Council of the United States has prepared a document with various governmental offices and departments to achieve a space-weather-ready nation. The report defined a set of policies, actions and timelines to increase the resilience of critical infrastructure and satellites to potential space weather impacts.[121]

[119] United States, National Aeronautics and Space Administration, *How Space Weather Affects Space Exploration.* Available at www.nasa.gov/mission_pages/rbsp/science/rbsp-spaceweather-human.html

[120] European Space Agency, "Space Safety". Available at www.esa.int/Space_Safety/Space_weather_and_its_hazards

[121] United States, National Science and Technology Council (2019). *National Space Weather Strategy and action plan.* Available at https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf.



Satellite imagery before and after the March 2011 tsunami in Japan, in the region near the city of Soma

Image courtesy of ESA and DLR

Chapter 7.
Space technologies for coastal hazards

More than 600 million people (around 10 per cent of the world's population) live in coastal areas less than 10 metres above sea level, and 40 per cent of the world's population lives within 100 km of the coastal zone. Meanwhile, by 2030, the coastal population is expected to increase by 50 per cent.[122] In the past two decades, climate change, unplanned development and increased population have considerably increased disasters in coastal zones. In the next 50 years, the impact of climate change is predicted to substantially affect the impacts of coastal hazards, particularly tsunamis, storm surges and coastal erosion due to sea level rise.

Coastal hazards are generally known as physical phenomena that impact human properties and the environment associated with the coastal zone. According to the UNDRR classification, coastal hazards can originate from hydrometeorological, geological, biological or technological phenomena.[123] The most prominent hazard types are tsunamis and storm surge.

Space technology is an effective and efficient tool to monitor, detect and assist in generating early warnings for coastal hazards. Satellite-derived coastal zone characteristics such as coastal elevation, bathymetry, topography and land use are essential variables that are used for coastal hazard assessments, specifically for tsunamis and storm surges. In addition, near-real image acquisition is used to detect and monitor changes in these hazard events during the disaster response and post-disaster damage assessment stages.

This chapter will start with a discussion on geospatial data that are essential to elaborate hazard maps and will include information on early warning systems developed in the case of tsunamis and storm surges and will conclude with additional information on satellite technologies to monitor sea level rise.

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[122] W. Neil Adger, Terry P. Hughes, and others, "Social-ecological resilience to coastal disasters". *Science*, vol. 309, issue number 5737 (12 August 2005) pp. 1036–1039. Available at https://doi.org/10.1126/science.1112122

[123] United Nations Office for Disaster Risk Reduction, "Hazard Definition & Classification Review: Technical Report". Available at www.irdrinternational.org/knowledge_pool/publications/858

7.1 Satellite-derived bathymetry[124]

One of the key parameters of coastal zones is bathymetry. Bathymetry measures water depth in oceans, rivers or lakes and is used to define submarine topography. Bathymetry is used for tsunami, storm surge and coastal flood modelling, and it is an essential parameter in generating early warnings.

Tsunami and storm surge inundation modelling needs both bathymetric and coastal elevation data. Due to continued changes in the bathymetric conditions caused by human and geomorphological processes, coastal hazard models must be regularly updated. This creates a high demand for bathymetric data.

In practice, the bathymetry is typically obtained from in situ measurement using echo sounders on ships and light detection and ranging (LiDAR) in aeroplanes. These methods are costly and do not provide extensive coverage; hence, bathymetry for 50 per cent of the world's shallow coastal zones is still not surveyed.[125] However, satellite-derived bathymetry (SDB) is an innovative way of generating bathymetry at a lower price and wider coverage. Historically, the horizontal resolution of bathymetry derived from satellite data is poorer than that provided by echo sounders and LiDAR. But as satellite technology has evolved and continues to develop, the resolution is being improved. For example, in the 1990s, GeoSat and ERS 1 provided 12 km horizontal resolution. In contrast, the Global Multi-Resolution Topography synthesis, which merges satellite and in situ sensor data, can provide a resolution of 50 m where data exist.[126]

Various optical and radar sensors are employed to generate SDB. The resolution and the maximum depth vary depending on the type of the sensor, depth of sunlight penetration, turbidity, location, season in the case of optical sensors and the method used to derive SDB.

Two methods are used to estimate bathymetry: multispectral inversion and wave-based inversion. Multispectral inversion uses attenuation of the light with depth in the water column, which is a function of wavelength. Wave-based inversion uses the influence of coastal topography on shallow-water ocean waves.

Wave-based inversion needs stereo, burst or video modes of images to calculate the depth, and high-resolution optical satellites such as IKONOS, WorldView-2, Spot-5 and Sentinel 2 are used in this method. In addition, SAR sensors such as Sentinel 1, TerraSAR-X and RISAT are also used to derive near-shore bathymetry.

Improved algorithms and machine learning methods also enhance the quality of bathymetric data compared to the more conventional, in situ analyses in isolation. Susa[127] derived near-shore bathymetry from Sentinel-2 satellite imagery near La Parguera, Puerto Rico utilizing a traditional band-ratio algorithm, a band-ratio switching method, a random forest machine learning model and the XGBoost machine learning model. The machine learning models returned comparable results and were markedly more accurate relative to other techniques demonstrated.

[124] Gillaume Cesbron, Angelique Melet, and others, "Pan-European Satellite-Derived Coastal Bathymetry—Review, User Needs and Future Services", *Frontiers in Marine Science*, Vol. 8 (2021). Available at https://doi.org/10.3389/fmars.2021.740830

[125] International Hydrographic Organization, "Status of Hydrographic Surveying and Charting Worldwide". Publication C-55 (3 October2023). Available at: https://iho.int/uploads/user/pubs/cb/c-55/c55.pdf

[126] Global Multi-Resolution Topography, "GMRT Overview". Available at www.gmrt.org/about/index.php

[127] Tyler Susa, "Satellite Derived Bathymetry with Sentinel-2 Imagery: Comparing Traditional Techniques with Advanced Methods and Machine Learning Ensemble Models". *Marine Geodesy*, vol. 45, issue number 5 (4 May 2022). Available at http://dx.doi.org/10.1080/01490419.2022.2064572

CASE STUDY

Measuring satellite-derived bathymetry with the Ice, Cloud and Elevation Satellite-2

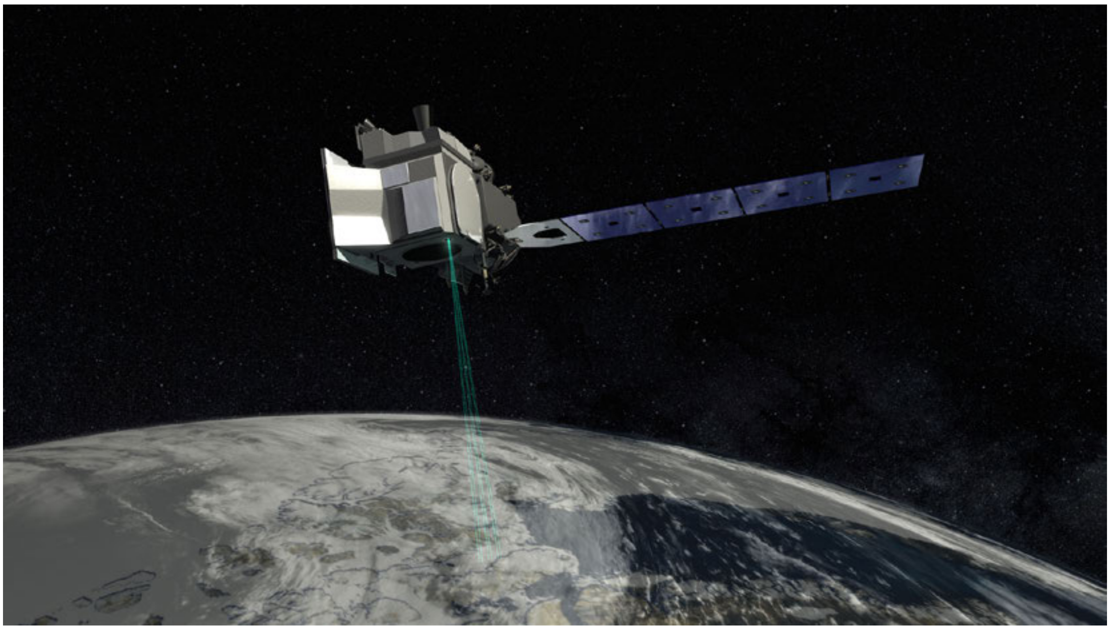
The Ice, Cloud and Elevation Satellite-2 (ICESat-2) is a laser altimetry satellite launched by NASA in September 2018. Originally designed to study polar ice elevation and tree canopy measurement, ICESat-2 has been successfully used to derive SDB.[a] The Advanced Topographic Laser Altimeter System comes with 532 nm laser beams that can sample 70 cm x 70 cm ground areas with a vertical resolution of 4 mm. The accuracy remains 95 per cent compared with ground-based LiDAR surveys. ICESat-2 can detect sea floor up to 40 m depth and has vertical accuracy in the range of Root-Mean-Square-Deviation 0.43 - 0.60 metres. Figure 7.1 presents an illustration of the ICESat-2 satellite. The data of the ICE Sat-2 is accessible from the following link: https://openaltimetry.org/data/icesat2/

ICESat-2 data were also used to develop the Earth Topographic Relief Model (ETOPO) 2022, a global relief model released in December 2022, which consists of more accurate bathymetry and elevation.[b] Bathymetry and coastal elevation data captured from ICESat-2 will improve the accuracy of tsunami risk assessment which is an essential step for better tsunami early warning systems.

[a] United States, National Aeronautics and Space Administration, *First ICESat-2 Global Data Released: Ice, Forests and More*. Available at https://icesat-2.gsfc.nasa.gov/articles/first-icesat-2-global-data-released-ice-forests-and-more

[b] United States, National Oceanic and Atmospheric Administration, *ETOPO Global Relief Model*. Available at www.ncei.noaa.gov/products/etopo-global-relief-model

Figure 7.1 ICESat-2 satellite - a laser altimetry satellite measuring polar ice, sea level and forest canopy



Source: NASA

7.2 Satellite-derived elevation data

Tsunamis, storm surges and sea level rise are critical coastal hazards influenced by the coastal landform and elevations. Therefore, elevation data play a crucial role in determining the potential impact of these hazards and provide the basis for developing early warning systems. As in the case of bathymetry, space observation offers elevation data at a lower cost than airborne or ground surveys.

The National Hazard Profile project conducted by the Disaster Management Centre of Sri Lanka with the assistance of UNDP has used satellite-derived elevation data to develop coastal hazard profiles for tsunami, storm surge and sea level rise. The 30-metre resolution imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the Terra satellite was used in this project to develop inundation maps for these hazards for multiple scenarios.[128]

7.3 Tsunami

A tsunami is a series of ocean waves that send water surges onto land, often causing widespread destruction. Large, undersea earthquakes or underwater volcanic eruptions and landslides typically cause tsunamis.[129] Large meteorites impacting the oceans or seas may also trigger tsunamis.

In open, deep water, tsunami waves have small amplitudes and long wavelengths. Tsunami waves travel at great speeds; for example, the 2004 Indian Ocean Tsunami took 2.5 hours to travel from Sumatra to Sri Lanka. However, once the waves reach coastal areas and the sea floor becomes shallower, the tsunami wave height can increase dramatically, bringing fast-moving, large and powerful tsunami waves onto coastal areas, causing extensive damage and a significant danger to life. In 2004, the Indian Ocean Tsunami killed 275,000 people across 14 countries and caused US$ 9.9 billion worth of damage.[130]

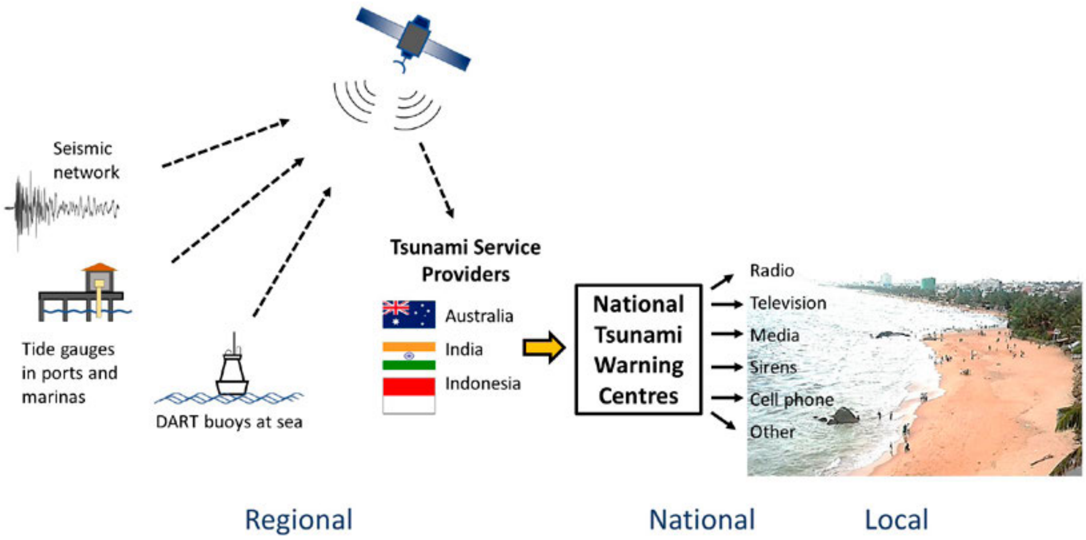
After the 2004 Indian Ocean Tsunami, the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS) was established to improve regional coordination. The initiative was supported by the Intergovernmental Oceanographic Commission (IGC) of UNESCO, and under the IOTWMS, three tsunami service providers have been established in Australia, India and Indonesia. IOTWMS has 28 member countries which benefit from tsunami detection and warnings. Figure 7.2 presents a schematic diagram of the Indian Ocean Tsunami Warning System.

[128] United Nations Development Programme, "Chapter 10 Tsunami in Hazard Profiles of Sri Lanka Report". Available at www.dmc.gov.lk/images/hazard/hazard/Report/UNDP%20BOOK%20CHAP%20010_%20TSUNAMI%20%20-%2019-12-2012.pdf

[129] National Geographic, *Tsunamis*. Available at www.nationalgeographic.com/environment/article/tsunamis

[130] Australian Disaster Resilience Knowledge Hub, "Tsunami Evaluation Coalition. The Boxing Day Tsunami in numbers". Available at https://knowledge.aidr.org.au/media/3767/tsunami-stats-facts.pdf

Figure 7.2 Indian Ocean Tsunami Warning System



Source: UN-SPIDER

7.3.1 Identifying tsunami risk

Recent tsunami incidents, such as the Indian Ocean tsunami and the Japan earthquake and tsunami, show that understanding tsunami risk is essential to risk reduction efforts, including early warning systems.

Numerical tsunami propagation and inundation models are typically used for tsunami hazard analysis and issuing warnings. Modelling provides tsunami travel time, inundation, wave height and water depth. Satellite-derived bathymetry and elevation of the coastal zone is an essential component of the tsunami modelling process, as the tsunami wave dynamics in shallow waters follow the coastal topography. Furthermore, satellite remote-sensing techniques offer data that can be used for mapping and estimating the exposure of vulnerable elements, such as residential buildings and critical infrastructure. The risk assessment data are critical for information impact assessments in early warning systems and enable effective preparedness and response activities to take place.

7.3.2 Detection and monitoring

SAR and GNSS techniques are helpful in identifying information related to the source deformation that can trigger tsunamis in real time.

Real-time GNSS data can be used to detect and estimate ground deformation caused by earthquakes with on-land epicentres close enough to the coast to potentially trigger a tsunami. Understanding ground deformation is necessary to calculate the potential energy released to the water column. Chile, Japan and New Zealand use dense GNSS networks, to produce insight into co-seismic ruptures rapidly in real time,[131] capturing fault ruptures, locations and slip amounts.

[131] Sergio Barrientos, "The Seismic Network of Chile". Available at https://doi.org/10.1785/0220160195

The Japanese GNSS network has demonstrated its capacity to detect the ground deformation of an earthquake in real time.[132] After the Tohoku earthquake and tsunami in 2011, the Geographical Information Authority of Japan established the Real-time Geonet Analysis system for rapid deformation monitoring, a tsunami warning system established using existing nationwide GNSS sensor stations at 1,300 locations to detect earthquakes and issue tsunami warnings within 3 minutes.[133]

In addition to GNSS, InSAR also enables detection of geomorphological characteristics that could lead to tsunamis, such as tsunamigenic catastrophic slope failures. For example, a recent study of the 2017 cliff collapse in Greenland found that InSAR techniques identified a possible second tsunami-genic landslide.[134]

From the propagation point, satellite altimetry can be used to detect tsunami waves that travel across the deep ocean. For example, the 2004 Indian Ocean tsunami was recorded 2 hours after the earthquake by Jason-1 and Topex/Poseidon satellites. However, researchers revealed that there are limitations to using satellite data to detect tsunami waves in real time, particularly when the source region is close to shore. Satellite altimetry is, however, useful for model verification and post-tsunami impact assessment purposes.[135]

Tsunamis, like earthquakes, can also trigger gravity waves that transmit upwards through the atmosphere and into the ionosphere.[136] The Gravity Field and Steady-State Ocean Circulation Explorer satellite, placed in a very low orbit of 270 km altitude, detected the gravity wave generated by the Tohuku tsunami in March 2011.

Researchers have established a theoretical relationship between the vertical and horizontal velocities of gravity waves and tsunami waves. Therefore, the identification of gravity waves triggered by tsunamis are a novel observation method, which has the potential for use in the early detection of tsunami waves. In addition, recent research suggests that the detection of internal gravity waves is much faster than DART and can be used as an alternative approach for detecting tsunamis for early warnings.[137]

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[132] Shinzaburo Ozawa, Takuya Nishimura, *and others*, "Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake". *Nature*, vol. 475 (15 June 2011), pp. 373–376. https://doi.org/10.1038/nature10227

[133] Satoshi Kawamoto, Yusaku Ohta, and others, "REGARD: A new GNSS-based real-time finite fault modelling system for GEONET". *Journal of Geophysical Research: Solid Earth*, vol. 122, issue number 2 (February 2017), pp. 1324–1349. Available at https://doi.org/10.1002/2016JB013485

[134] Alexandre Paris, Emile A. Okal, and others, "Numerical Modeling of the June 17, 2017 Landslide and Tsunami Events in Karrat Fjord, West Greenland". *Pure Applied Geophysics*, vol. 176, (11 February 2019), pp. 3035–3057. Available at https://doi.org/10.1007/s00024-019-02123-5

[135] Walter H. F. Smith, Remko Scharroo, and others, "Satellite Altimerters Measure Tsunami". *Oceanography*. Vol. 18, No. 2 (June 2005) pp 11–13. Available at www.gfdl.noaa.gov/bibliography/related_files/whfs0501.pdf

[136] Raphael F. Garcia, Eelco Doornbos, and others, "Atmospheric gravity waves due to the Tohoku-Oki tsunami observed in the thermosphere by GOCE". *Journal of Geophysical Research: Atmospheres*, vol. 119, issue number 8 (27 April 2014), pp. 4498–4506. Available at https://doi.org/10.1002/2013JD021120

[137] Zahra Foroodi, Mahdi Alizadeh, and others, "Alternative Approach for Tsunami Early Warning Indicated by Gravity Wave Effects on Ionosphere". *Remote Sensing*, vol. 13, issue number 11 (30 May 2021). Available at https://doi.org/10.3390/rs13112150

7.3.3 Disseminating tsunami detection data using satellite communication technology

Tsunami early warning systems rely on the timely and reliable acquisition of relevant data, either from buoys at sea or from tide gauges in ports, and its subsequent transmission to warning centres. Satellite communications provide a secure and reliable way to transmit that essential data to such warning centres. Compared to terrestrial communications, satellite communications are highly reliable as they are not affected by extreme events that happen on Earth.

The Pacific Tsunami Warning System (PTWC), for example, uses satellite technology both to collect information on the height of waves and to transmit tsunami warnings to national emergency centres. PTWC benefits from satellite telecommunications provided by the Iridium constellation of 66 cross-linked low-Earth orbit (LEO) satellites that provides high-quality, real-time data of the planet's entire surface.[138]

CASE STUDY

Tsunami buoys and satellite technology[a]

Once a tsunami is generated, the killer waves can propagate thousands of kilometres away from the source and make a damaging impact. Conventionally these waves are monitored and detected through tide gauges installed in harbours and tsunami buoys placed offshore, in deep oceans.

Deep Ocean and Assessment of Tsunami (DART) buoys are the advanced version of the buoys which capture tsunami waves in real-time and trigger the early warnings. Bottom Pressure Sensors detect changes in the sea depth and send the data to surface DART buoys. The DART buoy transmits the data to the Tsunami Warning Centre and the National Data Buoy Center via the western Geostationary Operational Environmental Satellite (GEOS-West).

The second-generation DART (DART II) became operational in 2005 with the capability of two-way communication between NDBC and the buoy via Iridium satellites. Two-way communication permits the changing of the sensor's sampling time to 15 seconds, in the event of possible tsunami threat. Further two-way communication also facilitates real time diagnosis and troubleshooting the system. The DART II full network with 39 stations has been operational since March 2009. Figure 7.3 presents a schematic diagram of the monitoring system and its data flow.

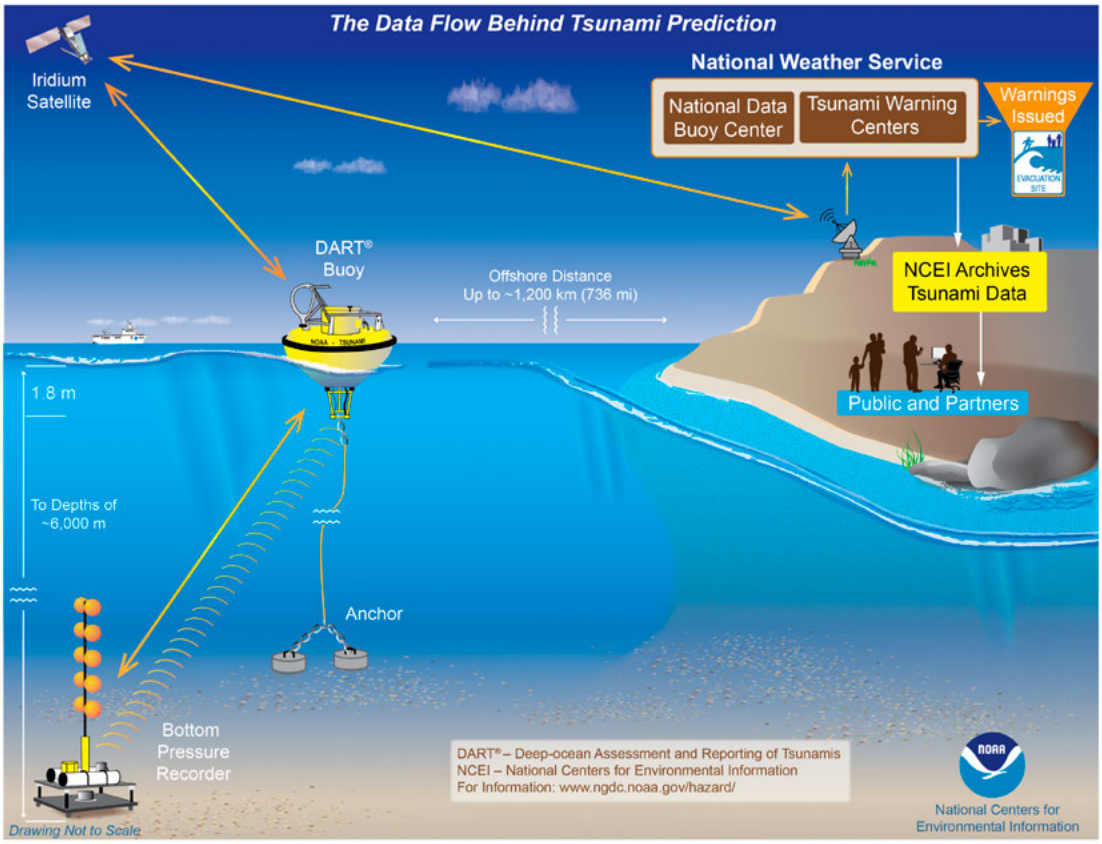
At the Tsunami Warning Centre, data are processed through tsunami models to forecast possible tsunami arrival times and inundation zones.

In addition to pressure sensors, GNSS can also be used to measure the position of buoys relative to the land-based receivers, using a real-time kinematic mode taking advantage of differential processing. As of 2019, Japan has installed 18 GNSS buoys along the Japanese coast, mainly in Sanriku, to detect potential tsunami waves.

[a] United States, National Oceanic and Atmospheric Administration, *Buoy Data Help Tsunami Preparedness*. Available at www.ncei.noaa.gov/news/buoy-data-help-tsunami-preparedness

[138] UN-SPIDER Programme, "UN-SPIDER Knowledge Portal: Satellite telecommunications in tsunami early warning systems". Available at https://un-spider.org/satellite-telecommunications-tsunami-early-warning-systems

Figure 7.3 The data flow behind tsunami prediction



Source: NOAA

Some countries are also using satellite communication to disseminate tsunami warnings rapidly from the national to the local level. For example, Sri Lanka has erected over 77 tsunami warning towers along the coastal zone to disseminate the warnings.

CASE STUDY

Satellite communication for tsunami warning dissemination in Sri Lanka

Sri Lanka is located in the impact zone of the two subduction zones of Sumatra and Makran. After the 2004 Indian Ocean Tsunami affected 14 coastal districts around the country, a broad tsunami warning system and preparedness plan was established and is updated on a regular basis, from the national to the local level.

The Meteorological Department is the focal point for issuing tsunami warnings at national level. The Department is connected with the regional tsunami service providers. The Global Telecommunication System (GTS) facilitates the dissemination of the tsunami warnings from the tsunami service providers to the national warning centres. GTS is a communication and data management platform, connecting weather stations, satellites and numerical weather prediction centres which provide critical meteorological forecasting and warnings, facilitated by the World Meteorological Organization (WMO). [a]

The Disaster Management Centre (DMC) is the national focal point for disaster risk management and responsible for preparedness planning, mitigation, public awareness and emergency response including early warning dissemination.

The local level tsunami dissemination consists of multiple warning methods including public media, telephones, mobile communication and conventional methods at local level. In addition, tsunami warning towers, erected in 77 locations around the coast of Sri Lanka, are also used for tsunami warning in the country. These warning towers are centrally controlled by the DMC head office in Colombo and activated via satellite (Inmarsat) and VHF communication systems. Pre-recorded warning messages in three local languages are played depending on the warning levels of "alert", "evacuation" and "cancellations". The audibility of these warning towers is in the range of 500 to 1,500 m. Figure 7.4 presents two examples of sirens in coastal areas of Sri Lanka. Communities are prepared through training, awareness and simulation exercises run by the disaster management coordinating units based at subnational level.

[a] World Meteorological Organization, "Global Telecommunication System". Available at https://public.wmo.int/en/programmes/global-telecommunication-system

Figure 7.4 Tsunami warning towers, which consists of satellite communication, sirens, and solar power systems, erected along the Sri Lankan coastal belt

Source: Disaster Management Centre, Sri Lanka.

7.4 Storm surge

Storm surge is an abnormal rise of water generated by a storm, over and above the predicted astronomical tides. Storm surge is produced by water being pushed towards the shore by the force of the winds moving cyclonically around the storm.[139]

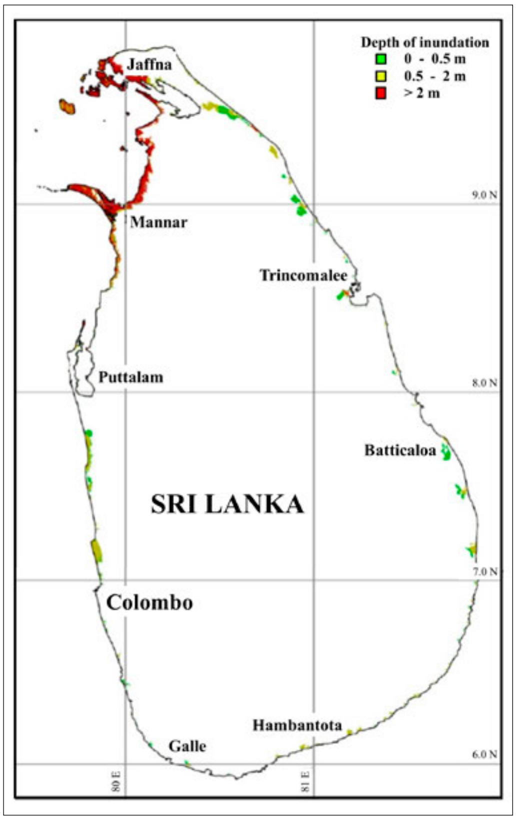
Along the coast, storm surge is often the greatest threat to life and property from a hurricane or tropical cyclone. Hurricane Katrina (2005) is a prime example of the damage and devastation that can be caused by surge. At least 1,500 persons lost their lives during Katrina and many of those deaths occurred directly, or indirectly, as a result of storm surge.

According to academic sources, over 700 storm surges have occurred globally since 1880, and approximately 56 per cent of those events are reported from the Western North Atlantic region. The highest surges, however, are repeatedly reported in the Northern Indian Ocean (Bay of Bengal).[140]

As with flood hazard maps and tsunami inundation hazard mapping, satellite remote-sensing techniques are also used to map potential storm surge inundation zones from satellite-derived bathymetry and elevation data. Indeed, Sri Lanka has demonstrated that potential storm surge inundation zones can be identified for multiple wind speeds using numerical simulations based on bathymetry and elevation data to develop probabilistic hazard maps.

Figure 7.5 presents an example of a storm surge inundation map for Sri Lanka related to wind speed of 215 km per hour.

Figure 7.5
Sri Lanka storm surge inundation map related to wind speed of 215 km/h and composed using numerical model predictions constructed on satellite-derived bathymetry and elevation data



Source: UNDP

Satellite-based radar altimetry is also used to detect storm surges and to validate storm surge models. Compared with tidal observation data, satellite altimetry has the advantage of providing offshore sea level information to an accuracy of 10 cm. In addition, satellite altimetry can provide more effective observations for studying storm surges, such as transient surge data.

The tide gauges and satellite altimeters are relatively sparse, and the spatial distribution is extremely uneven, which often seriously restricts the overall understanding of the spatial distribution features of storm surge activity.

[139] United States, National Oceanic and Atmospheric Administration, *Storm Surge Overview*. Available at www.nhc.noaa.gov/surge/

[140] Hal. F. Needham, Barry D. Keim, and David Sathiaraj, "A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts". *Reviews of Geophysics*, vol. 53, issue number 2 (June 2015). Available at https://doi.org/10.1002/2014RG000477

Numerical models can be used as a tool to overcome the above-mentioned shortcomings for storm surge monitoring, as they provide real-time spatio-temporal features of storm surge events.[141]

Although recent research[142, 143] on historical satellite data sets clearly shows that altimetry data can be used to detect storm surge, real-time and near-real-time altimetry missions to capture storm surges are of an opportunistic nature, and the presence of multiple satellite tracks in a region greatly enhances the probability of capturing signals of extreme events. Though satellite altimeters have been proven to be a complementary means of observing storm surges, effective strategies will be required for regular monitoring of storm surges in the future.[143]

CASE STUDY

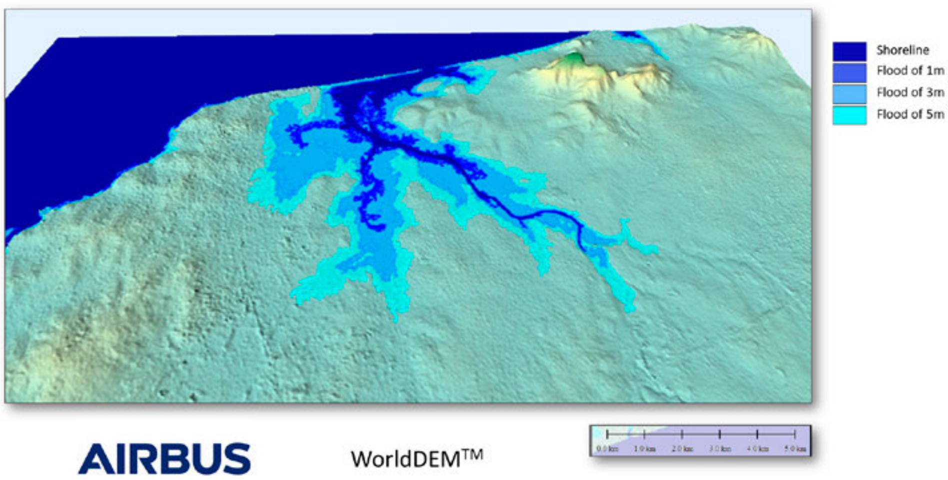
Using digital elevation models as a first approximation for storm surge hazard mapping

In recent years, coastal areas in Ghana have experienced storm surges. At the request of UN-SPIDER, experts from Airbus Defence and Space developed a step-by-step procedure to use the digital elevation model called WorldDEM™ as a first approximation to elaborate storm surge hazard maps. The procedure, available as an UN-SPIDER Recommended Practice,[a] extracts polygons at specific elevations above sea level.

Figure 7.6 presents a map of the potential geographical extents of storm surges in the coastal area of Accra in Ghana, with levels from 1 to 5 metres.

[a] UN-SPIDER programme, "UN-SPIDER Knowledge Portal. Recommended Practice "Drought monitoring using the Standard Vegetation Index (SVI)". Available at www.un-spider.org/advisory-support/recommended-practices/recommended-practice-drought-monitoring-using-standard

Figure 7.6 Map of the potential geographical extents of storm surges in the coastal area of Accra, with levels from 1 to 5 metres



Source : Airbus Defence and Space

[141] Tao Ji, and Guosheng Li, "Contemporary monitoring of storm surge activity". *Progress in Physical Geography: Earth and Environment*, vol 44, issue number 3 (2019), pp. 28–34. Available at https://doi.org/10.1177/0309133319879324

[142] O. B. Andersen, Y. Cheng, and others, "Using satellite altimetry and tide gauges for storm surge warning". *Proceedings of IAHS*, vol. 365 (02 March 2015). Available at http://dx.doi.org/10.5194/piahs-365-28-2015

[143] Tao Ji, Guosheng Li, and Yue Zhang, "Observing storm surges in China's coastal areas by integrating multi-source satellite altimeters". *Estuarine, Coastal and Shelf Science*, vol. 225 (30 September 2019). Available at https://doi.org/10.1016/j.ecss.2019.05.006

7.5 Sea level rise

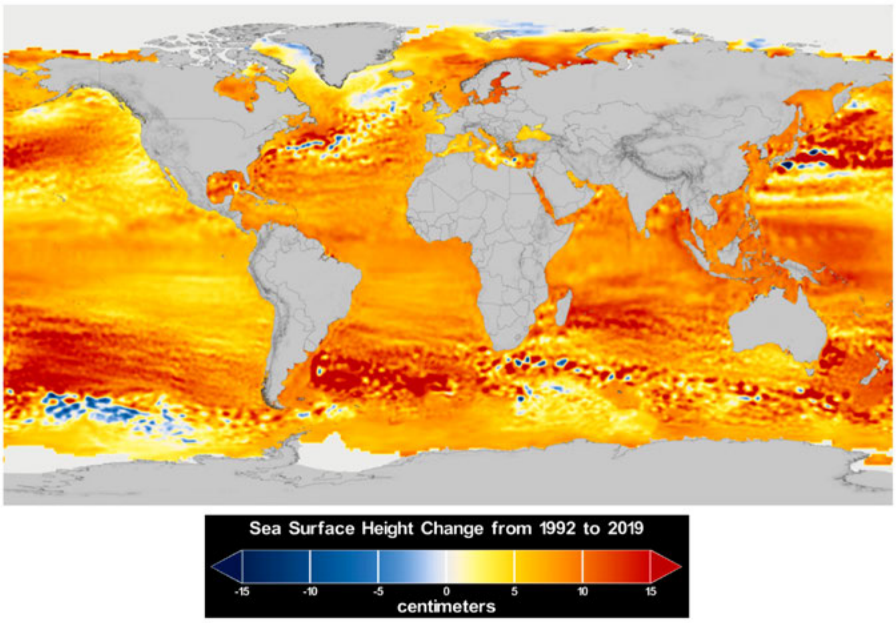
Sea level rise is increasing around the globe because of climate change. The rapid increment of carbon dioxide and other greenhouse gases in the atmosphere is increasing global temperatures. The oceans absorb the excessive heat from the atmosphere and hence ocean waters are becoming warmer. As ocean temperature increases, oceans expand and increase the average surface level of the ocean. The International Panel on Climate Change reports that if greenhouse gas emissions remain the same, the projected sea level rise will be in between 0.6 to 1.1 m by 2100.[144]

Sea level rise affects the potential impact of other coastal hazards, such as tsunami and storm surge, therefore continuous monitoring of seawater level for effective modelling, forecasting and early warning is essential.

Space applications have been developed to monitor oceanic condition, including surface water level, by various satellite altimeter applications.

Since 1991, many satellite altimetry missions have been designed to monitor sea level rise and, since 1992, global sea level change has been computed by various organizations and universities. Satellites that have been used for altimetry include CryoSat 2, ERS 1 and 2, GFO, Jason 1, 2 and 3, SARAL, Sentinel 3 and 6, and Topex/Poseidon. The synoptic coverage and frequent revisit capability of satellites provides a collection of altimetry data available at global scale and able to monitor the trend in sea level rise for the past few decades. The Jet Propulsion Laboratory (JPL) of the California Institute of Technology and NASA has presented sea level changes observed by Topex/Jason missions for the period of 1992–2019. Figure 7.7 presents a map of sea surface height changes between 1992 and 2019 measured by the Topex and Jason satellite missions.

Figure 7.7 Sea surface height changes 1992–2019 measured by the Topex/Jason missions



Source: NASA/JPL

[144] International Panel on Climate Change, "Chapter 4 - Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities". In *Special Report on the Ocean and Cryosphere in a Changing Climate.* Available at www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/

CASE STUDY

NASA study shows sea level rise exceeds the estimates[a, b]

A recent research study shows that the water level of United States coastline will increase 12 inches (30 cm) by 2050 according to the analysis of 28 years of satellite altimetry data, correlated to NOAA tide gauge records. The research has been conducted by multiple agencies including NASA, NOAA and USGS. The report further suggested the expected rise would be 10–14 inches in the east coast, 14–18 inches on the Gulf Coast and 4–8 inches in the West Coast.

Researchers also predict the increase of high tide floods along every coast in the United States in the mid-2030s due to changes in the moon's orbit, which usually occurs every 18.6 years. The impact of the lunar cycle together with sea level rise will worsen high tide floods during 2030–2040. The impact of El Niño and La Niña may also be affected by the changing sea levels.

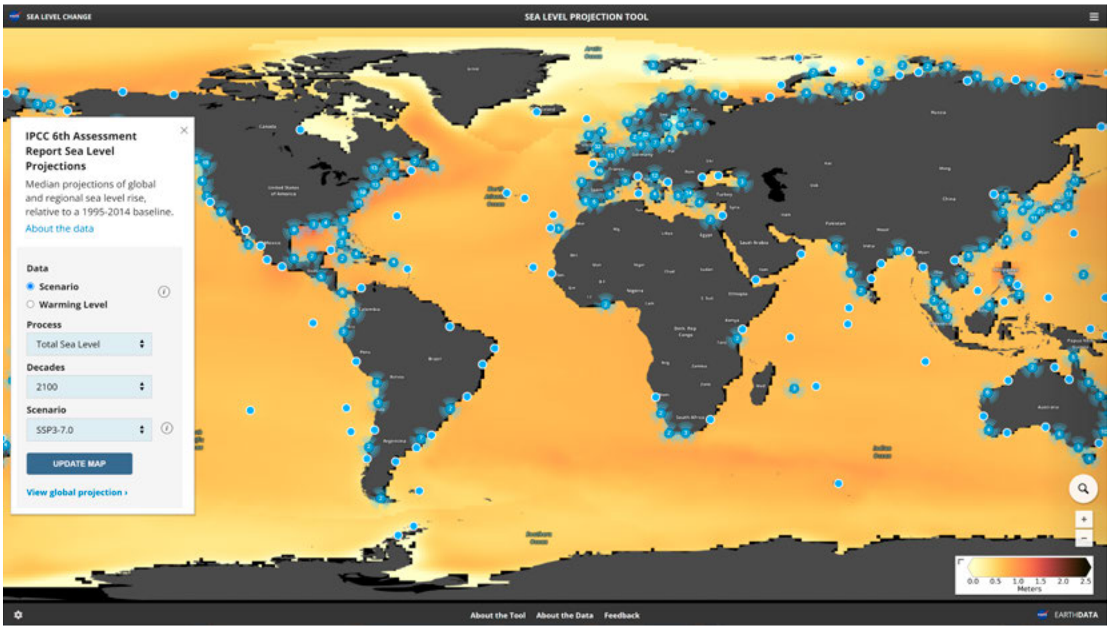
NASA and the space agency of France, Centre national d'études spatiales (CNES), started joint missions deploying satellite altimeters in the early 1990s, beginning a continuous space-based record of sea surface height with high accuracy and near-global coverage. In 2020, Sentinel 6 was launched: a continuation of sea surface height observation using altimetry. The mission is partnered by NASA, NOAA, ESA, EUMETSAT and CNES.

The researchers also released an online visualization tool for the public to understand how specific areas are affected by the sea level rise. Figure 7.8 presents information on the Sea Level Projection Tool of NASA.

[a] United States, National Aeronautics and Space Administration, Jet Propulsion Laboratory, *NASA Study: Rising Sea Level Could Exceed Estimates for U.S. Coasts*. Available at www.jpl.nasa.gov/news/nasa-study-rising-sea-level-could-exceed-estimates-for-us-coasts

[b] United States, National Aeronautics and Space Administration, *Sea Level Projection Tool*. Available at https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

Figure 7.8 An example of the Sea Level Projection Tool



Source: NASA

CASE STUDY

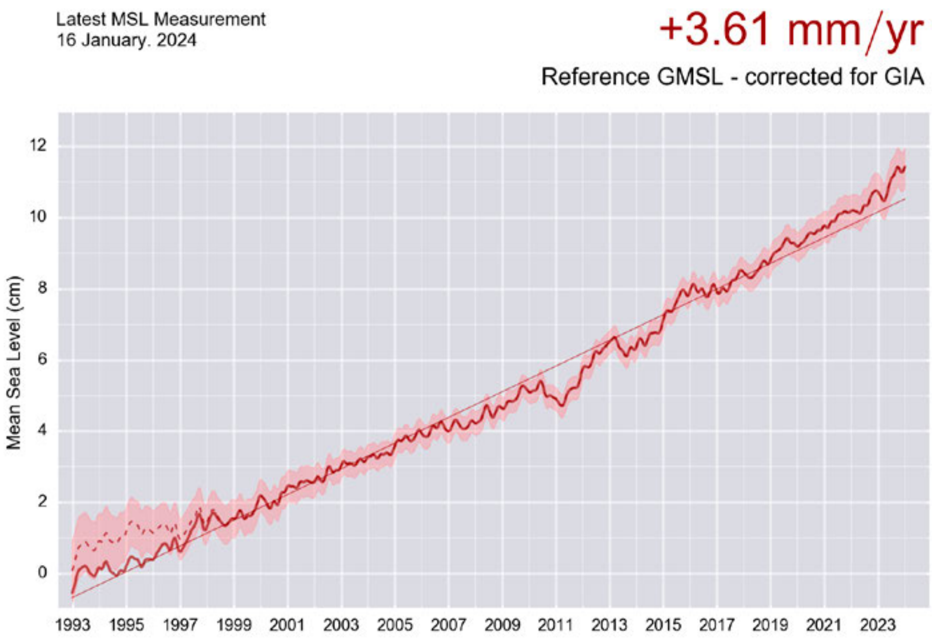
CNES AVISO initiative

The National Centre for Space Studies (CNES) launched the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) initiative to provide information on sea level rise data and related information.[a] Figure 7.9 presents a graph of the mean sea level extracted from satellite altimetry covering the period from 1993 to 2023.

AVISO has assessed sea level rise in different regions of the world and highlights that the spatial distribution of sea level rise is not evenly distributed around the globe. Local variations in sea level rise see higher or lower than the mean sea level rise levels. The variations may be the result of heat redistribution and ocean circulation in specific regions of the planet. Figure 7.10 presents a map of gridded regional sea level trends are reported by AVISO.

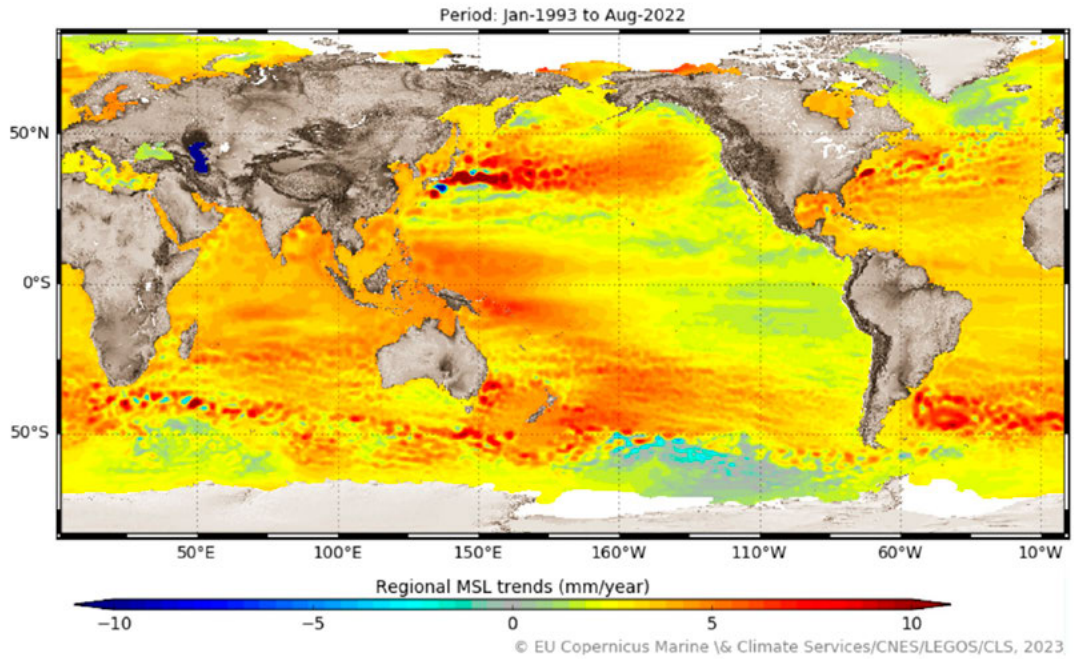
[a] National Centre for Space Studies, "AVISO". Available at www.aviso.altimetry.fr/en/home.html

Figure 7.9 Mean sea level from altimetry from 1993 to 2024



Source: CNES, LEGOS, CLS

Figure 7.10 Gridded regional sea level trends



Source: AVISO_CNES

Harmful algae blooms in the Baltic Sea near the island of Gotland

Image courtesy of ESA

Chapter 8.
Space technologies for health hazards

Biological health hazards are of organic origin and include bacteria, viruses or parasites, as well as mosquitoes carrying disease-causing agents.[145] The consequences of a biological health hazardous event may include severe economic and environmental losses.

Some recent examples of large outbreaks, epidemics or pandemics due to biological health hazards are:

- The COVID-19 virus that impacted most countries of the world between 2019 and 2022
- The Ebola Virus Disease outbreak in West Africa in 2013–2016, in the populations of Guinea, Liberia and Sierra Leone
- The outbreak of the Zika virus infection in the Americas and the Pacific region
- Significant increase in diarrheal disease incidences following recurrent floods in most African countries or significant increases following natural disasters, such as the 2004 tsunami in Indonesia and Thailand
- Outbreaks of yellow fever in Angola, the Democratic Republic of Congo and Uganda in 2016[146]

The management of risks due to biological health hazards is a national and community priority. It has been recognized as part of the Sendai Framework and is globally addressed under the International Health Regulations.[148]

Satellite technology provides mechanisms for monitoring environmental conditions that are favourable for the presence of biological health hazards, such as pathogenic microorganisms and mosquitoes. Like other biological hazards, pathogens and insects are too small to be detected directly by current satellite capability. However, proxy data can be used to detect the presence of biological health hazards. This information is proving valuable to health early warning systems.

This chapter addresses those health hazards such as harmful algae blooms, mosquito-borne diseases including malaria, and cholera.

[145] United Nations Office for Disaster Risk Reduction, "Hazard Definition & Classification Review: Technical Report". Available at www.irdrinternational.org/knowledge_pool/publications/858

[146] United Nations Office for Disaster Reduction, "Chapter 5. Biological Hazards Risk Assessment". In *Words into Action Guidelines: National Disaster Risk Assessment Hazard Specific Risk Assessment*. Available at www.undrr.org/publication/biological-hazards-and-risk-assessment

8.1 Harmful algal bloom

Harmful algal blooms (HABs) occur when certain kinds of algae grow very quickly, forming patches or "blooms", in the water. Blooms are more likely when water is warm, slow-moving and full of nutrients, such as nitrogen or phosphorous.[147] These blooms can emit powerful toxins which endanger human and animal health.[148]

Examples of harmful algal bloom [a, b, c]

Karenia brevis is commonly called red tide. *Karenia brevis* blooms can cause respiratory illness and eye irritation in humans. It can also kill marine life and lead to shellfish closures. Blooms are often patchy, so impacts vary by beach and throughout the day.

Cyanobacteria (blue-green algae) typically occurs when warmer water creates favourable bloom conditions. Blue-green algae can produce toxins that pose a risk to human and animal health, foul coastlines, and impact communities and businesses that depend on the water supply.

Alexandrium catenella blooms produce potent neurotoxins that accumulate in shellfish and cause paralytic shellfish poisoning (PSP) in human consumers.

[a] United States, National Centres for Coastal Ocean Science, *Gulf of Mexico Harmful Algal Bloom Forecast*. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/gulf-of-mexico/

[b] United States, National Centres for Coastal Ocean Science, *Gulf of Maine Alexandrium catenella Predictive Models*. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/gulf-of-maine-alexandrium-catenella-predictive-models/

[c] United States, National Oceanic and Atmospheric Administration, *Lake Erie Harmful Algal Bloom Forecast*. Available at: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/lake-erie/

Over the past three decades, national and international space agencies such as NASA, ESA and EUMETSAT, the China National Space Administration and State, the Indian Space Research Organisation (ISRO), JAXA, the Korean Space Agency and CNES have deployed and operated a range of ocean-colour sensors dedicated to measuring water-leaving radiance in the visible part of the spectrum.[149] As a result, ocean-colour products have continuously been developed, validated and used in operational applications for harmful algal bloom detection, tracking and prediction.

In the United States, HABs have been reported in every coastal state and have caused an estimated one billion dollars in losses in recent decades to coastal economies that rely on recreation, tourism and seafood harvesting. Blooms can also lead to odours that require more costly treatment for public water supplies.[150]

[147] United States, Centers for Disease Control and Prevention, *Avoid Harmful Algae and Cyanobacteria*. Available at www.cdc.gov/habs/be-aware-habs.html

[148] United States, National Centres for Coastal Ocean Science, *Harmful Algal Bloom Monitoring System*. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-monitoring-system

[149] Marie-Fanny Racault, Anas Abdulaziz and others, "Environmental Reservoirs of *Vibrio cholerae*: Challenges and Opportunities for Ocean-Color Remote Sensing". *Remote Sensing*, vol. 11, issue number 23 (24 November 2019). Available at https://doi.org/10.3390/rs11232763

To help public health authorities and emergency management organizations prepare for and manage blooms, HAB forecasts have been developed. These forecasts are based on an improved understanding of the causes of HABs and how they respond to changing weather and ocean conditions.

One critical component of a HAB forecast is the ability to routinely and remotely detect HABs, their toxins and the environmental conditions that foster blooms and enhance their toxicity.[150] To do this, HAB forecasts apply algorithms to process satellite imagery to develop proxies that identify the current position and extent of the bloom and then forecast how the bloom will move and change over time.

CASE STUDY

National Centres for Coastal Ocean Science Harmful Algal Bloom Monitoring System and Forecasting [a]

The Harmful Algal Bloom Forecasting Branch of the National Centre for Coastal Ocean Science (NCCOS) of the United States presents several remote-sensing products to aid public health officials in responding to fresh and saltwater HABs.

NCCOS developed the Algal Bloom Monitoring System to routinely deliver near-real-time products for use in locating, monitoring and quantifying algal blooms in coastal and lake regions of the United States. This application delivers a suite of bloom detection products in the form of geographic-based images. Products are available for selected regions, with new products being evaluated, and new regions being considered.

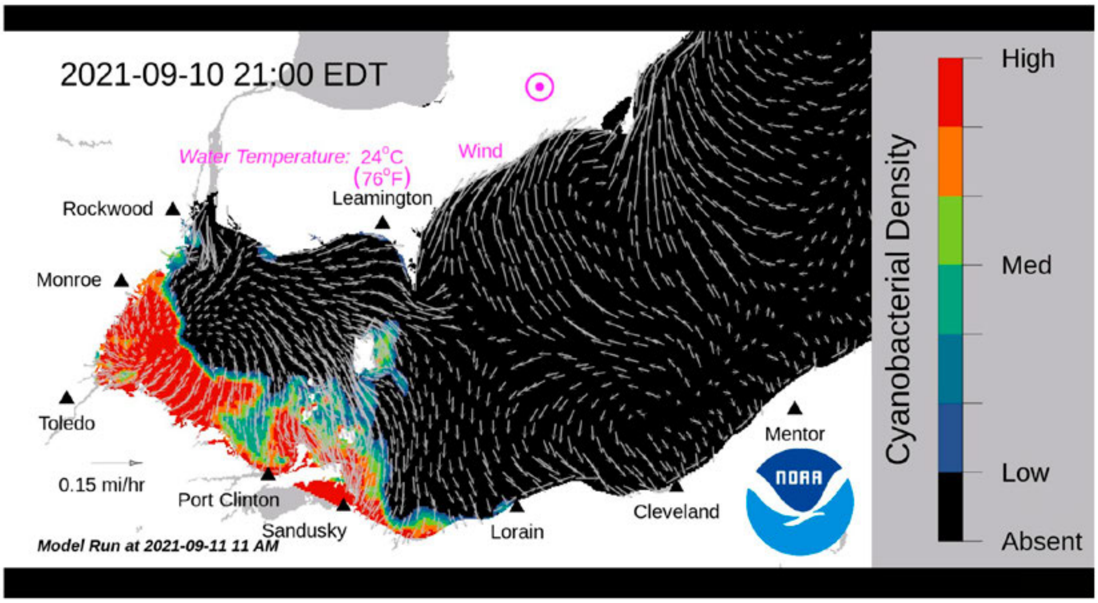
Algal bloom forecasts are produced using a combination of satellite image (for bloom location and extent), a forecasting model and a mixing model to provide information on the status of the bloom, forecasted position, both at the surface and at depth, and toxicity from field samples.

While phytoplankton species cannot be distinguished by satellite, high biomass blooms and separate bloom types can be detected by measuring proxies that estimate Chlorophyll-a, the main component of the blooms, or look at the optical characteristics of the bloom and surrounding waters in which they occur. To do this, several algorithms are applied to the Ocean Land Colour Imager (OLCI) on board the Sentinel 3 satellite suite and to the Multispectral Instrument (MSI) which is aboard the Sentinel 2 satellite suite. Figure 8.1 presents a map of the harmful algal bloom forecast for Lake Erie for 10 to 16 September 2021.

[a] United States, National Centres for Coastal Ocean Science, *Lake Erie Harmful Algal Bloom Forecast*. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/lake-erie

[150] United States, National Centres for Coastal Ocean Science, *Harmful Algal Bloom Forecasting*. Available at https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts

Figure 8.1 Lake Erie harmful algal bloom forecast for the period from 10 to 16 September 2021



Source: NCCOS/NOAA

CASE STUDY

The satellites providing data for monitoring water properties that could lead to harmful algal blooms [a]

The ESA Ocean-Colour Climate Change Initiative (OC-CCI) programme was launched in 2011 to develop and validate algorithms to meet requirements for consistent, stable, merged ocean-colour data from multi-sensor archives, including SeaWiFS, Aqua-MODIS, MERIS and VIIRS. The merged products provide the longest continuous record (more than two decades) of ocean-colour observations with global coverage at 1 to 4 km and daily resolution.

In addition to the OC-CCI data archive, observations at high-spatial resolution (~300 metres) are becoming increasingly available, following the launch of a series of Sentinel missions with sensors dedicated to measuring ocean colour, sea surface temperature (SST) and surface topography variables since 2016.

Ocean-colour sensors on board the Sentinel-3 missions are presently used and validated to retrieve data on phytoplankton and other water constituents and are currently being evaluated for their incorporation into the OC-CCI time series.

The Sentinel-3 Ocean and Land Colour Instrument (OLCI), which is operated by EUMETSAT, provides significant improvements when compared to previous ocean-colour sensors, including an increase in the number of spectral bands (from 15 in MERIS to 21 in OLCI), sun-glint mitigation, improved coverage of the global ocean (<2 days with two satellites in constellation, where MERIS is ~15 days), complete overlap with other sensors such as the Sea and Land Surface Temperature Radiometer, which allows analysis of ocean-colour and SST observations.

As part of the space component of the Copernicus programme, Sentinel-3 has moved ocean colour into the operational domain for the coming decade, with two platforms currently in orbit (Sentinel-3A and Sentinel-3B) and at least two further planned (3C and 3D). Furthermore, data archives of land-designed sensors such as Landsat-8 and Sentinel-2 have also been explored to develop algorithms to retrieve information on phytoplankton and particulate matter. The land sensors have the advantage of providing data at very high spatial resolution (~30 m), which is most relevant for investigating the dynamics of water constituents at local scale, such as in coastal areas and lakes.

[a] Marie-Fanny Racault, Anas Abdulaziz and others, "Environmental Reservoirs of *Vibrio cholerae*: Challenges and Opportunities for Ocean-Color Remote Sensing". *Remote Sensing*, vol. 11, issue number 23 (24 November 2019). Available at https://doi.org/10.3390/rs11232763

8.2 Mosquito-borne diseases

Mosquito-borne diseases infect almost 700 million people every year and are present in over 100 countries, causing many deaths annually. [151] Common types of mosquito-borne diseases include malaria, dengue, West Nile virus, chikungunya, yellow fever, Japanese encephalitis and Zika.[152]

Malaria is a parasitic infection transmitted by Anopheline mosquitoes. It causes an estimated 219 million cases globally, and results in more than 400,000 deaths every year. Most of the deaths occur in children under the age of 5 years.

Dengue is the most prevalent viral infection transmitted by Aedes mosquitoes. More than 3.9 billion people in over 129 countries are at risk of contracting dengue, with an estimated 96 million symptomatic cases and an estimated 40,000 deaths every year.[154]

The changing climatic and ecological conditions, global travel and trade, human behaviour, as well as rapid and unplanned urbanization, are key factors that influence the seasonal and geographic distribution of mosquito populations and therefore the transmission of the pathogens, causing an increase in these diseases and the emerging of these diseases in countries where they were previously unknown.[153]

CASE STUDY

Early warning system for West Nile virus[a]

The West Nile virus (WNV) infection in humans and animals was recorded in various areas of Greece, during the years 2010–2014 and 2017–2019, but also in other regions in Europe reaching a usually high record in 2018.

In Greece, the BEYOND Centre for Earth Observation Research and Satellite Remote Sensing of the National Observatory of Athens has developed an early warning system that utilizes new and enhanced satellite Earth observation sensors with the purpose of forecasting and risk mapping WNV outbreaks. The EarlY Warning System for Mosquito-borne Diseases (EYWA) transforms scientific knowledge into decision-making and contributes significantly to combating and controlling the threat of mosquito-borne diseases.

[151] BEYOND Centre for Earth Observation Research & Satellite Remote Sensing, "Thematic Areas – Epidemics". Available at http://beyond-eocenter.eu/index.php/thematic-areas/epidemics

[152] World Health Organization, "Vector-borne diseases". Available at www.who.int/news-room/fact-sheets/detail/vector-borne-diseases

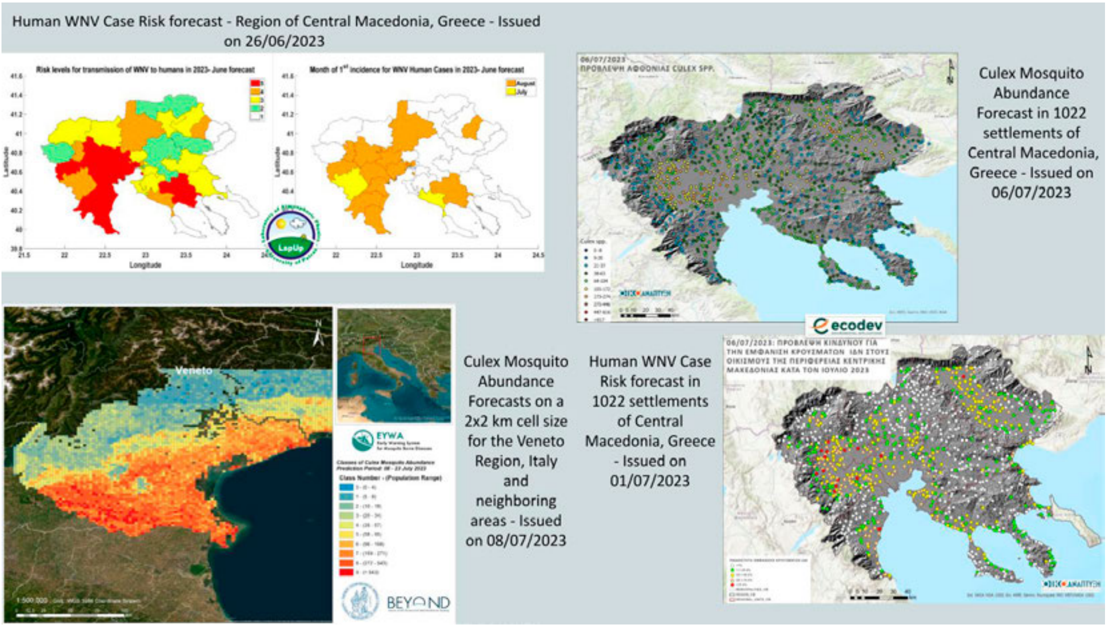
CASE STUDY *(continued)*

The technological novelty of EYWA lies in its efficient handling of multiple data sources such as entomological, epidemiological, Earth observation, crowd and ancillary geospatial data; along with dynamic and data driven models to generate knowledge on the abundance of mosquitoes and the transmission of pathogens. Thanks to data provided by Copernicus satellites and Copernicus Core Services, EYWA reliably depicts the dynamics of mosquito habitats and breeding sites. The system capitalizes on European investments in Earth observation and cloud-based data repositories and capacities (i.e. DIAS, GEOSS, NextGEOSS).

The EYWA models provide continuous operational predictions to inform on mosquito abundance and pathogen transmission risk on a weekly and monthly schedule working towards suggesting preventive and awareness- raising actions in the villages at risk. The system is expanding each year to new regions facing different climatic and socioeconomic conditions and the models are adapted at the end of each mosquito season based on user feedback. Figure 8.2 presents an example of the output of the predictive model used in the EYWA system.

[a] BEYOND. *Thematic Areas – Epidemics*. Available at: http://beyond-eocenter.eu/index.php/thematic-areas/epidemics

Figure 8.2. Output of the predictive models used in the EYWA system



Source: BEYOND Center of Earth Observation and Satellite Remote Sensing

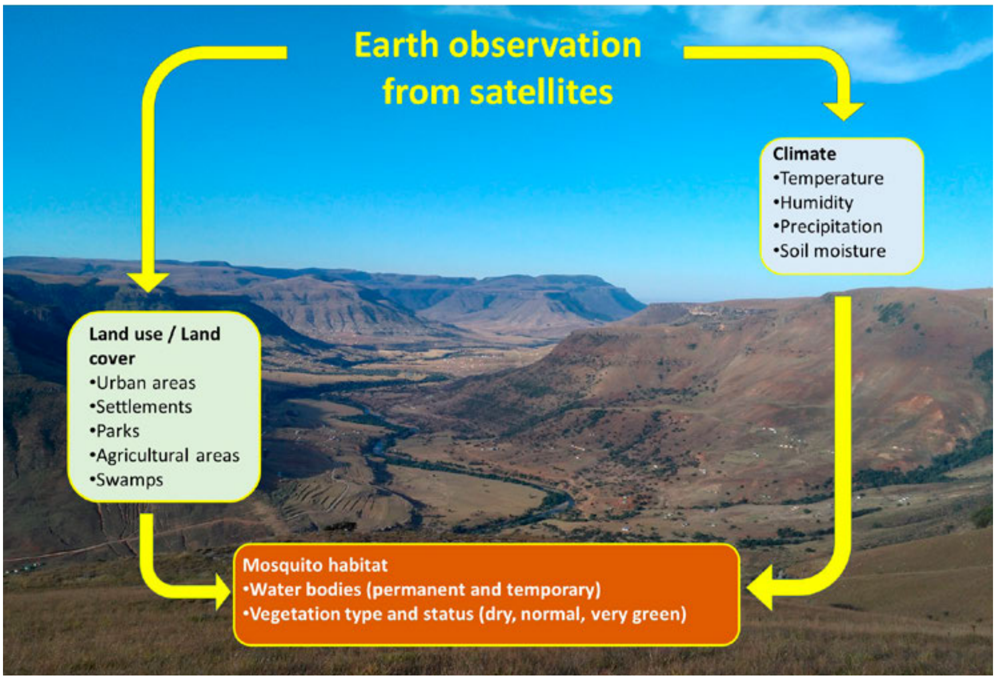
8.2.1 Malaria

Wimberly et al (2021),[153] state that satellite remote sensing provides a wealth of information about environmental factors that influence malaria transmission cycles and human populations at risk. Long-term observations facilitate analysis of climate–malaria relationships, and high-resolution data can be used to assess the effects of agriculture, urbanization, deforestation and water management on malaria. Furthermore, new sources of very-high-resolution satellite imagery and synthetic aperture radar data will increase the precision and frequency of observations.

Satellite remote sensing is now routinely used in malaria research to measure environmental conditions that influence mosquito populations, human vulnerability and malaria transmission cycles. These relationships provide the basis for risk maps that highlight locations with the highest malaria risk and early warning systems that forecast malaria outbreaks, based on lagged responses to environmental variation.

Satellite data can also be used to map buildings, estimate human population density and identify land-use practices that affect human exposure to mosquitoes. Figure 8.3 presents information regarding how satellite observations contribute to assessing the habitat of mosquitoes.

Figure 8.3 How satellite data provide information about malaria



Source: UN-SPIDER

Despite the potential, satellite observations are not routinely incorporated into malaria decision support, and there are few published studies focused on their operational use.

[153] Michael C. Wimberly, Kirsten M. de Beurs, and others, "Satellite Observations and Malaria: New Opportunities for Research and Applications". *Trends in Parasitology*, vol. 37, issue number 6 (June 2021). Available at https://doi.org/10.1016/j.pt.2021.03.003

CASE STUDY

Operational malaria forecasting: Ethiopia[a]

The Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment (EPIDEMIA) system was designed and implemented to integrate disease surveillance with environmental monitoring in support of operational malaria forecasting in the Amhara region of Ethiopia. The EPIDEMIA project encompassed 47 pilot woredas (districts) that were selected to encompass the most malaria-prone parts of the region.

The system integrated epidemiological data, uploaded weekly by the Amhara Regional Health Bureau, with remotely-sensed environmental data freely available from online archives.

Environmental variables were obtained from remotely-sensed Earth observation data products produced by NASA. To support the goals of conducting malaria early detection and early warning, products were selected that had global coverage, free access, high data quality and low latency (the delay between the times when raw data are collected and when processed data products are made available for use). Data on rainfall, temperature and various spectral indices of vegetation greenness and surface moisture were used, based on previous studies that demonstrated their potential for predicting malaria outbreaks in the Amhara region.

These products were used to calculate a variety of spectral indices related to the greenness and wetness of the Earth's surface, including NDVI, EVI, the Soil-Adjusted Vegetation Index and two forms of the Normalized Difference Water Index (NDWI).

Environmental data were acquired and processed automatically by the EASTWeb software program. Additional software was developed to implement a public health interface for data upload and download, to harmonize the epidemiological and environmental data into a unified database, to update automatically time series forecasting models and to generate formatted reports. Reporting features included district-level control charts and maps summarizing epidemiological indicators of emerging malaria outbreaks, environmental risk factors and forecasts of future malaria risk.

The woreda control charts highlighted an *early detection window* (the past six weeks) and an *early warning forecast window* (the upcoming four weeks) over which data and model outputs were summarized. Within each of these summary windows, the mean observed or forecasted incidence was classified as being above the mean outbreak threshold, between the mean threshold and the mean expected incidence, or below the mean expected incidence. The overall trend in malaria incidence was also classified as increasing, decreasing or stable for each summary window. To do this, the differences between the observed or forecasted malaria incidence and the outbreak detection threshold were calculated for each week.

The EPIDEMIA system has several similarities to online information systems that have previously been developed for malaria and other mosquito-borne diseases, but also has several unique characteristics. Although the value of integrating climatic information and other types of remotely-sensed data into online sharing portals has been widely acknowledged, most efforts at near-real-time data sharing have focused primarily on epidemiological surveillance.

EPIDEMIA is thus distinctive in that it facilitates the rapid acquisition and processing of malaria surveillance and environmental monitoring data to produce harmonized data sets for modelling. This novel system has enabled near-real-time malaria forecasting in the Amhara region.

The EPIDEMIA system has facilitated the integration of malaria surveillance data and environmental monitoring data to enable near-real-time malaria forecasts in the Amhara region of Ethiopia. As a result, it has been possible to disseminate malaria forecasts to public health partners for an extended period and engage end users in a continuous process of feedback and improvement. The development and implementation of EPIDEMIA have highlighted several

CASE STUDY *(continued)*

considerations for anyone wishing to build such a system. Critical points include the need to develop software tools and an enabling environment to provide timely harmonized epidemiological and environmental data, the importance of continual stakeholder input throughout design, implementation and operation of the system, and the need to be adaptable to changes in the input data.

[a] Christopher L. Merkord, Yi Liu, and others, "Integrating malaria surveillance with climate data for outbreak detection and forecasting: the EPIDEMIA system". *Malaria Journal*, vol.16, article number 89 (23 February 2017). Available at https://doi.org/10.1186/s12936-017-1735-x http://creativecommons.org/licenses/by/4.0/

8.3 Cholera

Cholera is an acute, waterborne infectious diarrheal illness caused by infection of the intestine with the toxigenic bacterium *Vibrio cholerae*.[154] Cholera affects 1.3 to 4 million people each year worldwide, with 21,000 to 143,000 reported fatalities. Outbreaks are devastating to affected communities. The key to support preparedness and public health response is the ability to forecast cholera outbreaks with sufficient lead time.

According to Ogata et al,[155] how *Vibrio cholerae* survives in the environment outside a human host is an important route of disease transmission. Thus, identifying the environmental and climate drivers of these pathogens is highly desirable.

In addition, environmentally favourable habitats for waterborne pathogens are expanding under climate change, and specifically, the habitat suitability of *Vibrio cholerae* is estimated to have increased by approximately 10 per cent globally, compared with a 1980s baseline. The distribution of *Vibrio cholerae* population and transmission routes of cholera disease has been shown to be influenced by extreme climate and weather events such as droughts, floods, and storm surges. [157]

An increasing number of human health and epidemiological studies are using a combination of in situ and remote-sensing data for monitoring, surveillance, forecast and risk mapping of pathogen occurrence and disease outbreaks. Although the *Vibrio cholerae* pathogens cannot be sensed directly by satellite sensors, remotely-sensed data can be used to infer their presence.[157]

There is growing research in the field of using satellite-derived data to identify areas where cholera outbreaks have the potential to occur, and satellite-based information on cholera may help support the Sustainable Development Goals and targets on Health (Goal 3), Water quality (Goal 6), Climate (Goal 13), and Life below water (Goal 14).

[154] United States, Centers for Disease Control and Prevention, *Cholera – Vibrio cholerae infection. General Information*. Available at www.cdc.gov/cholera/general/index.html.

[155] Tomomichi Ogata, Marie-Fanny Racault and others, "Climate Precursors of Satellite Water Marker Index for Spring Cholera Outbreak in Northern Bay of Bengal Coastal Regions". *International. Journal of Environmental Research and Public Health*, vol. 18. Issue number 19 (28 September 2021). Available at https://doi.org/10.3390/ijerph181910201 Creative Commons Attribution (CC BY) license https://creativecommons.org/licenses/by/4.0/.

Ocean-colour remote-sensing observations are increasingly used to map and forecast cholera disease outbreaks and the distribution of *Vibrio cholerae* in fresh, coastal and open-ocean systems. The ocean-colour data have been found to relate to the increase in phytoplankton that can be associated with an increase in zooplankton, which forms key environmental reservoirs of *Vibrio cholerae*, and reflect the intrusion of coastal waters carrying plankton laden with *Vibrio cholerae* into inland waters. Human infection may then be caused by drinking water and/or consuming seafood contaminated with pathogenic *Vibrio cholerae* bacteria. [156]

CASE STUDY

Satellite-measured radiance data used to investigate links between climate variability and cholera outbreaks[a]

Ogata et al identified a mechanistic link between climate variability and cholera, using the Satellite Water Marker (SWM) index in the Bengal Delta. This allowed cholera outbreaks to be predicted up to two seasons earlier. High values of the SWM index in autumn were associated with above-normal summer monsoon rainfalls over northern India. In turn, these correlated with the La Niña climate pattern that was traced back to the summer monsoon and previous spring seasons.

In addition, high-resolution daily rainfall data of the Indian Meteorological Department, gridded monthly sea surface temperature anomalies derived from OISST, and gridded monthly HadISST data were used.

The results from the study bear novel implications for developing outbreak-risk forecasts, demonstrating a crucial need to account for multi-decadal variations in climate interactions and underscoring the need to understand better how the south Asian summer monsoon responds to climate variability.

[a] Tomomichi Ogata, Marie-Fanny Racault, and others, "Climate Precursors of Satellite Water Marker Index for Spring Cholera Outbreak in Northern Bay of Bengal Coastal Regions". *International. Journal of Environmental Research and Public Health*, vol. 18. Issue number 19 (28 September 2021). Available at https://doi.org/10.3390/ijerph181910201 Creative Commons Attribution (CC BY) license https://creativecommons.org/licenses/by/4.0/

CASE STUDY

How satellite data, machine learning and essential climate variables can identify cholera risk

Campbell and others[a] investigated the use of satellite data and machine learning to identify cholera risk in India.

Surveillance data of cholera outbreaks at the district level in India over the period July 2009 to December 2019 were collected. Weekly cholera data is publicly available from the Integrated Disease Surveillance Programme of India. The weekly cholera data records were aggregated by month (based on the month of the outbreak "start date") and by district, based on the Level 2 administrative zones for India, provided in shapefile format by the Database of Global Administrative Areas. Cholera outbreaks were converted into a binary data format and the data were then used as an effective variable type for machine learning applications.

[156] Amy Marie Campbell, Marie-Fanny Racault and others, "Cholera Risk: A Machine Learning Approach Applied to Essential Climate Variables". *International. Journal of Environmental Research and Public Health*, vol. 17, issue number 24 (15 December 2020). Available at https://doi.org/10.3390/ijerph17249378 Creative Commons Attribution (CC BY) license http://creativecommons.org/licenses/by/4.0/.

CASE STUDY *(continued)*

A total of six Essential Climate Variables (ECV) data sets were obtained from the European Space Agency Climate Change Initiative programme, which provides climate-quality controlled data from Earth observation satellites.

In addition, the satellite altimetry data product, produced by Salto/Duacs and distributed by AVISO, was downloaded for the period 2016–2018 to complement the CCI Sea Level data available over the period 2010–2015. Finally, the ECV data of total precipitation of the European Reanalysis Interim synoptic monthly means were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). All data sets were extracted and prepared in NetCDF format for the period 2010–2018 and bounding box region located between 0–40° N and between 100–60° E.

When applied to the unseen test data for all coastal districts, the RF Model has an accuracy of 0.99, an F1 Score of 0.942 and a sensitivity score of 0.895, meaning 89.5 per cent of outbreaks were correctly identified. One occasion saw a false positive of an outbreak being predicted when there were none recorded.

The RF model was also tested on unseen data for 36 individual districts that contained reported outbreaks in the test data, to evaluate the spatial variation of model performance and its applicability to regions in India on a more localized scale. The model was able to correctly identify all of the outbreaks and non-outbreaks in districts that had multiple outbreaks in the test data.

The model showed promising results when tested on individual districts in coastal India, underlining its potential to perform accurately across a country with large climatological differences evident spatially. The model performed better in areas with outbreaks reported routinely or annually but was less effective in areas where there are fewer cholera outbreaks to both train and test the model. These findings suggest that the model would be more suited for detecting cholera outbreaks in endemic areas but might be less likely to detect more sporadic, epidemic cholera events. The latter are more likely to occur due to an import by a contaminated traveller, and/or following a natural disaster or civil disorder which would affect living conditions.

[a] Amy Marie Campbell, Marie-Fanny Racault and others, “Cholera Risk: A Machine Learning Approach Applied to Essential Climate Variables”. *International. Journal of Environmental Research and Public Health*, vol. 17, issue number 24 (15 December 2020). Available at https://doi.org/10.3390/ijerph17249378 Creative Commons Attribution (CC BY) license http://creativecommons.org/licenses/by/4.0/

Sargassum off the coast of Cancun, Mexico, near Puerto Aventuras, captured by Sentinel 2 on 7 July 2019

Image courtesy of ESA

Chapter 9.
Space technologies for other biological hazards

Biological hazards are of organic origin or conveyed by biological vectors, including pathogenic microorganisms, toxins and bioactive substances. Examples of biological hazards include bacteria, viruses or parasites, as well as venomous wildlife and insects, poisonous plants and mosquitoes carrying disease-causing agents.[157]

Biological hazards are a major source of risk that may result in emergencies and disasters. These hazards are usually the result of a natural occurrence but can also result from deliberate or accidental release. They cause significant loss of life, affect many thousands of people's health (chapter 8), have the potential for major economic losses through loss of livestock and crops, and may also cause damage and loss to the natural heritage, including to endangered fauna and flora.[158]

Satellite technology contributes to the monitoring of biological hazards, assessing the risk they pose and forecasting where hazards may occur. In the context of Earth observations, biological hazards, such as microorganisms and locusts, are incredibly small, and current satellite technology cannot distinguish them. However, Earth observation data can be analysed for proxies that indicate the presence of biological hazards and determine characteristics that are useful for early warning systems.

This chapter will address locust swarms and sargassum.

9.1 Locust swarms

The desert locust (*Schistocerca gregaria*) is the most destructive migratory pest in the world. Dense and highly mobile desert locust swarms can form in response to environmental stimuli. They are ravenous eaters that consume their own weight per day, targeting food crops and forage. Just a single square kilometre of swarm can contain up to 80 million adults, with the capacity to consume the same amount of food in one day as 35,000 people. Large swarms pose a major threat to food security and rural livelihoods.[159]

[157] United Nations Office for Disaster Risk Reduction, "Hazard Definition & Classification Review: Technical Report". Available at www.irdrinternational.org/knowledge_pool/publications/858

[158] United Nations Office for Disaster Risk Reduction, "Chapter 5. Biological Hazards Risk Assessment". In *Words into Action Guidelines: National Disaster Risk Assessment Hazard Specific Risk Assessment*. Available at www.undrr.org/publication/biological-hazards-and-risk-assessment

[159] Food and Agricultural Organization, "Desert Locust". Available at www.fao.org/locusts/en

Desert locust plagues can severely affect yields and therefore food security. The high mobility of these insects, their rapid reproduction and the amount of vegetation they can destroy on a daily basis make desert locust plagues one of the most dangerous disasters in the semi-arid regions of Africa. In 2020, the most severe desert locust outbreak in many decades occurred in Eastern Africa and the Middle East, bringing the topic into focus once more.[160,161,162]

The desert locust has a lifespan of up to five months. The Middle East and the northern half of Africa are the habitable zones for desert locusts. The insect thrives on lush vegetation-patches for feeding and shelter, especially in critical development stages after hatching. Throughout the various stages of its life cycle the desert locust is very dependent on favourable environmental conditions – most of which can be monitored via Earth observation. Their speed of development, for example, is directly related to soil temperature. The higher the temperature, the more rapidly their eggs develop.[163]

Although outbreaks are common, only a few lead to upsurges, or swarms. Similarly, few swarms lead to plagues. The last major plague was in 1986–1989 and the last major upsurge, or regional plague, was in 2003–2005. Upsurges and plagues do not occur overnight; they take many months to develop. During plagues, desert locusts may spread over an area of some 29 million km2, extending over or into parts of some 60 countries.[164]

Locust swarms cannot be detected by satellite, however favourable conditions for locust breeding and feeding can be detected, and it is these data that are used to identify potential sites at risk from locust infestation. Vegetation cover and soil moisture are the two main parameters for estimating the suitability of desert locust habitats. While NDVI-based vegetation maps can help desert locust managers prioritize surveys and guide teams to potential infestations, the maps might not arrive early enough for planning purposes. On the other hand, soil moisture products should allow desert locust managers to plan surveys earlier because soil moisture precedes vegetation growth.

Soil moisture is a very good indicator of desert locust reproduction potential because locust females select moist sandy areas to lay their eggs. While rainfall imagery can be used to estimate soil moisture, it does not account for rain that may fall far from the breeding area and moves through wadis to reach the breeding area. In this way, soil moisture can be a more precise indicator of where reproduction may occur.

Applications for remotely-sensed data and GIS for desert locust related studies are manifold. Possible breeding grounds, for example, can be located by analysing rainfall, areas with lush vegetation, which are necessary for locust development, or soil moisture, which is needed for successful egg development. For example, Gómez et al. used ESA soil moisture data sets for various time steps to detect regions where locusts were breeding within their study area (Mauretania).[165] Damaged areas can also be detected, for example by tracking vegetation indices before and after an outbreak. Ji et al. (2004) used MODIS data to monitor outbreaks of oriental migratory locusts in China using a simple approach. In their application, two MODIS scenes were taken, one before damages were

[160] Food and Agricultural Organization, "Desert Locust Bulletin Number 498", 4 April 2020. Available at www.fao.org/emergencies/resources/documents/resources-detail/en/c/1270288/ (accessed 31. December 2020).

[161] Food and Agricultural Organization, "Global Information and Early Warning System on Food and Agriculture (GIEWS); Country Brief on Kenya". Available at www.fao.org/giews/countrybrief/country.jsp?code=KEN

[162] Food and Agricultural Organization, Global Information and Early Warning System on Food and Agriculture (GIEWS), Country Brief on Ethiopia. Available at www.fao.org/giews/countrybrief/country.jsp?code=ETH

[163] P. M. Symmons and Keith. Cressman. Desert Locust Guidelines. 1: Biology and behaviour. Available at www.researchgate.net/profile/Keith-Cressman/publication/265217762_Desert_Locust_Guidelines_1_Biology_and_Behaviour/links/563b3ea808ae45b5d285c7fe/Desert-Locust-Guidelines-1-Biology-and-Behaviour.pdf

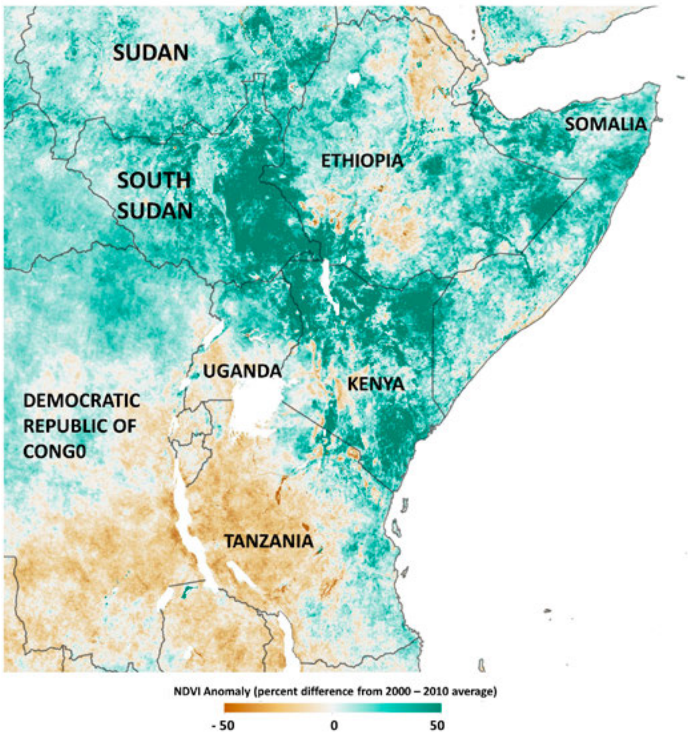
[164] World Meteorological Organization and Food and Agricultural Organization, "Weather and Desert Locusts". WMO publication number 1175. Available at https://library.wmo.int/doc_num.php?explnum_id=3213

[165] Diego Gómez, Pablo Salvador, and others, "Machine learning approach to locate desert locust breeding areas based on ESA CCI soil moisture", *Journal of Applied Remote Sensing*, vol. 12 (July 2018).

caused and one immediately after the damage reached its maximum. NDVI was calculated for both scenarios. Pixels were sorted into one of four damage classes ranging from "no damage" to "heavy". The authors conducted a field survey to compare the results based on NDVI with ground truth. The study concludes that NDVI-changes can function as a clear indicator of locust damage.[166] Geng et al. observed the 2020 desert locust outbreak for six different countries. The authors used all available MODIS data (2000 to June 2020) in combination with land cover and rainfall data. Using these parameters, seasonal, periodic patterns were analysed for different land cover types. Changes from these patterns were attributed to locust damage.[167] Figure 9.1 shows a comparison of the NDVI for Eastern Africa for the period between December 15 2019, and March 15 2020, compared to the same months averaged over 2000–2001.

Figure 9.1 NASA Normalized Difference Vegetation Index (NDVI) eastern Africa between 15 December 2019 and 15 March 2020, compared to the same months averaged over 2000–2001

Derived from data collected by MODIS on the Terra satellite. NDVI is used to identify potential feeding, and breeding, areas for locusts



Source: NASA

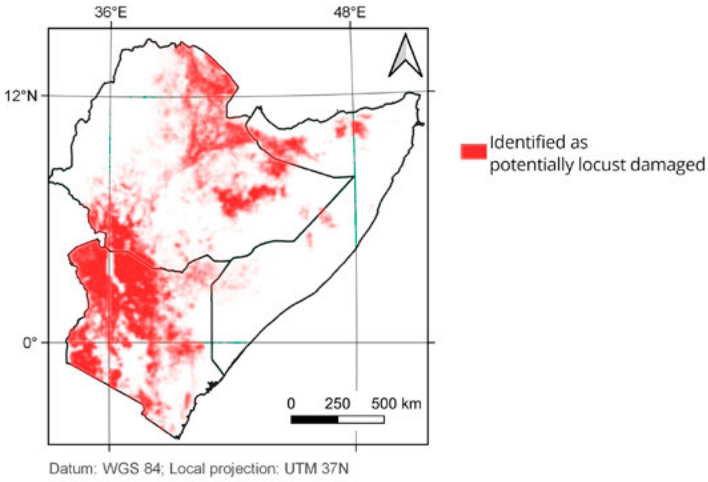
Overall, remote sensing and Earth observation can support the tracking and monitoring of locust activity throughout most stages of the disaster management cycle – a weakness being the impossibility of identifying the swarms themselves with optical satellite data, even when using very high-resolution data. The analysis of proxy-parameters,

[166] R. Ji, B.-Y. Xie, and others, "Use of MODIS data to monitor the oriental migratory locust plague", *Agriculture, ecosystems & environment*, vol. 104, issue number 3 (December 2004), pp. 615–620. Available at www.sciencedirect.com/science/article/abs/pii/S0167880904001008.

[167] Yun Geng, Yingving Dong, and others, "Desert locust plague monitoring using time series satellite data", *International Journal of Precision Agricultural Aviation*, vol. 3, issue number 4 (2020).

for example, vegetation indices, and their behaviour throughout time series, is therefore required.[168, 169] Figure 9.2 shows an example of a map of locust damaged areas at the end of the year 2020 based on remote-sensing analyses. The map was elaborated by experts from the Centre for Remote Sensing of Land Surfaces of the University of Bonn.

Figure 9.2 Example of a map on locust damaged areas based on remote-sensing analyses (Ethiopia, Kenya, Somalia 2020)



Source: ZFL, University of Bonn

CASE STUDY

The Locust Hub Soil Moisture Service[a]

The Locust Hub Soil Moisture Service was developed by Lobelia Earth for the global Locust Watch: Desert Locust early warning system. Locust Watch provides a service to monitor the worldwide locust situation and keep affected countries and donors informed of expected developments. It is operated by the Desert Locust Information Service of FAO.

The Locust Hub Soil Moisture Service is a new online and mobile phone viewer to explore soil moisture in desert locust breeding areas in Africa, the Near East and South-West Asia.

The Locust Hub Soil Moisture Viewer is a large-scale operational service that visualizes the soil moisture data at 1 km resolution. The service is systematically updated every 10 days. It offers a high-resolution time series of the previous three months, equivalent to the length of one Desert Locust generation.

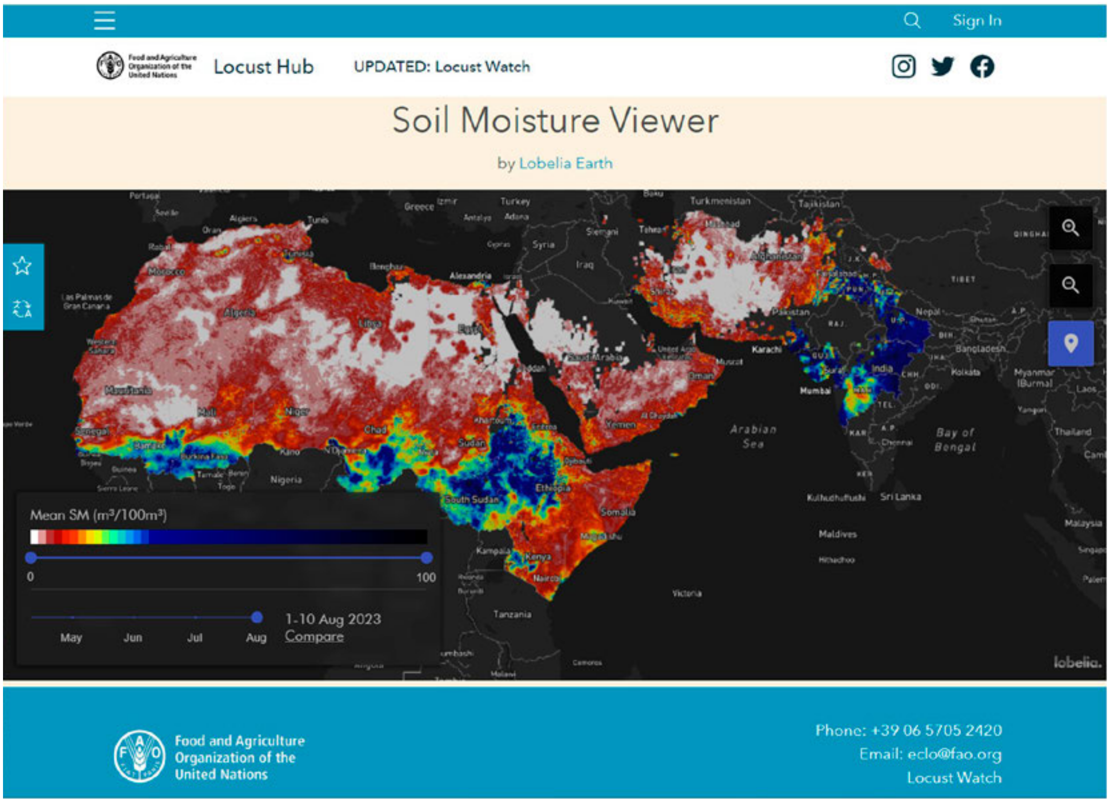
The 1-km resolution soil moisture is based on the application of DISPATCH disaggregation methodology to the coarser resolution products obtained from the SMAP satellite mission. The disaggregation is allowed by the relationship existing between the soil evaporation efficiency, defined as the ratio of actual to potential evaporation, and the surface soil moisture. Figure 9.3 presents an example of a map of the soil moisture viewer developed by Lobelia Earth for FAO.

[a] Food and Agriculture Organization, *The Locust Hub Soil Moisture Service*. Available at https://locust-hub-hqfao.hub.arcgis.com/pages/lobelia-viewer.

[168] Keith Cressman, "The Use of New Technologies in Desert Locust Early Warning, Outlooks on Pest Management", *Outlooks on Pest Management*, vol. 19 (April 2008), pp. 55–59. Available at: www.researchgate.net/publication/233516616_The_Use_of_New_Technologies_in_Desert_Locust_Early_Warning.

[169] Alexandre V. Latchininsky, "Locusts and remote sensing: a review", *Journal of Applied Remote Sensing*, vol. 7, issue number 1 (January 2013). Available at: www.researchgate.net/publication/258794835_Locusts_and_remote_sensing_A_review.

Figure 9.3 Soil Moisture Viewer by Lobelia Earth



Source: FAO/Lobelia Earth

CASE STUDY

Mitigating locust infestations in Algeria and Libya with space data[a]

The Algerian Space Agency (ASAL) was established in 2002 and implements national policies concerning the promotion and development of the use of space for technological, scientific and practical applications. The Department on Major Risks and Geo-environment in the Space Applications Centre deals with the management and the follow-up of major disasters in Algeria using space-based information, thus supporting national disaster management and civil protection agencies, including locust infestations.

In January 2012 the locust activity in the Wilaya d'Illizi region in south-east Algeria had significantly increased with several swarms coming from source regions in south-west Libya and south-east Algeria. Consequently, ASAL supported the National Institute for the Protection of the Vegetation (INPV) by creating a map indicating the risk zones for the region, analysing the ecological conditions for the migratory locust for the period January to April 2012.

Medium resolution satellite imagery was made available by the Disaster Monitoring Constellation and the Regional Centre for Mapping of Resources for Development which facilitated the tasking of the United States-satellite EO-1. Several 22-metre resolution images were analysed to precisely identify zones with high chlorophyll levels. High chlorophyll levels indicate favourable conditions for the locust to reproduce thus representing a high risk for the locust infestation to increase.

CASE STUDY *(continued)*

Thirty-nine high potential reproduction zones, spread over 330,000 km^2, were identified for the period January through April 2012, namely along the riverbeds (Oueds) in Wilaya d'Illizi and in the south-west of Libya.

The analysis was made available to INPV to enable prevention actions in Algeria and shared with FAO, which closely monitors the global Desert Locust situation 24/7 and provides forecasts, early warning and alerts on the timing, scale and location of invasions and breeding through its global Desert Locust Information Service.

[a] UN-SPIDER Programme, "Knowledge Portal Interview: Mitigating locust infestations in Algeria and Libya with space data". Available at https://un-spider.org/interview-mitigating-locust-infestations-algeria-and-libya-space-data

9.2 Sargassum

Sargassum is a genus of large brown algae that includes over 300 species. Two prevalent species in the Atlantic *Sargassum natans* and *Sargassum fluitans*, are found in free-floating mats, held afloat by gas-filled bladders. The floating sargassum provides food and protection for a range of marine wildlife, including fish, mammals, marine birds and crabs. It serves as a critical habitat for threatened loggerhead sea turtles and as a nursery area for a variety of commercially important fish.[170]

Once confined to the Sargasso Sea, recent studies suggest that changing wind patterns allowed sargassum to proliferate across the tropical Atlantic.[171] Thousands of tons of sargassum end up on beaches in the Caribbean, Americas and West Africa. It releases gas which attracts flies, deters tourists and causes respiratory problems. [172] Figure 9.4 presents a satellite image of sargassum as captured with the Sentinel 2 satellite on 1 April 2023 off the west coast of the island of Guadeloupe.

In the Caribbean alone, over 22 million metric tons of the seaweed arrives each year, clogging coral reefs, affecting the ecosystem, impeding the fishery community and becoming increasingly irritating to the tourism sector. Removal and containment efforts are often expensive, posing a health hazard to humans and puts marine life at risk. In 2018, the sargassum clean-up reportedly cost the Caribbean approximately US$120 million.[174]

Decomposing sargassum generates hydrogen sulphide gas. In small amounts and in open areas, it presents an annoying sulphurous odour. However, in quantities seen in 2018 and 2022 on the beaches of Mexico, scientists say it can be dangerous to workers with respiratory problems as they work to clear the sargussum.[173]

[170] Sargassum Information Hub. "What is Sargassum?". Available at https://sargassumhub.org/about-sargassum.

[171] Elizabeth M. Johns, Rick Lumpkin, and others, "The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event". *Progress in Oceanography*, vol. 182. (March 2020). Available at https://doi.org/10.1016/j.pocean.2020.102269.

[172] Interamerican Development Bank, "Turning Trash into Treasure: Tackling Sargassum in Jamaica". Available at www.iadb.org/en/improvinglives/turning-trash-treasure-tackling-sargassum-jamaica.

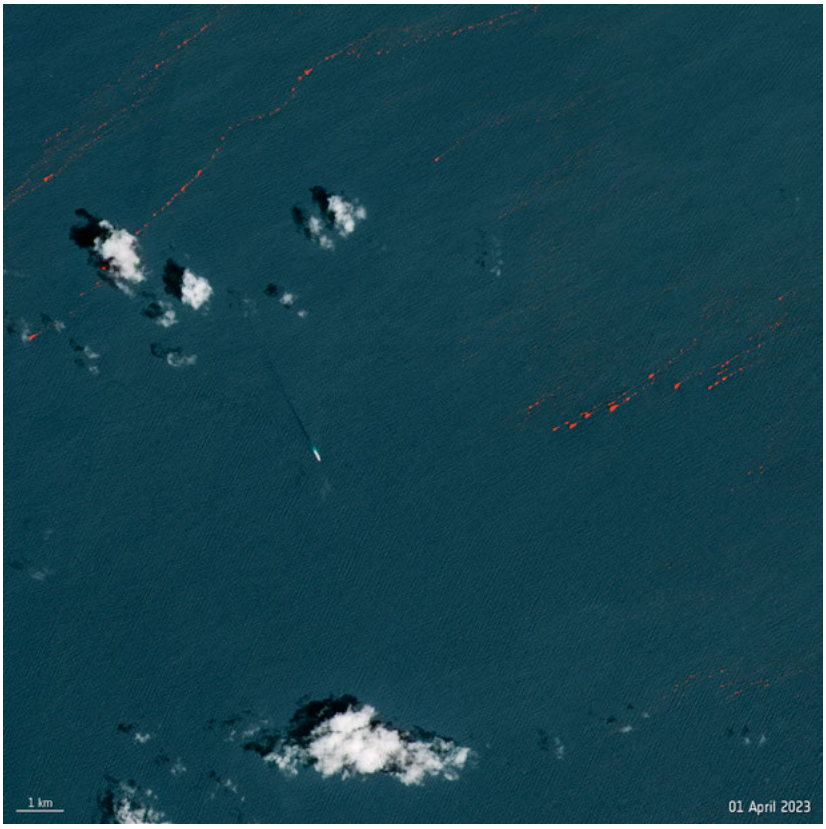
[173] Saragssum Monitoring. "Mexico: On Mexico's Caribbean coast, mountains of seaweed grow". Available at https://sargassummonitoring.com/2022/08/31/mexico-on-mexicos-caribbean-coast-mountains-of-seaweed-grow.

Sargassum holds a chlorophyll pigment that reflects infrared light, making it easy to detect with satellite imagery, but with coarse spatial resolution and low-revisit frequency, it has been challenging for local management to monitor when, where and how much algae will arrive on the beach.

Researchers from the University of Southern Florida and Planet have investigated if Planet's Dove satellites, with their daily imaging capabilities and 3-metre resolution, offer enough data to support a deep learning computer model to predict sargassum events. The model results revealed two major sargassum inundation events on Miami beach and Cancun beach that were consistent with local reports. With the availability of 3 m resolution PlanetScope/Dove and PlanetScope/SuperDove data around the globe, the findings suggested that it is possible to monitor dynamic inundation events of Sargassum but also other macroalgae in many other regions.[174]

Figure 9.4 Sargassum as captured with Sentinel 2 on 1 April 2023 off the west coast of the island of Guadeloupe

The sargassum is displayed in bright red



Source: ESA

In addition, the initiative entitled Teleconnected SARgassum risks across the Atlantic: building capacity for TRansformational Adaptation in the Caribbean and West Africa (SARTRAC) is identifying new transformational

[174] Planet, "Monitoring Sargassum on Beaches And In Nearshore Waters Using PlanetScope Observations". Available at www.planet.com/pulse/publications/monitoring-sargassum-on-beaches-and-in-nearshore-waters-using-planetscope-observations.

developmental opportunities that build resilience equitably, for the poorest people affected by mass algal blooms of sargassum seaweed in the tropical Atlantic basin. Drawing on satellite imagery to detect and monitor sargassum in the tropical Atlantic, SARTRAC is aiming to co-develop a sargassum monitoring and dissemination system with stakeholders, providing information on sargassum strandings, developing an early-warning system for the Atlantic and then transferring the development for use in Ghana.[175]

CASE STUDY

SAMtool: sargassum detection by CLS [a]

CLS, a subsidiary of the French Space Agency (CNES) and CNP, has operated as a worldwide company and pioneer provider of monitoring and surveillance solutions for the Earth since 1986. Its mission is to deploy innovative satellite-based monitoring solutions to understand and protect the planet, and to manage its resources sustainably.[b]

Since 2011, huge sargassum mass stranding has occurred in the wider Caribbean region. Since that date, CLS has been working on an operational service using radar and optical satellite sensors to detect sargassum and predict its drift.

In 2018, with the backing of the European Space Agency, CLS and its partners worked with a group of 40+ local users to design and validate the service that is today known as SAMtool.

SAMtool is a key operational tool to help the daily monitoring of the sargassum situation over the Caribbean area: raising awareness of the upcoming sargassum influx and preparing the mitigation plan in advance to reduce the devastating effects of sargassum stranding on local economies; and preparing and supporting timely sargassum collection operations.

The SAMtool offers daily detection of sargassum at 300 m and 20 m resolution, combining state-of-the-art satellite data from seven optical sensors and SAR sensors. Detection is based on a unique combination of six Earth observation ocean colour satellite instruments (MODIS-Aqua, Sentinel 3A and 3B at 300 m resolution, Sentinel 2A and 2B, Landsat-8 at 20 m resolution). To complement detection at night and independent of the cloud coverage, CLS also offers high-resolution satellite radar expertise.

The SAMtool uses a proven operational drift model for predicting sargassum landing up to five days ahead. The model used in SAMtool combines surface current and wind models with sargassum detections to predict where landings are likely to occur.

[a] Datastore, "SAMtool. Sargassum Detection". Available at https://datastore.cls.fr/products/samtool-sargassum-detection.

[b] Datastore, "CLS, world recognized expert in satellite data and services". Available at https://datastore.cls.fr/why-choose-cls.

[175] Teleconnected SARgassum risks across the Atlantic: building capacity for TRansformational Adaptation in the Caribbean and West Africa (SARTRAC), "Sargassum Early Warning System". Available at www.sartrac.org/work-areas/sargassum-early-warning-system

A forest fire captured by the Landsat 9 satellite in north-eastern Argentina in February 2023

Image courtesy of NASA

Chapter 10.
Space technologies for environmental hazards

Environmental hazards can cause widespread harm to humans and the physical environment and arise through the degradation of natural systems, such as the deterioration of air and water quality, land and soil degradation, and loss of biodiversity. Degradation can be a very gradual process, and hard to discern on a day-to-day basis, or it can be very rapid, with sudden contamination and destruction of the environment from hazards such as wildfire.

Satellite technologies contribute to monitoring actual and potential degradation over time, allowing disaster management practitioners to monitor how the risk of environment hazards is changing, which in turn can be used to inform the risk picture for early warning services for a range of hazards.

10.1 Wildfires

A wildfire is an unplanned fire that burns in a natural area such as a forest, a grassland or a prairie; it can happen anywhere at any time. Wildfires are often caused by human activity or triggered by a natural phenomenon, such as lightning. In 50 per cent of wildfires recorded, it is not known how they started.[176]

The risk of wildfires increases in extremely dry conditions, such as drought, and during high winds. Wildfires can disrupt transportation, communications, power and gas services, and water supply. They also lead to a deterioration of air quality, and loss of human life, property, crops, resources and animals. In Europe, the losses caused by wildfire are estimated at 2.7 billion Euro every year.[177]

The size and frequency of wildfires are growing due to climate change. Hotter and drier conditions are drying out ecosystems and increasing the risk of wildfires. Wildfires also simultaneously impact weather and the climate by releasing large quantities of carbon dioxide, carbon monoxide and fine particulate matter into the atmosphere. The resulting air pollution can cause a range of health issues, including respiratory and cardiovascular problems.

[176] World Health Organization, "Wildfires". Available at www.who.int/health-topics/wildfires.

[177] European Commission, Copernicus Programme, "The European Forest Fire Information System (EFFIS)". Available at https://emergency.copernicus.eu/mapping/sites/default/files/files/EMS_FireEWS_A0_v2.pdf.

Beyond fatalities, wildfires and the resulting smoke and ashes, can cause:

- Burns and injuries
- Eye, nose, throat and lung irritation
- Decreased lung function, including coughing and wheezing
- Pulmonary inflammation, bronchitis, exacerbations of asthma and other lung diseases
- Exacerbation of cardiovascular diseases, such as heart failure

Wildfires also release significant amounts of mercury into the air, which can lead to impairment of speech, hearing and walking, and muscle weakness and vision problems for people of all ages.[178]

Wildfire behaviour is complex and can change suddenly, making early warnings essential for triggering prevention and mitigation measures, such as evacuation. For early warning systems to be effective, there are four stages that need to operate effectively:

1. Monitoring and assessing the potential for wildfires to start and take hold, if a source of ignition is applied – ignition risk indices
2. Identifying fire hotspots early
3. Using forecast systems to identify the potential propagation of the flame front[178]
4. Communicating wildfire early warnings to those in need

Satellite technologies contribute to each of these warning stages, through Earth observation data for monitoring and forecasting weather conditions, assessing the geographic layout of the landscape, assessing ground conditions, identifying the location of critical infrastructure and homes, and satellite telecommunication capability for the rapid dissemination of environmental data and warnings. As with other hazards, satellites can provide data from remote areas that are inaccessible to other, predominantly ground-based, technologies, which immediately makes satellite-derived data valuable to wildfire monitoring and prediction.

Fire detection algorithms compare the temperature of a potential fire with the temperature of the land around it. If the difference is over a given threshold, it confirms the "hotspot" as an active wildfire. But if the fire is too small to detect, due to the spatial resolution of the sensor, the satellite will not be able to detect it.[179]

The MODIS sensor on board Terra and Aqua satellites detects active fires by comparing temperature to neighbouring pixels but detection is dependent on the severity and extent of the fire. Likewise, VIIRS, on board the NASA/NOAA Suomi NPP, detects active forest fires based on thermal anomalies. Because of its finer spatial resolution (375 metres), it can detect smaller fires on the ground with more accuracy.[181]

[178] CAE Innovation for a Safer World, "Wildfire monitoring and early warning systems". Available at www.cae.it/eng/solutions/wildfire-warning-system/wildfire-monitoring-and-early-warning-systems-sl-31.htm.

[179] GISGeography, "3 Wildfire Maps: How the Track Real-Time Fires around the World". Available at https://gisgeography.com/wildfire-maps-real-time.

CASE STUDY

The Worldview and Fire Information for Resource Management System applications of NASA

The Worldview[a] application provides active fire maps and live imagery maps. This means that forest fires and (coarse) imagery can be seen as they are collected in near-real time The WorldView service offers 18 data layers for wildfire, including fires and thermal anomalies data from a range of satellites: the amalgamated Aqua and Terra/MODIS, NOAA-20/VIIRS, Suomi NPP/VIIRS and Terra/MODIS. Figure 10.1 displays hotspots detected on 26 to 27 August 2023.

The Fire Information for Resource Management System (FIRMS)[b] is a feature-rich interactive fire map. This web map visualizes daily global fire locations within 3 hours of satellite overpass from both MODIS and VIIRS satellites.

[a] United States, National Aeronautics and Space Administration, *Worldview*. Available at https://worldview.earthdata.nasa.gov.

[b] United States, National Aeronautics and Space Administration, *Fire Information for Resource Management Systems* (FIRMS). Available at https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@0.0,0.0,3z.

Figure 10.1 NASA FIRMS geoviewer displaying hotspots detected on 26 and 27 August 2023

Source: NASA FIRMS

CASE STUDY

Global Wildfire Information System[a]

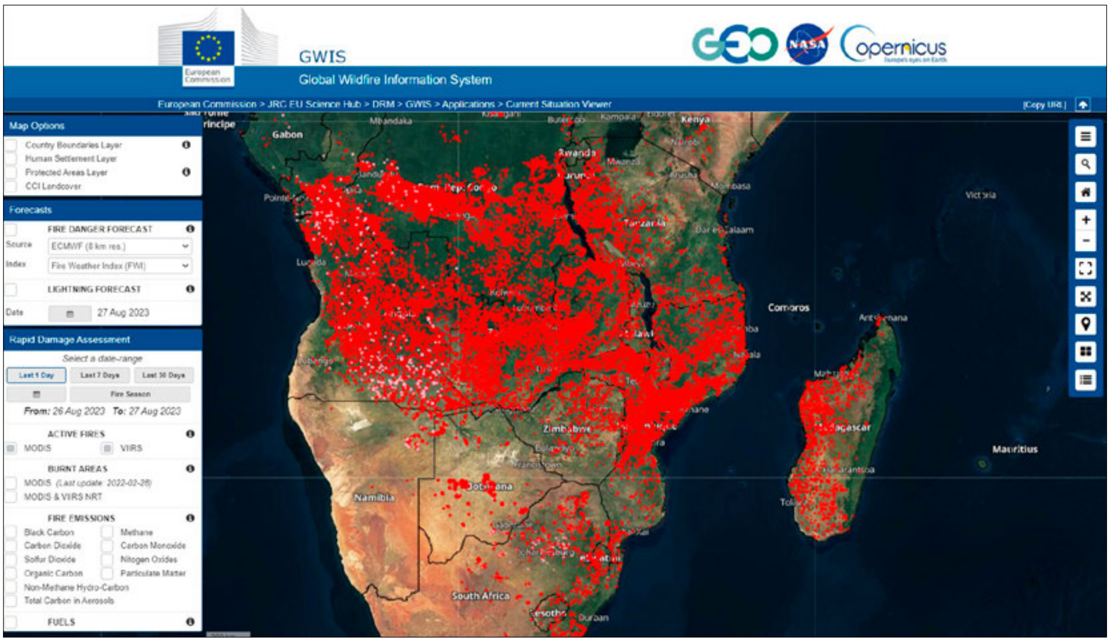
The Global Wildfire Information System (GWIS) is a joint initiative of the Group on Earth Observations (GEO), NASA and the Copernicus Programme. It brings together existing information sources at regional and national level to provide a comprehensive view and evaluation of fire regimes and fire effects at global level and to provide tools to support operational wildfire management from national to global scales.

GWIS builds on the ongoing activities of the European Forest Fire Information System (EFFIS), the Global Terrestrial Observing System, the Global Observation for Forest Cover and Land Dynamics, the GOFC Fire Implementation Team, and the associated regional networks, complementing existing activities that are ongoing around the world with respect to wildfire information gathering. The development of GWIS is supported by partner organizations and space agencies. Support to GWIS is provided by NASA through its GEO-GWIS activities in the ROSES programme.

GWIS offers five applications that provide a range of data layers for monitoring wildfires and assessing fire risk: current situation viewer, current statistics portal, country profile, long-term fire weather forecast, and data and services. GWIS uses active fire detection from NASA FIRMS, MODIS and VIIRS, which is also used to calculate burned areas. Figure 10.2 shows a map of the GWIS geoviewer displaying hotspots extracted from MODIS and VIIRS, in central and southern Africa on 27 August 2023.

[a] More information in GWIS is available at https://gwis.jrc.ec.europa.eu

Figure 10.2 GWIS geoviewer showing the fire danger for central and southern Africa on 27 August 2023



Source: GWIS

CASE STUDY

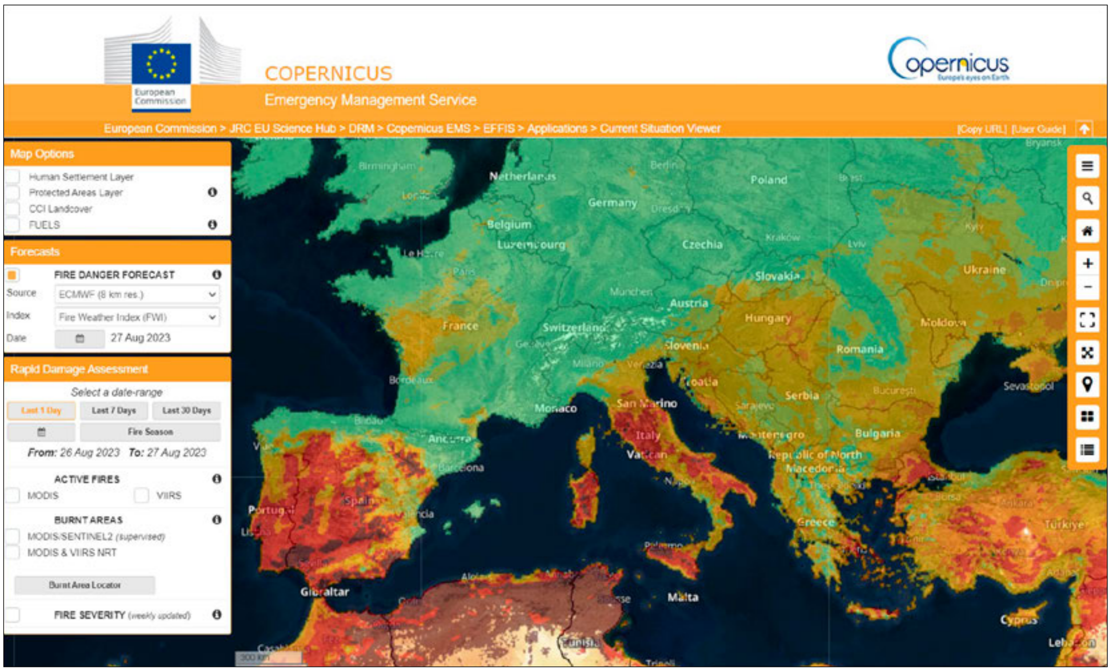
The European Forest Fire Information System[a]

The European Forest Fire Information System (EFFIS) uses MODIS and VIIRS to track thermal anomalies which are visualized through the Copernicus EMS. The EMS situation viewer displays active fires, burned areas with a polygon extent, and fuel maps. The platform also provides fire danger forecasts using the Canadian Forest Fire Weather Index System as the method to assess the fire danger level in a harmonized way throughout Europe.[b] Figure 10.3 shows the Copernicus EFFIS fire danger forecast for southern Europe, Türkiye and a region of northern Africa on 27 August 2023.

[a] European Commission, Copernicus Programme, "European Forest Fire Information System EFFIS". Available at: https://effis.jrc.ec.europa.eu

[b] European Commission, Copernicus Programme, "Fire Danger Forecast". Available at https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast

Figure 10.3 Copernicus EFFIS fire danger forecast for 27 August 2023, covering southern Europe, Türkiye and a region of northern Africa visualized through the Copernicus Emergency Management System



Source: EFFIS, Copernicus

CASE STUDY

Forest fire early warning system in Mexico[a]

Like many other countries of the world, Mexico suffers the impacts of forest fires. According to the National Forestry Commission of Mexico (CONAFOR), the average number of forest fires per year is in the order of 7,070. The average number of hectares per year affected is in the order of 260,000 hectares.[b]

Advances in Earth observation technologies allowed the National Commission on the Knowledge and Use of Biodiversity (CONABIO) to develop a monitoring system and an early warning system for forest fires (SATIF) using information on hotspots. SATIF is operated in coordination with the Danger Prediction System of CONAFOR in Mexico and provides geospatial information derived from near-real-time satellite observations. SATIF makes use of the MODIS imagery acquired by the Terra and Aqua satellites, visible infrared imaging radiometer (VIIRS) imagery form the Suomi-NPP and JPSS/NOAA20 satellites, and advanced very high-resolution radiometer (AVHRR) imagery from the NOAA18 and NOAA19 satellites. Figure 10.4 presents an example of the SATIF web page displaying vegetation anomalies and hotspots 27 August 2023.

SATIF generates a model of dead fuel based on the percentage of humidity of the vegetal material deposited on the ground. The model is based on the combination of data from the previous day regarding humidity, temperature and precipitation. This is done using daily satellite imagery from the MODIS sensor. In addition, SATIF generates an index regarding the anomaly of the vegetation derived from a time series analysis of NDVI. NDVI is updated every 10 days and has a time series in excess of 10 years.

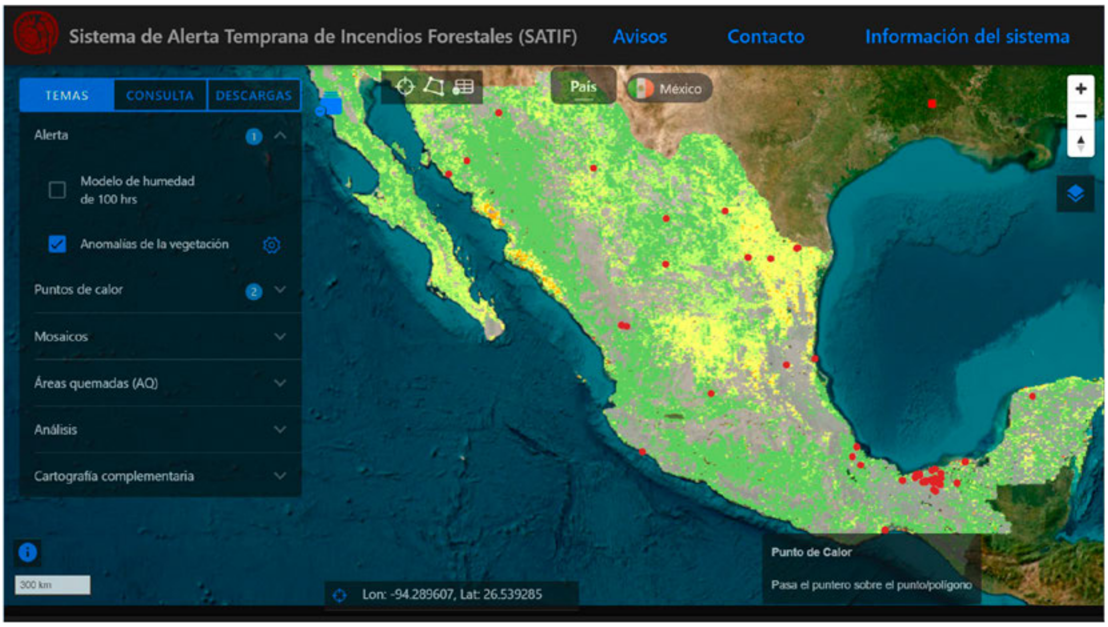
The combination of data on the humidity of combustible material, the index of vegetation anomaly and on hotspots provides information on geographic areas which may be dry enough to propagate fires and is used as a warning.

Information generated by SATIF is displayed on the SATIF web pages (http://incendios-beta.conabio.gob.mx) and disseminated via emails to users, Web Map Service (WMS), Web Feature Service (WFS) and File Transfer Protocol (FTP). SATIF also reports information on the detection of forest fires within 30 minutes of the reception of a MODIS or VIIRS image and is completed with data on hotspots generated with ABI-GOES, as well as information on burn severity generated by processing Sentinel 2 satellite imagery with Google Earth Engine.

[a] Mexico, National Commission for the Knowledge and Use of Biodiversity, *Sistema de Alerta Temprana de Incendios Forestales (SATIF)*. Available at http://incendios-beta.conabio.gob.mx.

[b] Mexico, National Forestry Commission, *Reporte Semanal Nacional de Incendios Forestales*. Available at www.gob.mx/cms/uploads/attachment/file/604834/Cierre_de_la_Temporada_2020.PDF.

Figure 10.4 SATIF web page displaying vegetation anomalies and hotspots for 27 August 2023



Source: SATIF, CONABIO

CASE STUDY

Fighting wildfires with satellite data in the United Republic of Tanzania[a]

Just 10 years ago, authorities in the United Republic of Tanzania largely relied on networks of lookout towers to observe and manage fires across the country's vast landscapes. Today, satellite data delivered through the EUMETCast multi-service dissemination system are helping local communities vastly improve fire management and suppression strategies.

The country's Ministry of Natural Resources and Tourism reports that, despite growing challenges, average burned areas caused by wildfires have been reduced by around 75 per cent during the past decade.

Since 2011, these efforts have been supported by near-real-time products and services such as weather and fire danger indices, which make use of meteorological satellite data distributed through EUMETCast. Fire monitoring experts in the country explain that observing, tackling and responding to wildfires is a hugely complex undertaking, requiring the combined efforts of a wide range of professionals working in forest and land management.

When wildfires in the United Republic of Tanzania were predominantly monitored using networks of lookout towers, early fire outbreaks in the dense and mainly inaccessible forests frequently went unnoticed. By the time they were spotted, it was often too late to mount an effective response.

However in July 2011, a satellite receiving station installed in Dar es Salaam, was opened as part of the European Union African Monitoring of Environment for Sustainable Development. It was maintained and improved during the European Union-funded Monitoring for Environment and Security in Africa programme. The initiative was supported by data,

CASE STUDY *(continued)*

infrastructure, technology, products and services provided by EUMETSAT. Figure 10.5 displays an image of wildfires at Mount Kilimanjaro, United Republic of Tanzania, as captured on 15 October 2020.

In the United Republic of Tanzania, fire lookouts remain an important means of monitoring fires; lookouts know the terrain and can help direct firefighting resources. Furthermore, the information delivered daily by remote-sensing technologies can help authorities predict, assess and respond to the impacts of wildfires.

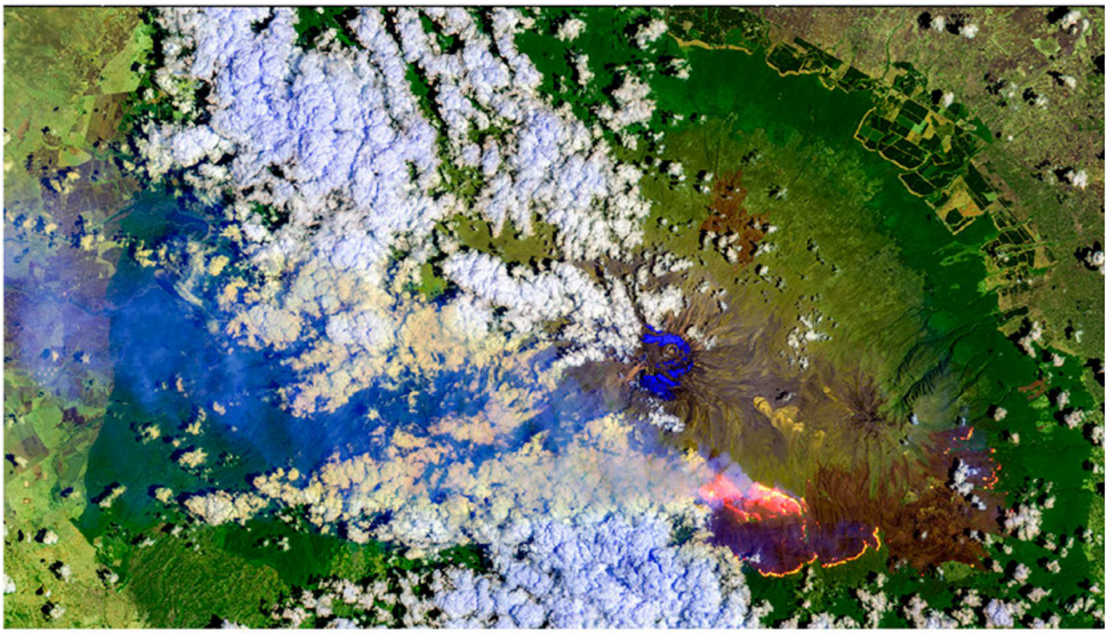
Meteorological satellite data is used in mapping active fires and burned areas, monitoring changes in vegetation cover, and producing policy planning reports. The data are also crucial for community-based fire management approaches that empower local communities to decide the objectives and practices for preventing, controlling and using fire.

The satellite data also contribute to the better management of restorative efforts in some ecosystems and improved practices to tackle the devastating effects of unwanted wildfires.

[a] European Organisation for the Exploitation of Meteorological Satellites, "Fighting wildfires with satellite data in Tanzania". Available at www.eumetsat.int/features/fighting-wildfires-satellite-data-tanzania.

Figure 10.5 Satellite image of a wildfire at Mount Kilimanjaro, United Republic of Tanzania as of 15 October 2020, presented in infrared view

Contains modified Copernicus Sentinel data (2020). The image is about 66 km wide



Source: EUMETSAT

CASE STUDY

Automating the assessment of California wildfires for rapid detection[a]

A pilot programme in California, funded by the Gordon and Betty Moore Foundation, aimed to push the boundaries of existing tools for the remote detection and assessment of wildfires. The collaborative project, between Moraga Orinda Fire District, Planet and the University of California Berkeley Department of Electrical Engineering and Computer Sciences, sought to autonomously gather and integrate wildfire data into a single cohesive system.

The goal of the pilot was to connect networks of ground fire sensors to an automated system that would then rapidly gather timely, high-resolution and location-accurate satellite imagery from Planet, capturing fires in their earliest stages.

Every 10 seconds, a network of ground-based sensors send temperature and humidity data over a network to a nearby gateway, which subsequently routes to a web interface called BurnMonitor.com. BurnMonitor detects signals of potential fires from drops in humidity and spikes in temperature and notifies subscribers in real time about the location and presence of fires.

The research team at Berkeley developed a Python script to connect the fire notifications from BurnMonitor to the collection of satellite imagery.

The script processes detections of fire from BurnMonitor and links them to Planet's Tasking API, which triggers a request for satellite imagery at the latitude and longitude where the sensors signal a potential fire. One fire can generate multiple fire-alert messages, so the script filters out repeated and false alarms.

Key to the pilot programme's aim was to collect high-resolution satellite imagery automatically, without the need for human involvement.

Synced to the ground-based sensors and filtered through the BurnMonitor integration and the Python script, Planet's Tasking API is able to ingest requests for imagery and autonomously task a SkySat satellite to collect data from the specific latitude and longitude where a fire is detected.

Planet's 21 SkySats can collect very high-resolution images of one point on Earth multiple times per day. This revisit cadence ensures that calls for imagery can be delivered shortly after they are requested.

By automatically delivering high-resolution satellite imagery and integrating ground sensor data with the Tasking API, this seamless and autonomous process saves time and friction in image collection, reducing the period between the detection of a potential fire and the delivery of data in its critical early hours.

[a] Planet, "Linking Ground and Space Systems to Autonomously Assess Wildfires". Available at https://learn.planet.com/wildfires-case-study.html.

CASE STUDY

FireHub [a, b]

The BEYOND Center of Earth Observation and Satellite Remote Sensing, hosted by the National Observatory of Athens in Greece, has developed a tool called FireHub to facilitate early warning and decision-making in emergency response and evacuation processes. FireHub also addresses diachronic and near-real-time Burn Scar Mapping (BSM) needs, at various spatial resolutions. Both active-fire and BSM services cover the wider Mediterranean, North Africa, the Balkans, the Middle East and the Black Sea territories.

The service is used by many operational users, including fire brigade authorities, Copernicus EMS Risk and Recovery, ministries and organizations for forest protection and territorial recovery and planning, the World Wide Fund for Nature, private sector entities, and national, regional and local authorities.

From 2018, FireHub was integrated to the European Forest Fire Information System (EFFIS), and to the web system of the Global Fire Monitoring Center. The FireHub system uses a multitude of daily acquisitions of satellite images gathered by the antennas of the BEYOND Center, such as the X-/L-band antenna receiving EOS/AQUA, EOS/Terra, SUOMI-NPP, JPSS NOAA-20 satellites and the Hellenic Mirror Site that offers near-real-time acquisitions of Sentinel-1, 2 and 3.

FireHub continuously ingests real-time satellite data every 5 minutes. This data is processed to detect active fires by using three classification steps:

1. EUMETSAT fire mapping algorithm based on fixed thresholding approach, applied on the spectral bands IR 3.9 and IR 10.8 -> dynamic
2. Create and integrate classification evidence through geospatial ontology schemes and reasoning queries, accounting for the (a) thematic consistency by eliminating false alarms and (b) time persistence of the fire observations
3. Downscaling the first classification output and calculating the fire occurrence probability in sub-areas of 500 m x 500 m wide, inside the initial observation area of 3.5 km x 3.5 km

When a fire is detected, FireHub issues a fire alert. In the example below, the fire alert was displayed 5–7 minutes after the official start of the fire. Using FireHub, all users can see the alerts as they appear. The system provided the starting area (red rectangle – 500 m x 500 m wide) at 17:05 local time and is updated every five minutes. The redder the cell, the higher the active-fire occurrence in it. The masked-out area is urban land use. FireHub does not update the fire occurrence picture inside the urban zones. Figure 10.6 shows the FireHub geowiewer presenting data as of 21 August 2023.

The use of satellite data in FireHub contributes towards a range of advantages over traditional fire monitoring systems:

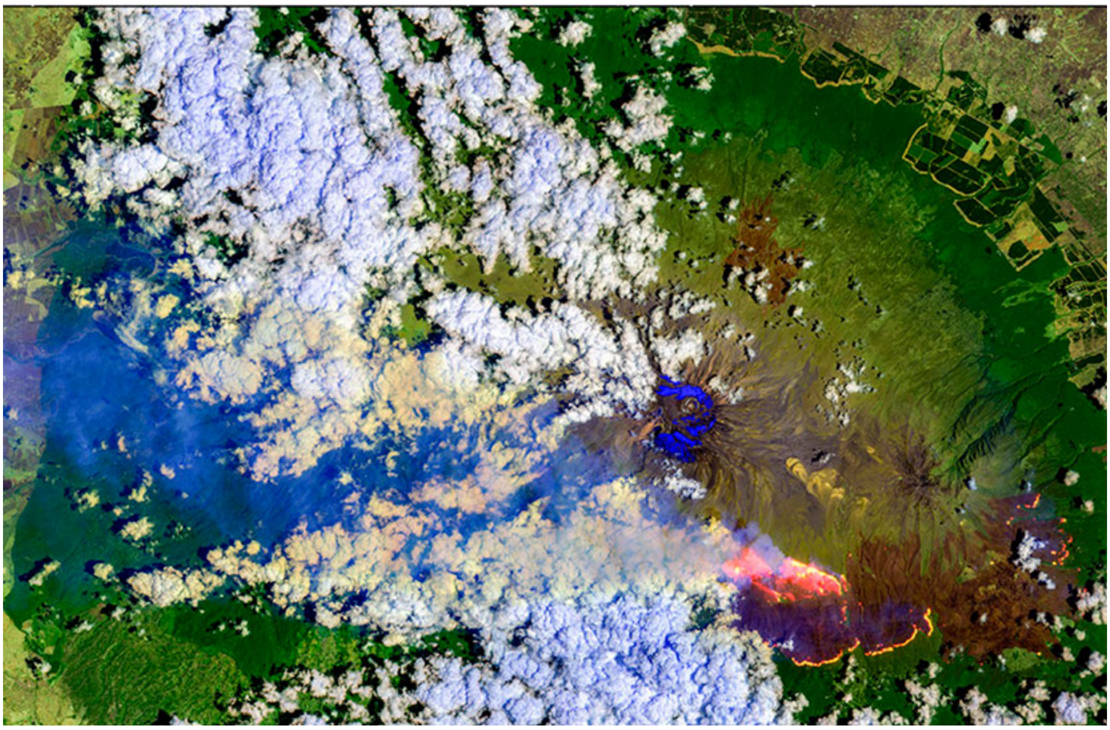
- 25–30 per cent of the detected fires are reported 10–15 minutes earlier than fire brigades logs
- Sixty per cent of the detected fires are reported in the first 15 minutes after the ignition timestamp reported in the fire brigade logs
- All the fires larger than 112 ha are detected
- Fifty per cent of smaller fires [4.7 ha–112 ha] are detected
- The smallest detected fire has been of the order of 4.7 ha
- Fires not detected make up 5.8 per cent of the total burned area
- 82–85 per cent of the 500 m x 500 m cells that are assigned a high fire occurrence probability are located in the burned area polygon

Detection errors are mainly due to (a) cloud cover, (b) fire intensity (e.g. small fires – small burned areas), (c) area topography, and (d) fuel characteristics (e.g. less vegetative areas, pasture lands, sparse vegetation resulting in low fire intensities).

[a] Greece, National Observatory of Athens, BEYOND Centre of Earth Observation Research and Satellite Remote Sensing, *FireHub*. Available at http://beyond-eocenter.eu/index.php/web-services/firehub.

[b] Haris Kontoes and Stella Girtsou, "Use of space technologies to forecast and monitor forest fires in Greece". Available at www.un-spider.org/sites/default/files/11_Conf2021_NOA_BeyondCenter.pdf.

Figure 10.6 FireHub geoviewer displaying information on fires as of 21 August 2023



Source: BEYOND Center of Earth Observation and Satellite Remote Sensing

CASE STUDY

Forest fire risk early warning system of the Friends of Nature Foundation in the Plurinational State of Bolivia[a]

In recent years, forest fires have been impacting rural areas in the Plurinational State of Bolivia. In December 2022, thousands of families were affected by fires in the Los Yungas region[b] and in previous years, hundreds of thousands of hectares were burned.

Recognizing the need to address these challenges, the Friends of Nature Foundation of Bolivia (FAN) developed and implemented a forest fire risk early warning system (SATRIFO) with the aim of providing practical and timely

CASE STUDY *(continued)*

information to plan prescribed burns, and for prevention, control and monitoring of forest fires in the country. The system operates on two scales: scenery and community-level.

On a scenery scale, a geospatial model is used to generate daily maps of the probability of forest fires, combining data on relative humidity, precipitation, wind velocity, distance to accumulated hotspots and to historically deforested areas, and on the location of areas which have experienced fires annually in the last 21 years. The geospatial information is disseminated to relevant institutions, local organizations and other actors engaged in risk reduction, preparedness and combating forest fires. Sensors in satellites such as GOES, AQUA, Terra METEOSAT, TRMM and NPP are used to detect heat sources, with Landsat and MODIS being used to detect burned areas. Figure 10.7 shows concentrations of hotspots on 27 August 2023 and the fire risk for the coming 48 hours.

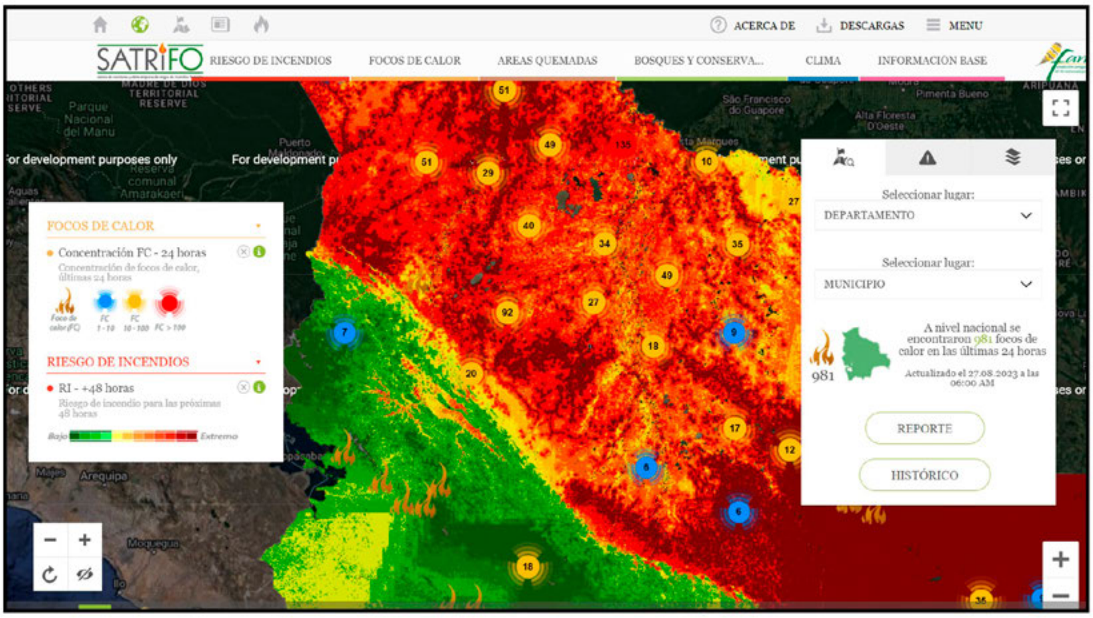
On a community-level scale, SATRIFO aims to reach communities who are direct users of this information, and representatives that have been trained by FAN. These representatives also compile and transmit relevant weather conditions.

FAN has developed an Android mobile application to link these two scales and to facilitate the interaction of stakeholders regarding the monitoring of local conditions and the report of fires. The app allows for the generation of coordinates, automatic calculation of areas, generation of warnings and the provision of information to fire brigades in the field.

[a] Bolivia, Friends of Nature Foundation (FAN). *Bienvenidos a SATRIFO*. Available at https://incendios.fan-bo.org.

[b] Deutsche Welle. "Bolivia: miles de familias son afectadas por incendios forestales", 4 December 2022. Available at www.dw.com/es/bolivia-miles-de-familias-son-afectadas-por-incendios-forestales/a-63978658.

Figure 10.7 SATRIFO web page showing the concentrations of hot spots on 27 August 2023 and the fire risk for the coming 48 hours



Source: SATRIFO, FAN

10.2 Air quality

Air quality is a measure of how clean or polluted the air is. Poor air quality, or polluted air, is the result of gas and particle emissions, and chemical reactions that have occurred in the atmosphere. Poor air quality can be caused by natural sources such as volcanic eruptions (see chapter 5), sea spray, lightning and desert dust. But the majority are caused by five types of human activity: household, industry, transportation, agriculture and waste.[180]

The United Nations Environment Programme indicates that around 7 million people die every year from diseases and infections related to air pollution. The impact of poor air quality on global health is estimated at US$5.7 trillion, equivalent to 4.8 per cent of the world's GDP,[181] with outdoor and indoor air pollution causing respiratory and other diseases and being sources of morbidity and mortality.

Air pollution also has negative consequences for the economy, productivity and tourism. It affects biodiversity loss, causes acidification of soil and lake ecosystems, and reduces forest and crop yields, threatening food security.[183]

Fine particulate matter ($PM_{2.5}$) and ground level ozone are particularly dangerous. Invisible to the naked eye and present both indoors and out, $PM_{2.5}$ penetrates lungs and allows toxic compounds into the bloodstream. Ground level ozone is both a greenhouse gas and an air pollutant – damaging to human and ecosystem health. Exposure to ground level ozone causes 472,000 premature deaths every year.[182]

Monitoring, forecasting and warning for poor air quality is key to reducing the impacts of poor air quality on lives and livelihoods.

CASE STUDY

airTEXT [a, b]

Scientists in Latvia and the United Kingdom have used the Copernicus Atmosphere Monitoring Service (CAMS) to produce airTEXT: a free, independent air quality service, operated by Cambridge Environmental Research Consultants (CERC) Ltd. The service is available for major cities in the United Kingdom, including London, Cambridge, Chelmsford and Colchester, and Riga in Latvia.

The app draws on CAMS air quality forecasting data and combines these forecasts with air quality information from the air quality modelling system for urban areas of CERC to produce air quality maps at 7-metre resolution. This comprehensive system is used to model pollutant dispersion across large urban areas, to show what happens on a range of scales, from individual streets to entire cities.

The service provides forecasts of local air quality up to three days ahead of time and is accessible through a website or on a free mobile app. Free text and email alerts are also available to push information to the public about local air quality, keeping people informed.

The hourly concentrations of four pollutants are calculated: nitrogen dioxide (NO_2), particulates (PM_{10} and $PM_{2.5}$) and ozone (O_3). From the hourly concentrations the daily air quality index of each pollutant is derived. The overall air

[180] World Health Organization, "Air Pollution". Available at www.who.int/health-topics/air-pollution#tab=tab_1

[181] United Nations Environment Programme. "Across the globe, nine out of every ten people are breathing unclear air". Available at www.unep.org/interactive/all-you-need-to-know-air-pollution

CASE STUDY *(continued)*

quality index is determined by the highest index for any of these pollutants. airTEXT issues an alert for a local authority or region if at least 10 per cent of the geographical area is predicted to reach MODERATE or above. Figure 10.8 shows the forecast of air quality for 9 December 2022 for Riga, as presented by airTEXT. [c]

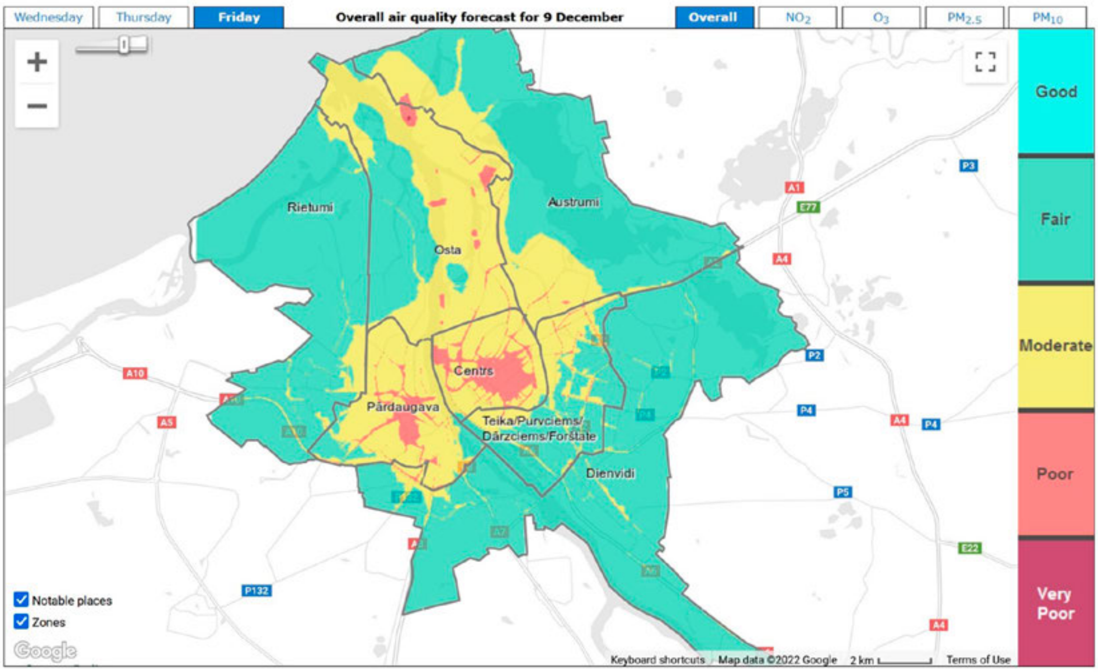
[a] Cambridge Environmental Research Consultants Ltd, "Air quality forecasting". Available at www.cerc.co.uk/forecasting/air-quality.html.

[b] Cambridge Environmental Research Consultants Ltd, "What is airTEXT?" Available at www.airtext.info/about.

[c] Riga airTEXT. "Gaisa kvalitates, UV starojuma, ziedputeksnu un gaisa temperaturas prognose Rigai". Available at: https://rigaairtext.lv.

Figure 10.8 airTEXT Air Quality Map for Riga, 7 December 2022

The image shows the forecast air quality for Friday 9 December 2022



Source: Riga airTEXT

Satellites orbiting Earth collect information about what is in the atmosphere. For example, satellites of the GOES-R Series monitor particle pollution. The Joint Polar Satellite System (JPSS) also collects information about particles in the air. These particles include smoke particles from wildfires, airborne dust during dust and sandstorms, urban and industrial pollution, and ash from erupting volcanoes. Ground level ozone can also be measured by the JPSS series of satellites.

GOES-R Series satellites track particle pollution approximately every five minutes during the day. JPSS satellites can provide a higher resolution measurement of aerosols over the entire planet once a day. JPSS can also observe the movement of aerosols from one side of the planet to the other and measure carbon monoxide, which is associated with poor air quality resulting from wildfires.[182]

[182] United States, National Oceanic and Atmospheric Administration, SciJinks. *How is Air Quality Measured?* Available at https://scijinks.gov/air-quality

Earth observation data from satellites, combined with ground-based monitoring instrument data, are used to provide real-time measurements of air quality around the world. Combined with forecasting models, air quality levels can be forecast, and alerts and warnings issued for sectors including health, aviation, agriculture and local populations.

The Copernicus Atmosphere Monitoring Service (CAMS) monitors and forecasts phenomena that contribute towards changes in air quality, such as human induced air pollution and dust. CAMS provides quality-controlled and free data for use in creating new applications to help a range of users across the world.[183]

CAMS draws on Earth observations combined with numerical models of weather and atmospheric composition to create detailed analyses and forecasts of atmospheric composition and air quality. These data are used for initializing forecasts of global conditions, as well as to assess European air quality. To acquire all the observations that are needed to produce the CAMS services, it collaborates with ESA and EUMETSAT as well as with many other organizations that provide satellite and in situ observations.[184]

10.3 Dust

Dust comprises small particles of loose soil and sand. These particles are lifted into the atmosphere by gusts of surface winds and can be transported and deposited thousands of kilometres away.[185]

ECMWF notes that the transport of dust is vital to the functioning of many ecosystems; however, dust can detrimentally affect health, through respiratory impacts; agriculture, when dust lands on crops, it can limit photosynthesis and impact yield; and transport, where dust can damage aircraft, affect road conditions, railway tracks and overhead lines.[187] Sand and dust storms have become a serious global concern in recent decades due to their significant impacts on the environment, health, agriculture and socioeconomic well-being.[186]

CAMS tracks dust transport using satellite observations of aerosol optical depth (AOD). AOD measures how much sunlight is blocked by small solid particles or liquid droplets floating in the atmosphere.[187] CAMS uses these satellite observations as input for its forecasts, and also estimates the contribution to AOD of different components such as sea salt, desert dust, organic matter, black carbon and sulphate aerosols. CAMS AOD forecasts can be evaluated and validated against ground-based remote sensing.

By accurately forecasting and analysing the extent of dust storms, CAMS contributes to the United Nations Sustainable Development Goals (SDGs). SDG 3.9 aims to reduce the number of deaths and illnesses from air pollution by 2030. With effective forecasting of dust storms, authorities, communities and citizens can prepare for events a few days in advance and avoid them where possible. This will also reduce the financial burden on health services caused by respiratory ailments and other health problems.[187]

[183] European Centre for Medium-Range Weather Forecasts, "Tracking air pollution". Available at https://stories.ecmwf.int/tracking-air-pollution/index.html

[184] European Commission, Copernicus Programme. Available at https://atmosphere.copernicus.eu/about-us

[185] European Centre for Medium-Range Weather Forecasts, "Forecasting dust storms". Available at https://stories.ecmwf.int/forecasting-dust-storms/index.html

[186] World Meteorological Organization, "New sand and dust forecast website launched". Available at https://public.wmo.int/en/media/news/new-sand-and-dust-forecast-website-launched

CASE STUDY

World Meteorological Organization sand and dust forecasting[a]

The increasing demand for sand and dust monitoring and forecasting capability, as well as the successes brought by the Sand and Dust Storm Warning Advisory and Assessment System,[b] has led WMO to establish two Regional Specialized Meteorological Centres on Atmospheric Sand and Dust Forecast (RSMC-ASDF). In 2014, the first WMO RSMC-ASDF became operational in Barcelona (Spain). In May 2017, the second was established in Beijing and began operations.

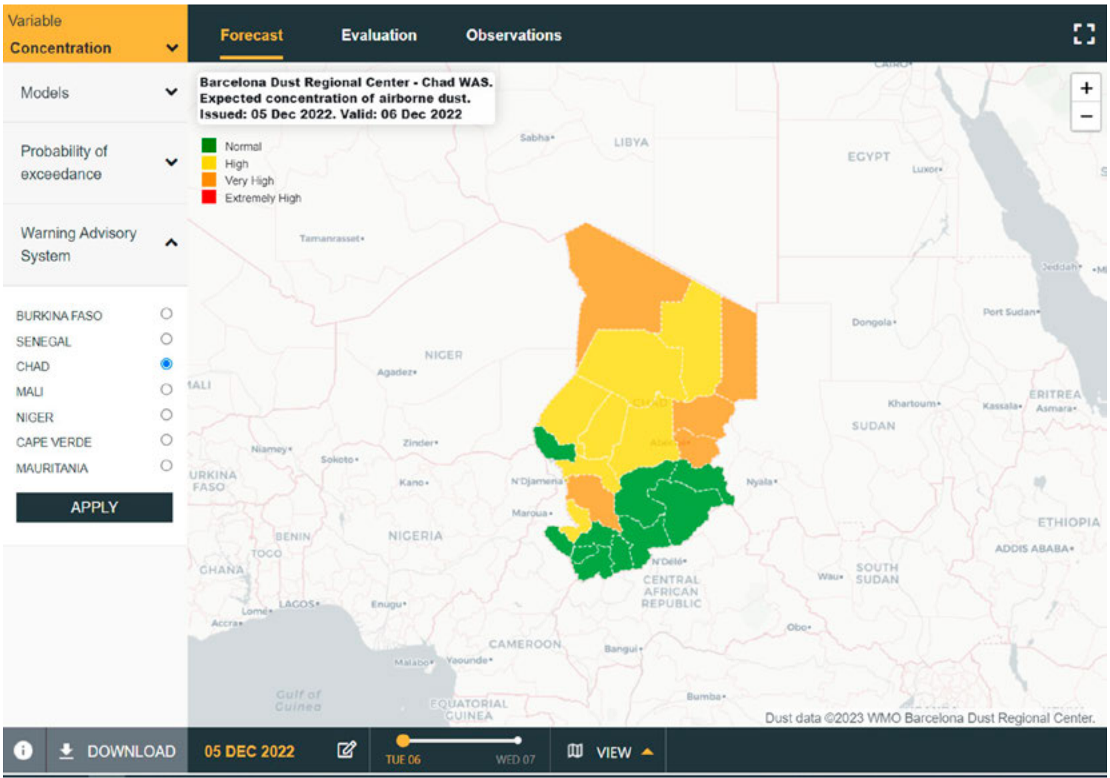
The WMO Barcelona Dust Regional Centre manages and coordinates the research activities and operations of WMO related to sand and dust storms across Europe, Northern Africa and the Middle East.

The Barcelona Centre uses CAMS data alongside a range of hydrometeorological models to provide access to high-quality dust information. The Centre predicts the occurrence of sand and dust storms and provides information to allow their effects and impacts to be managed. Figure 10.9 shows a map of dust concentration warnings for Chad valid on 6 December 2022 as generated by the Warning Advisory System at the Barcelona Dust Regional Centre.

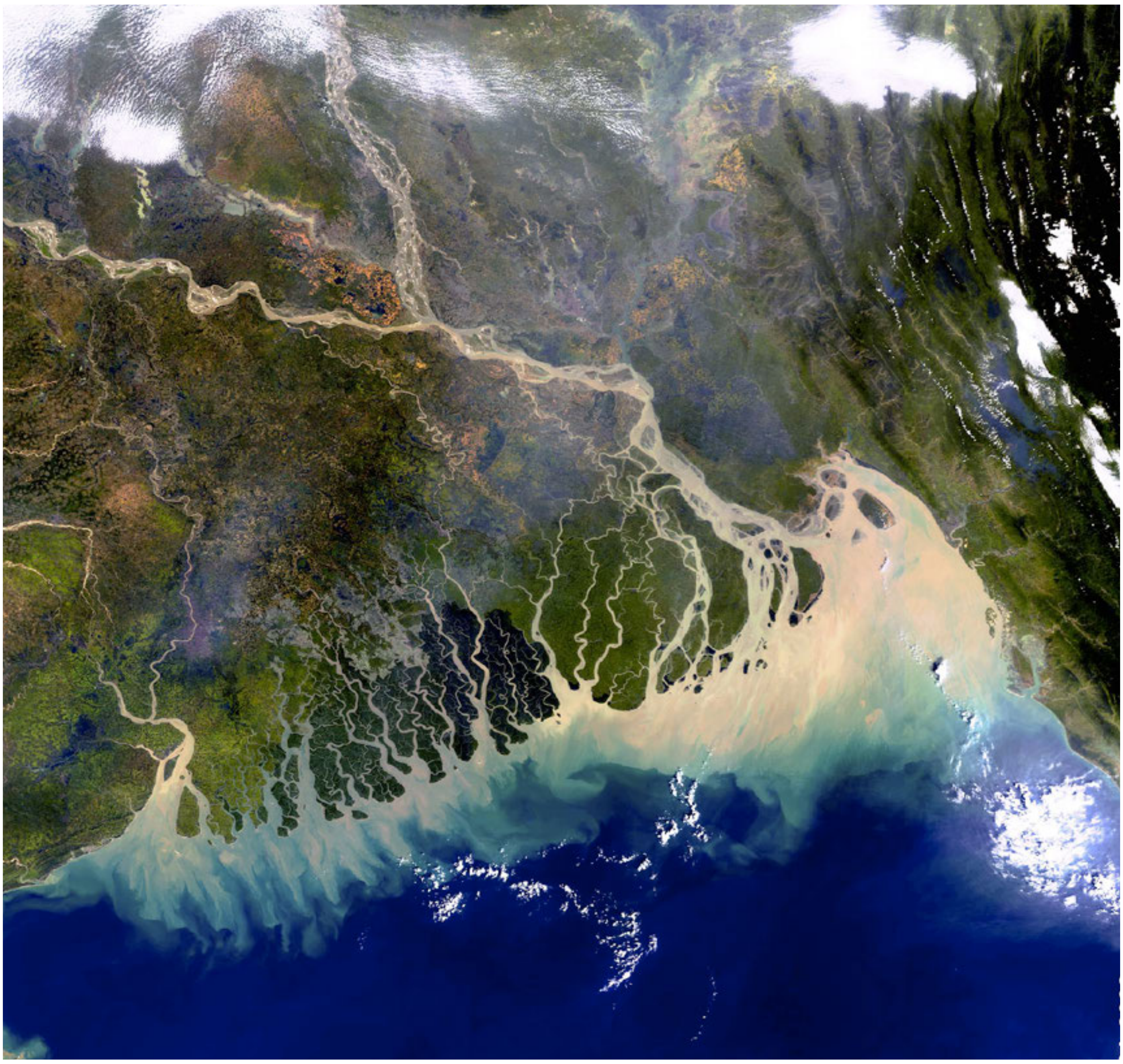
[a] World Meteorological Organization, Barcelona Dust Regional Centre, "Daily Dust Forecast". Available at https://dust.aemet.es

[b] World Meteorological Organization, Northern Africa, Middle East, Europe Regional Centre, "Overview & History". Available at https://sds-was.aemet.es/about-us

Figure 10.9 Barcelona Dust Regional Centre Warning Advisory System showing dust concentration warnings for Chad valid on 6 December 2022



Source: WMO Barcelona Regional Dust Centre



Capture of the coastline of Bangladesh by ENVISAT

Image courtesy of ESA

Chapter 11.
Multi-hazard early warning systems

Recognizing the need to continue advocating for the implementation of multi-early warning efforts around the world, the Sendai Framework for Disaster Risk Reduction 2015–2030 included a dedicated Priority 4 to confront the steady growth of disaster risk, including the increase of people exposed to hazards and the exposure of assets. At the national level, the Sendai Framework calls for efforts to be implemented "to invest in, develop, maintain and strengthen people-centred multi-hazard, multisectoral forecasting and early warning systems, disaster risk and emergency communications mechanisms, social technologies and hazard-monitoring telecommunications systems."[187]

At the international level, the Sendai Framework calls for efforts to promote the further development of and investment in effective, nationally compatible, regional multi-hazard early warning mechanisms, where relevant, and facilitate the sharing and exchange of information across all countries.

Meteorological departments or institutes carry out multi-hazard early warning efforts through the monitoring of a variety of meteorological hazards and forecasting potentially catastrophic events. In a similar fashion, some geological observatories monitor geological hazards such as landslides, volcanic activity and earthquakes, and issue warnings in the case of volcanic activity and landslides. In a parallel fashion, health centres in countries around the world keep an eye on a variety of communicable diseases and use the notions of nowcasting to confront those that may reach the level of epidemics.

To contribute to such efforts, many organizations of the United Nations, several space agencies, and other international, regional and national organizations launched the International Network on Multi-Hazard Early Warning Systems (IN-MHEWS) in Sendai, Japan during the fourth World Conference on Disaster Risk Reduction to contribute to the implementation of the Sendai Framework.

The space community contributes to the generation of timely space-based data that are used to monitor hazards and issue warnings in case of potentially catastrophic events. In a sense, this can be understood as a multi-hazard effort, as the imagery is used in a multi-hazard environment by many institutions worldwide.

[187] United Nations Office for Disaster Risk Reduction, "Sendai Framework for Disaster Risk Reduction 2015–2030". Available at www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf

CASE STUDY

The PRISM system of the World Food Programme[a]

Recognizing the usefulness of geospatial information compiled from Earth observation and from other sources to address the challenges posed by natural hazards and climate change, the World Food Programme (WFP) launched its PRISM information system in 2016 to facilitate the visualization of the latest available information on hydrometeorological hazards and WFP data on vulnerability. The aim of PRISM is to provide actionable information to decision makers to facilitate the provision of assistance to those who need it the most.

PRISM combines data on current conditions of hydrometeorological hazards and on the level of exposure and vulnerability of communities to present decision makers with maps, charts, tables and reports. This information can be used in early warning efforts.

[a] United Nations World Food Programme (WFP), "PRISM, combining remote sensing and vulnerability data for risk and impact analysis". Available at: https://innovation.wfp.org/project/prism

CASE STUDY

Mayday.ai: real-time and near-real-time intelligence solutions and services for disaster management worldwide [a]

Mayday.ai is a German company whose activities are supported by ESA, NOAA and DLR. The company's risk and disaster intelligence platform covers multiple disasters and all geographical regions of the world thanks to its real-time and near-real-time capabilities. Mayday's solutions are based on Esri architecture and have been commercially available to public and private customers since the first quarter of the year 2022.

Mayday covers a broad range of disaster types. Its solutions achieve this timeliness and high accuracy by ingesting into Mayday's proprietary AI fusion engine a high number of Earth observation and ancillary data relevant for risk and disaster management and processing them with machine learning. These data range from satellite imagery, traffic cameras, specialized Internet sensors to social media. The approach is combined with innovative detection methods, such as using geostationary satellite imagery for detection (including through partial clouds – the "Clear Sky" innovation) and machine-learning-driven masking. This allows the detection of forest fires within minutes with minimal false positives. Figure 11.1 presents Mayday's jurisdiction- and community-centred hubs covering multiple disasters in real and near-real time.

Mayday contributes to Sendai efforts through a multi-hazard early warning by dynamic risk modelling (targeted risk forecasting at the parcel level), early detection, but also a live common operating picture (COP), rich visualizations (including 3D) and dashboard reporting. Post-event mapping is supported with high-resolution drone or satellite imagery on demand, as well as "before-after" analyses with in-depth SAR analytics and economic damage assessment. As events are being detected, a real-time COP is crucial in all phases of a disaster life cycle. Figure 11.2 displays an image of Mayday's wildfire prevention tool.

The platform is built on a modular approach. This allows the easy integration of any additional imagery or other sources at the disposal of customers, as well as features tailored to verticals, such as emergency response, insurance or agriculture.

The company's SaaS solution is supported by a human-operated 24/7 disaster management centre, which acts as an extended arm of organizations for disaster management prevention and response. Mayday also provides a mobile app enabling two-way communication with civilians and profiling during crises.

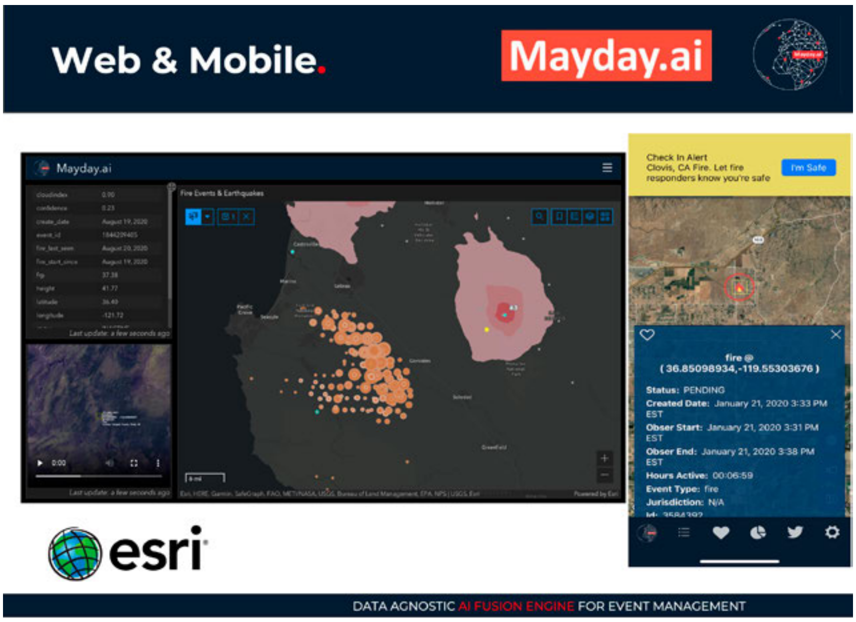
While having industry-leading capabilities for disaster detection and early containment, Mayday's primary mission is to contribute to a culture shift towards risk reduction in line with Sendai goals with its democratization of pertinent fused data and risk reduction through the inclusive engagement of stakeholders.

[a] Mayday.ai. Available at https://mayday.ai

Figure 11.1 Mayday's jurisdiction- and community-centred hubs cover multiple disasters in real and near-real time

Source: Mayday.ai

Figure 11.2 Mayday's wildfire prevention tool allows rich visualizations through the Esri platform



Source: Mayday.ai

Earth as seen by
Apollo 17 astronauts
in December 1972

Image courtesy of NASA

Chapter 12.
Future outlook

The space community continues to develop missions to enhance the capacity of space technologies to improve early warning systems. Several satellites have been launched into orbit recently and are undergoing initial tests before becoming operational. In addition, several experiments have been carried out in recent years that may become an operational reality once resources are found for their implementation.

This chapter presents information on such efforts and is divided into four segments:

- Novel satellites
- Improved hazard monitoring
- Improved on-board data processing
- Warning and communication

12.1 Novel satellites

Many space agencies are launching new satellites to monitor various physical and environmental parameters of the Earth. Some of these are being launched by private companies to enhance the frequency of observations of any place on Earth. Space agencies are launching others to improve the capacity to monitor a variety of hazards using novel instruments.

The following examples provide information on some of the satellites being launched by several space agencies such as NASA, ESA and JAXA.

The Surface Water and Ocean Topography satellite [a]

The Surface Water and Ocean Topography (SWOT) satellite was developed by NASA and CNES and benefited from contributions from the Canadian Space Agency (CSA) and the Space Agency of the United Kingdom (UK Space). It was launched in December 2022. Its orbit around the Earth will be at an altitude of nearly 860 km, and it will repeat the same orbit every 21 days. It will have a 120-km-wide swath and its design life is around three years.

This satellite will help hydrologists assess changing volumes of fresh water across the globe, including reservoirs and wetlands. In addition, it will provide run-off data at a higher resolution for hydrologists to improve their hydrological models. Such information will be beneficial in case of floods and droughts. For example, SWOT will allow hydrologists to map the extent of floods and monitor the reduction in the water level of lakes and other water bodies in case of severe droughts.

[a] Canada, Canadian Space Agency, *"Overview"*. Available at www.iafastro.org/membership/all-members/canadian-space-agency.html

Geostationary Operational Environmental Satellite[a]

The Geostationary Operational Environmental Satellite (GOES-T) was launched in March 2022, and after its testing in orbit, it will be renamed GOES 18 and then go into service. This satellite will complement other GOES satellites in monitoring the weather and hazardous conditions in the Western Hemisphere.

Like other geostationary satellites, GOES-T is positioned in orbit 36,000 km above the Earth and is expected to provide continuity to the Earth observations carried out by the constellation of GOES satellites launched several decades ago. Like the GOES-R satellite, GOES-T also carries a magnetometer to monitor space weather. In addition, it also carries sensors to track lightning activity.

[a] United States, National Aeronautics and Space Administration, *"NASA, ULA Launch NOAA's Newest Earth Observing Satellite"*. Release No. 22-023, 2 March 2022. Available at www.nasa.gov/press-release/nasa-ula-launch-noaa-s-newest-earth-observing-satellite

Earth Cloud Aerosol and Radiation Explorer (EarthCARE) mission[a]

ESA is expected to launch this satellite in 2023 to improve the models of the atmosphere. It will contribute to improved and more precise weather forecasts. ESA will place the satellite in orbit 393 km above the Earth, and its repeating cycle will be 25 days.[b]

The satellite will monitor aerosols and thin clouds through its Atmospheric LiDAR instrument. In addition, it will collect information about larger clouds through its Cloud Profiling Radar instrument. ECMWF will use the two types of observations from this satellite to improve its understanding of cloud dynamics.

[a] European Space Agency, "EarthCARE". Available at www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE

[b] European Space Agency, "EarthCARE mission to improve weather forecasts". www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/EarthCARE_mission_to_improve_weather_forecasts

The Meteosat Third Generation Imager-1 (MTG-I1) satellite[a]

The Meteosat Third Generation Imager-1 (MTG-I1) geostationary satellite was launched by ESA and EUMETSAT on 13 December 2022 to provide data for use in the early detection and prediction of fast-developing severe storms and for weather forecasting and climate monitoring. As a geostationary satellite, it will orbit Earth at an altitude of 36,000 km above the Equator. Its lifespan is expected to be in the order of 20 years.

MTG-I1 is the first of six satellites to conform to the MTG constellation, aiming to facilitate early detection of potentially severe weather events in the next 20 years.[b] The satellite will observe oceans, land and the atmosphere, and track clouds, water vapour, cloud from forest fires and lightning.

[a] European Space Agency, "Meteosat third-generation". www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/meteosat_third_generation

[b] European Space Agency, "A new era of weather forecasting" begins www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/meteosat_third_generation/A_new_era_of_weather_forecasting_begins

Upcoming Copernicus Sentinel satellites [a]

The constellation of Copernicus satellites allows an unprecedented understanding of hazards and environmental stressors worldwide. The Sentinel 1 satellites allow disaster managers to become aware of areas impacted by floods, tsunamis, storm surges and debris flows, and to track the deformation of volcanic domes in active volcanoes and slow-moving landslides, even under cloud cover. A new Sentinel 1C satellite will be launched in 2023 to complement the currently operational Sentinel 1A satellite, as the Sentinel 1B satellite experienced a malfunction. The Sentinel 1D satellite is expected to be launched in 2024.

The Sentinel 2 satellites complement the Sentinel 1 satellites by providing imagery in the optical and near-infrared regions of the electromagnetic spectrum at a high resolution for improved monitoring of many hazards. The Sentinel 2A satellite was launched in 2015, and subsequently, the Sentinel 2B satellite was launched in 2017. The Sentinel 3C satellite is expected to be launched in 2024 or 2025.

[a] European Space Agency, "Launches secured for five Sentinel satellites". www.esa.int/Applications/Observing_the_Earth/Copernicus/Launches_secured_for_five_Sentinel_satellites

12.2 Improved hazard monitoring

The combined data from different types of satellites will allow forecasters to improve procedures for the forecasting of potentially catastrophic events. One example is the combined use of imagery extracted from Earth observation satellites and high-resolution positioning data from GNSS. The following segment presents information on examples of this combined use of Earth observation satellites and GNSS data in the case of mass movements.

European Global Navigation Satellite System and Copernicus for Risk Monitoring[a]

The synergistic use of the European Global Navigation Satellite System (EGNSS) and components of the Copernicus Programme provide the necessary elements to build integrated applications that improve risk monitoring for geological hazards (e.g., landslides, deformation due to volcanic activity, etc.). During the risk identification phase, Copernicus data and services (e.g., Copernicus Land Monitoring) are employed and fused with local geospatial layers to detect risk-prone areas, providing initial risk assessments on the potential impact on local communities and infrastructure. For example, interferometric synthetic aperture radar (InSAR) methods based on Copernicus Sentinel-1 data allow acceleration detection, a precursor to slope failures. At the same time, the time series can also reveal displacements and pre-failure motions of landslides.

The information above can be fused with data streams from local Galileo ground stations and other in situ sensors, such as inertial measurement units, to monitor ground deformations, landslides and subsidence. This synergistic approach can improve the detection of land deformations with millimetric-level accuracies and frequent measurement rates. Moreover, the integration of in situ accelerometers can deliver real-time alerts in case of sudden movements.

[a] Information provided by the European Union Agency for the Space Programme (EUSPA).

Geodetic Integrated Monitoring System – the Geodetic Integrated Monitoring System project of the European Union Agency for the Space Programme[a]

An example of the development of an integrated system is the Geodetic Integrated Monitoring System (GIMS), a project implemented by the European Union Agency for the Space Programme (EUSPA). The main objective of GIMS is to develop an advanced low-cost system based on EGNSS, Copernicus synthetic aperture radar (SAR) and in situ sensors to monitor ground deformations in real-time, with a focus on landslides and subsidence. The system will track ground deformations with millimetre-level accuracies and a daily acquisition rate combining several inputs:

- GNSS and accelerometer data collected from ground stations and retrieved from the Internet
- Synthetic aperture radar (SAR) data retrieved directly from ESA Copernicus Sentinel servers

The deformation results will be used to produce a report for easy consultation by interested stakeholders (e.g., public authorities, civil protection, citizens, etc.)

GIMS will contribute to a better understanding of the geophysical behaviour of parts of the Earth's surface and its hindrances on structures, allowing for the mitigation of casualties and injuries to the population and better planning of maintenance intervention.

GIMS has received funding from the European Union Agency for the Space Programme (EUSPA) Horizon 2020 research and innovation programme the under the European Union, under grant agreement No. 776335.

[a] European Union Agency for the Space Programme, "Geodetic Integrated Monitoring System (GIMS)". Available at www.euspa.europa.eu/geodetic-integrated-monitoring-system

The NASA model of models for improved flood early warning[a]

Scientists from the NASA Earth Applied Sciences Disaster programme are joining forces with several researchers from leading scientific institutions to develop a model of models (MoM) to improve flood forecasting worldwide. MoM will fuse data from the Copernicus Global Flood Awareness System (GLoFAS) and the NASA-funded Global Flood Monitoring System (GFSM) with information on local watersheds to improve the forecast of potential floods.[b] Warning information derived by MoM will be sent to communities exposed to floods using the Pacific Disaster Center's DisasterAWARE® platform. MoM uses InSAR data to measure changes in the level of water in rivers to validate and calibrate the model outputs. In the future, MoM will incorporate machine learning to enhance its precision using more data when they become available.[c]

[a] United States, National Aeronautics and Space Administration, *NASA Partnership Launches Ground-breaking New Global Flood*. Available at : https://appliedsciences.nasa.gov/our-impact/news/nasa-partnership-launches-groundbreaking-new-global-flood-early-warning-technology

[b] United States, National Aeronautics and Space Administration, *Early Access to Global Flood Tracking*. Available at https://appliedsciences.nasa.gov/our-impact/story/early-access-global-flood-tracking

[c] UN-SPIDER Programme, "UN-SPIDER Knowledge Portal: NASA Disasters Programme". Available at https://un-spider.org/sites/default/files/nasa-eo-disasters_0.pdf

Improving tornado warnings with weather satellites with GEOXO SOUNDER[a]

Modern hyperspectral sounding instruments on board satellites deployed in low-Earth orbit, such as L3Harris' Cross-Track Infrared Sounder (CrIS), allow meteorologists to assess moisture and temperature profiles in the atmosphere. Such data are useful for detecting weather patterns associated with hazards such as tornadoes.

While these sounders have been incorporated in Earth observation satellites in low-Earth orbit, early warning in the case of tornadoes could be drastically improved if such sounders are incorporated in geostationary satellites that can transmit data every 30 minutes or sooner. The more frequent observations made through such geostationary satellites will allow forecasters to benefit from such data to forecast the path of tornadoes.

[a] L3Harris (2022), "Weather Satellites: The Key to Life-Saving Tornado Warnings". Available at www.l3harris.com/newsroom/editorial/2022/04/weather-satellites-key-life-saving-tornado-warnings

Improving teletsunami warning

The detection of tsunamis is usually carried out using networks of seismometers, Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, and tide gauges in coastal areas. But tsunamis triggered by underwater volcanic eruptions, mass movements prompted by volcanic activity in volcanic islands or by near-Earth objects impacting oceans are nearly impossible to track in remote areas.

To address this challenge, scientists at Deep Blue Globe[a] developed the ONEWAVE prototype procedure to detect the propagation of tsunamis in the deep ocean using Sentinel satellite altimetry data. The procedure uses AI to process near-real-time satellite data to see the wavefront of such tsunamis. The ONEWAVE approach would be most beneficial for detecting teletsunamis that propagate across the Pacific or the Indian Ocean, where there is enough time for satellites to fly over the tsunami to be detected.[b]

[a] Deep Blue Globe. Available at www.deepblueglobe.eu/

[b] Deep Blue Globe, "ONEWAVE -Tsunami Verification from Space-". Available at https://onewave.deepblueglobe.eu/

12.3 Improved on-board data processing

Benefiting from the development of greater computing capacities of novel processors and novel ways of processing data, future satellites may not only be able to acquire and transmit satellite imagery down to Earth but also process satellite imagery on board to speed up the use of space-based information in early warning applications. The following example presents information on a project geared to demonstrate the feasibility of such on-board developments.

Earth observation alert[a]

Earth observation alert is a project carried out by a group of partners that includes the Deimos Elecnor Group, the German Aerospace Centre (DLR), the Graz University of Technology, the Polytechnic Institute of Torino, OHB SE and Deimos Imaging. The project benefits from the contributions of the State Meteorological Agency of Spain.

The project aims to incorporate Earth observation data-processing technology within the satellite to speed up the generation of ready-to-use information. The project will develop hardware and software tools to enhance the on-board capacity of satellites to process satellite imagery and generate relevant products. One potential application is to detect and track convective storms as quickly as possible to create relevant and timely alerts.[b]

[a] EO-ALERT, "Objectives". Available at http://eo-alert-h2020.eu/objectives

[b] Deimos Elecnor Group, "A Novel Satellite Architecture for Detection and Monitoring of Extreme Events". Technical Presentation made during the 2020 Session of the Scientific and Technical Subcommittee of the Committee on the Peaceful uses of Outer Space. Available at www.unoosa.org/documents/pdf/copuos/stsc/2020/tech-46E.pdf

12.4 Warning and communication

Experience has shown that warning and communication are essential elements of early warning systems. However, alerts must reach those at risk to respond to such warnings promptly to minimize damages and losses.

Being aware of the need to utilize different types of satellites to communicate warnings, the space community is developing procedures to transmit such warnings via satellites such as those used for global navigation. The following example presents a project implemented by the Government of Japan to contribute to early warning and disaster management efforts in Asia and Oceania.

Satellite Report for Disaster and Crisis Management (DC Report)[a]

The Government of Japan is implementing the Satellite Report for Disaster and Crisis Management as a service to convey warnings and other disaster-related information to people at risk in regions within Asia and Oceania with limited or no telecommunication network available, and when local telecommunication networks have been damaged or are inoperative. The service will convey messages to end users quickly using the Michibiki satellites. These satellites are designed to fly over Japan and complement the GPS network of the United States, so that accurate positioning information is available anywhere in Japan regardless of location. The need for such complementary satellites arises as certain areas in Japan have high topographic relief and normal GPS data. Warning messages and relevant information are expected to be shared via audio and displays using low-power wide-area networks (LPWA network).

The project will include designing and implementing dedicated receivers that can convert data streams from the Michibiki satellites into warnings in various formats (speakers, digital signate, beacon light, etc.). The receivers will also convey the information to the LPWA networks so it can be disseminated to end users.

The project envisions an assessment of requirements in countries in Asia and Oceania, developing the dedicated receivers and testing using scenarios to complete the design of the proposed service.

[a] Japan Aerospace Exploration Agency, “Overview of the First Quasi-Zenith Satellite MICHIBIKI”. Available at https://global.jaxa.jp/countdown/f18/overview/michibiki_e.html

Acronyms

Acronym	Definition
ABI	Advanced Baseline Imager
AIRS	Atmospheric Infrared Sounder
ALOS	Advanced Land Observing Satellite
AOD	Aerosol optical depth
ASAL	Algerian Space Agency
ASIS	Agricultural Stress Index System
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced very high-resolution radiometer
AVISO	Archiving, Validation, and Interpretation of Satellite Oceanographic data
BSM	Burn Scar Mapping
CAMS	Copernicus Atmosphere Monitoring Service
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CERC	Cambridge Environmental Research Consultants Ltd
CGMS	Coordination of Geostationary Meteorological Satellites
CHIRPS	Climate Hazards InfraRed Precipitation with Stations
CIIFEN	International Research Centre on El Niño Phenomena
CLS	Collecte Localisation Satellites, subsidiary of CNES
CME	Coronal mass ejections
CNES	National Centre for Space Studies (France)
CONABIO	National Commission on the Knowledge and Use of Biodiversity
CONAFOR	National Forestry Commission of Mexico
COPUOS	Committee on the Peaceful Uses for Outer Space
COSMO-SkyMed	Constellation of small Satellites for the Mediterranean basin Observation
CSA	Canadian Space Agency
D-SDA	German Satellite Data Archive
DART	Deep-ocean Assessment and Reporting of Tsunami
DART - NASA	Double Asteroid Redirection Test
DE AFRICA	Digital Earth Africa

Acronym	Definition
DEM	Digital elevation models
DEMETER	Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions
DEWS	Drought early warning systems
DInSAR	Differential interferometry synthetic aperture radar
DLR	German Aerospace Center
DMC	Disaster management centre
ECMWF	European Centre for Medium-Range Weather Forecasts
EC-JRC	Joint Research Council of the European Commission
ECV	Essential Climate Variables
EEWS	Earthquake early warning system
EFFIS	European Forest Fire Information System
EMS	Copernicus Emergency Management Services
ENSO	El Niño-Southern Oscillation
EOC	Earth Observation Center
EPIDEMIA	Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment
ERS	European Remote Sensing
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUSPA	European Union Agency for the Space Programme
EVI	Enhanced Vegetation Index
EYWA	EarlY Warning System for Mosquito-borne Diseases
FAN	Friends of Nature Foundation of Bolivia
FAO	Food and Agriculture Organization of the United Nations
FbF	Forecast-based financing
FEWS NET	Famine Early Warning Systems Network
FIRMS	Fire Information for Resource Management System (NASA)
GALILEO	European Global Navigation Satellite System
GDO	Global Drought Observatory
GEO	Group on Earth Observations
GEOGloWS	GEO Global Water Sustainability
GEOSS	Global Earth Observation System of Systems
GFMS	Global Flood Monitoring System

Acronym	Definition
GFZ	German Geosciences Research Centre
GHSL	Global Human Settlement Layer
GIM	Global Ionospheric Map
GIMS	Geodetic Integrated Monitoring System
GLoFAS	Global Flood Awareness System
GLONASS	Global Navigation Satellite System of the Russian Federation
GNSS	Global navigation satellite system
GOES	Geostationary Operational Environmental Satellites
GOES-R	Geostationary Operational Environmental Satellites-R Series (NASA-NOAA)
GOME-2	Global Ozone Monitoring Experiment–2
GPM	Global Precipitation Measurement
GPS	Global Positioning System of the United States
GTS	Global Telecommunication System
GWIS	Global Wildfire Information System
HABs	Harmful algal blooms
HMaaS	Hydrologic Modelling as a Service
HRSL	High-Resolution Settlement Layer
IASI	Infrared Atmospheric Sounding Interferometer
IAWN	International Asteroid Warning Network
ICE Sat	Ice, Cloud and Elevation Satellite
IDNDR	International Decade for Natural Disaster Reduction
IN-MHEWS	International Network on Multi-Hazard Early Warning Systems
InSAR	Interferometric synthetic aperture radar
INPV	National Institute for the Protection of the Vegetation
IRNSS	India Regional Navigation Satellite System
ISRO	Indian Space Research Organisation
ISWI	International Space Weather Initiative
IWMI	International Water Management Institute
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory (NASA)
JPSS	Joint Polar Satellite System (NASA-NOAA)
LEO	Low-Earth orbit
LHASA	Landslide Hazard Assessment for Situational Awareness

Acronym	Definition
LiDAR	Light detection and ranging
LPWA	Low-Power Wide-Area networks
LST	Land surface temperature
MHEWS	Multi-hazard early warning systems
MIR	Middle infrared
MIROVA	Middle InfraRed Observation of Volcanic Activity
MODIS	Moderate resolution imaging spectroradiometer
MoM	Model of models
MOUNTS	Monitoring Unrest from Space
MSI	Multispectral instrument
MTG-I1	Meteosat Third Generation Imager-1 (ESA)
NASA	National Aeronautics and Space Administration of the United States
NBS	National Bureau of Statistics
NEOs	Near-Earth objects
NCCOS	National Centres for Coastal Ocean Science of the United States
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NOAA	National Oceanic and Atmospheric Administration of the United States
NWP	Numerical weather prediction
OC-CCI	Ocean-Colour Climate Change Initiative
OGC	Open Geospatial Consortium
OLCI	Ocean Land Colour Imager
OLI	Operational Land Imager
PPEW	Platform for the Promotion of Early Warning
PTWC	Pacific Tsunami Warning Centre
RDT-CW	Rapidly Developing Thunderstorm - Convection Warning
RISAT	Radar Imaging Satellite
RSMC-ASDF	Atmospheric Sand and Dust Forecast
SACRED	Space Application Centre for Response in Emergency and Disasters of Pakistan
SADMS	South Asia Drought Monitoring System
SANSA	South African National Space Agency
SAR	Synthetic aperture radar
SARTRAC	Teleconnected SARgassum risks across the Atlantic

Acronym	Definition
SATIF	Early Warning System for Forest Fires, Mexico
SATRIFO	Forest Fire Risk Early Warning System, FAN, Plurinational State of Bolivia
SBAS	Small Baseline Subset
SDB	Satellite-derived bathymetry
SDGs	Sustainable Development Goals
SE-CONRED	Guatemala Coordinating Agency for Disaster Reduction
ShakeAlert	Emergency preparedness mobile application
SIAGSE	Joint Italian-Argentinian Satellite System for Disaster Management and Economic Development
SMA	Soil moisture anomaly
SMPAG	Space Mission Planning Advisory Group
SRTM	Shuttle Radar Topography Mission
SST	Sea surface temperature
SUPARCO	Space and Upper Atmosphere Research Commission of Pakistan
SVI	Standard Vegetation Index
SWIR	Short-wave infrared
SWM	Satellite Water Marker
SWOT	Surface Water and Ocean Topography
TCI	Temperature Condition Index
TEC	Total electron content
TIR	Thermal infrared
TIROS	Television Infrared Observation Satellite
TRMM	Tropical Rainfall Measuring Mission
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNOOSA	United Nations Office for Outer Space Affairs
UN-SPIDER	United Nations Platform for Disaster Management and Emergency Response
USGS	United States Geological Survey
VAACs	Volcanic Ash Advisory Centres
VALS	Volcanic alert level systems
VCI	Vegetation Condition Index
VHI	Vegetation Health Index

Acronym	Definition
VIIRS	Visible infrared imaging radiometer suite
VIs	Vegetation indices
VOLCAT	Volcanic Cloud Analysis Toolkit
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WMS	Web Mapping Services
WNV	West Nile virus
WORLD VIEW	High-resolution commercial Earth imaging satellites
WOfS	Water Observations from Space
WSF Evolution	World Settlement Footprint Evolution
WWW	World Weather Watch

Quick reference tables

Examples of space-based resources for
STORM EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas			Potential areas, communities, critical infrastructure, agricultural crops, and roads which may be affected
	Data				
PRODUCTS		Land use/land cover maps			
SERVICES		IAWN	Weather forecasts	Weather forecasts	Impact-based forecasting
		EC-JRC GHSL			
		DLR WSF			Forecast-based financing
		WorldPop	Satellite communications to transmit raw data from the field		
		LandScan			

Examples of space-based resources for
FLOOD EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Polygons of historic floods			Potential extent of flooded areas based on hydraulic modelling
		Exposed areas			
	Data		Satellite-derived estimations of rainfall (GPM)		Potential areas, critical infrastructure, agricultural crops, and roads which may be affected
PRODUCTS		Digital elevation models for flood hazard mapping and modelling			
		Land use/land cover maps			Impact-based forecasting
SERVICES			ECMWF, NOAA, National Meteorological Offices	Weather forecasts	
		Copernicus GLOFAS	Copernicus GLOFAS	Copernicus GLOFAS	
		EC-JRC GHSL	GEOGloWS ECMWF	GEOGloWS ECMWF	
		DLR WSF	FloodHub (Greece)	FloodHub (Greece)	
		WorldPop	Satellite-derived estimations of rainfall (GPM)		
		LandScan	Satellite communications to transmit raw data from the field		

Examples of space-based resources for
AGRICULTURAL DROUGHT EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	Simple indices:	NDVI, EVI, TCI Soil moisture		Potential agricultural/ livestock areas which could be affected Impact-based forecasting Risk transfer (index-based insurance) Forecast-based financing
			Multi-temporal indices:	VCI, SVI, VHI		
	Data		Precipitation	CHIRPS		
PRODUCTS		Digital elevation models for flood hazard mapping and modelling				
		Land use/land cover maps				
SERVICES		IAWN	Weather forecasts		Weather forecasts	
		EC-JRC GHSL	Copernicus GDO		Copernicus GDO	
		DLR WSF	FAO ASIS		FAO ASIS	
		WorldPop	FEWSNET		FEWSNET	
		LandScan	SADMS (Asia)		SADMS (Asia)	
			Satellite communications to transmit raw data from the field			

Examples of space-based resources for
HYDROLOGIC DROUGHT EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	Optical imagery, radar imagery	Water body contraction		Services (provision of electrical energy, irrigation, ship traffic) which may be affected Impact-based warning
	Data		Precipitation	CHIRPS		
PRODUCTS						
SERVICES			Weather forecasts		Weather forecasts	
			Digital Earth Africa			
			Satellite communications to transmit raw data from the field			

Examples of space-based resources for

VOLCANIC ACTIVITY EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	DinSAR, multitemporal radar interferometry to detect uplift in the cone. Detection hotspots (higher temperature than sorroundings). Spatial and temporal dispersion of ash clouds.		Potential areas, communities, critical infrastructure, agricultural crops, and roads which may be affectedy Impact-based forecasting Information for aerial transportation
RAW DATA	*Data*		Differential GPS data to monitor deformations around the cone.		
PRODUCTS		Land use/land cover maps			
SERVICES		EC-JRC GHSL		Satellite telecommunications to warn pilots and ships about volcanic activity	
SERVICES		DLR WSF			
SERVICES		WorldPop	Satellite communications to transmit raw data from the field		
SERVICES		LandScan			

Examples of space-based resources for

EARLY WARNING IN CASE OF MASS MOVEMENTS

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	DinSAR, multitemporal radar interferometry to detect mass movements		Potential areas, communities, critical infrastructure, and roads which may be affected Impact-based forecasting
RAW DATA	*Data*	GPS data for precise location of critical infrastructure	Differential GPS data to monitor deformations in areas prone to mass movements		
RAW DATA	*Data*		Satellite-derived estimations of rainfall (GPM)		
PRODUCTS		Digital elevation models for landslide susceptibility			
PRODUCTS		Land use/land cover maps			
SERVICES		NASA LHASA -2	NASA LHASA -2		
SERVICES		EC-JRC GHSL			
SERVICES		DLR WSF			
SERVICES		WorldPop	Satellite communications to transmit raw data from the field		
SERVICES		LandScan			

Examples of space-based resources for

EARLY WARNING IN CASE OF EARTHQUAKES

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas			Potential areas, communities, critical infrastructure, and roads which may be affected
RAW DATA	*Data*	GPS data for precise location of critical infrastructure	Total electron content from GPS signals (experimental)		
PRODUCTS		Land use/land cover maps			Impact-based forecasting
SERVICES		EC-JRC GHSL	Satellite communications to transmit raw data from the field		
		DLR WSF			
		WorldPop			
		LandScan			

Examples of space-based resources for

EARLY WARNING IN CASE OF NEAR-EARTH OBJECTS (NEOS)

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposure	Imagery from space telescopes		Potential urban and rural areas which may be affected
PRODUCTS		Land use/land cover maps			Impact-based forecasting
SERVICES		IAWN	IAWN	Satellite telecommunications	SMPAG for potential deflection of NEO in outer space
		EC-JRC GHSL			
		DLR WSF			
		WorldPop			
		LandScan			

Examples of space-based resources for

EARLY WARNING IN CASE OF SPACE WEATHER

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposure	Imagery from space telescopes		Potential areas, communities, critical infrastructure, and services (electrical energy, telecommunications) which may be affected
PRODUCTS					
SERVICES		EC-JRC GHSL	National Space Weather Forecasting Centres	Satellite telecommunications	Impact-based forecasting
		DLR WSF			
		WorldPop	National Space Agencies in selected countries		
		LandScan	Astronomical observatories		
			European Space Agency		
			Helmholtz Centre in GFZ		

Examples of space-based resources for

TSUNAMI EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	DinSAR and multitemporal radar interferometry to detect mass movements or lateral deformation of cones in island volcanoes		Bathymetry for tsunami propagation near the shore Digital elevation models for tsunami propagation modelling inland Land use/land cover maps
	Data	GPS data for precise location of critical infrastructure	GNSS data from stations in coastal areas and in DART buoys		
			Gravity waves		
PRODUCTS		Bathymetry for tsunami propagation near the shore			
		Digital elevation models for tsunami propagation modelling inland			
		Land use/land cover maps			
SERVICES		EC-JRC GHSL	Satellite communications to transmit raw data from the field	Satellite telecommunications to transmit warnings across regions and continents and to small island States	
		DLR WSF			
		WorldPop			
		LandScan			

Examples of space-based resources for

STORM SURGE EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas			Potential coastal areas, communities, critical infrastructure, and roads which may be affected
	Data	GPS data for precise location of critical infrastructure			
PRODUCTS		Bathymetry for storm surge propagation near the shore			Impact-based forecasting
		Digital elevation models for storm surge propagation modelling inland			
		Land use/land cover maps			
SERVICES		EC-JRC GHSL			
		DLR WSF			
		WorldPop			
		LandScan			

Examples of space-based resources for

EARLY WARNING IN CASE OF HARMFUL ALGAE BLOOMS (HAB)

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING	WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	HAB detection and monitoring		Potential coastal areas, communities, and coastal liveli-hoods which may be affected
PRODUCTS					Impact-based forecasting
SERVICES			National centres like NCCOS of the United States	National centres like NCCOS of the United States	
			ESA Ocean-Colour Climate Change Initiative	ESA Ocean-Colour Climate Change Initiative	

Examples of space-based resources for

EARLY WARNING IN CASE OF MALARIA, MOSQUITOS AND CHOLERA

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	HAB detection and monitoring			Potential areas and communities which may be affected
			Simple indices:	NDVI, EVI, SAV, NDWI, Satellite Water Marker index (SWM)		
	Data		Precipitation	CHIRPS		Impact-based forecasting
			Climate	Temperature, humidity, soil moisture, sea surface temperature		
			Climate	Essential Climate Variables (ECVs)		
PRODUCTS						
SERVICES		EC-JRC GHSL	EPIDEMIA (Ethiopia)			
		DLR WSF	EYWA (Greece)			
		WorldPop				
		LandScan				

Examples of space-based resources for

EARLY WARNING IN CASE OF LOCUST SWARMS

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	HAB detection and monitoring			Potential areas, communities, agricultural areas, and livelihoods which may be affected
			Simple indices:	NDVI		
	Data		Precipitation	CHIRPS		Impact-based forecasting
			Climate	Temperature, soil moisture		
PRODUCTS						
SERVICES		EC-JRC GHSL	FAO Locust Hub Soil Moisture Service			
		DLR WSF	EYWA (Greece)			
		WorldPop				
		LandScan				

Examples of space-based resources for

EARLY WARNING IN CASE OF SARGASSUM

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	Simple indices:	NDVI, NDWI		Potential coastal areas, communities, and livelihoods which may be affected
PRODUCTS						Impact-based forecasting
SERVICES			SARTRAC		SARTRAC	
			SAMtool (CNES)			

Examples of space-based resources for

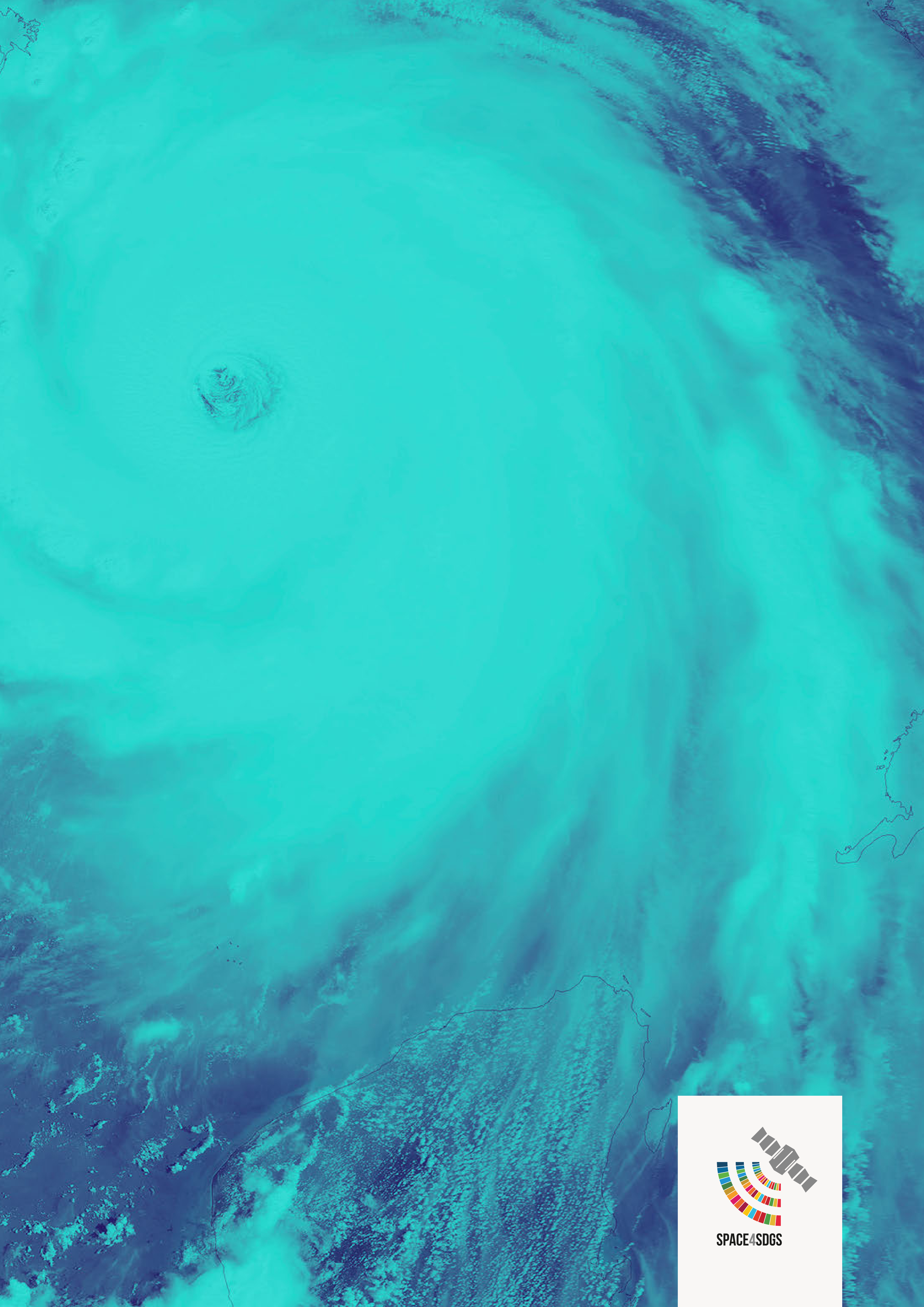
FOREST FIRE EARLY WARNING

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	Simple indices:	NDVI		Potential areas, communities, critical infrastructure, and agricultural crops, which may be affected
	Data		Temperature	Hotspots, thermal anomolies		Impact-based forecasting
			Weather	Temperature, precipitation		
PRODUCTS		Land use/land cover maps				
SERVICES		EC-JRC GHSL	NASA FIRMS and Worldview		NASA FIRMS and Worldwiew	
		DLR WSF	Copernicus/GEO/NASA GWIS		Copernicus/GEO/NASA GWIS	
		WorldPop	EFFIS (Europe)		EFFIS (Europe)	
		LandScan	SATIF (Mexico)		SATIF (Mexico)	
			FigrHUB (Greece)		FigreHub (Greece)	
			SATIFRO (FAN, Bolivia)		SATIFRO (FAN, Bolivia)	
			BurnMonitor (California, United States, experimental)		BurnMonitor (California, United States, experimental)	
			Mayday ai (commercial)		Mayday ai (commercial)	

Examples of space-based resources for

EARLY WARNING IN CASE OF DUST STORMS AND POOR AIR QUALITY

		RISK ASSESSMENT	HAZARD MONITORING AND FORECASTING		WARNING COMMUNICATION	PREPAREDNESS
RAW DATA	*Satellite imagery*	Exposed areas	Simple indices:	NBR, dNBR		Potential areas, communities, and critical infrastructure which may be affected Impact-based forecasting
	Data		Temperature	Hotspots, thermal anomalies		
			Weather	Temperature, precipitation		
PRODUCTS		Land use/land cover maps				
SERVICES		EC-JRC GHSL	WMO Barcelona Dust Regional Centre		WMO Barcelona Dust Regional Centre	
		DLR WSF	Copernicus CAMS		Copernicus CAMS	
		WorldPop	airTEXT (Latvia)		airTEXT (Latvia)	
		LandScan				



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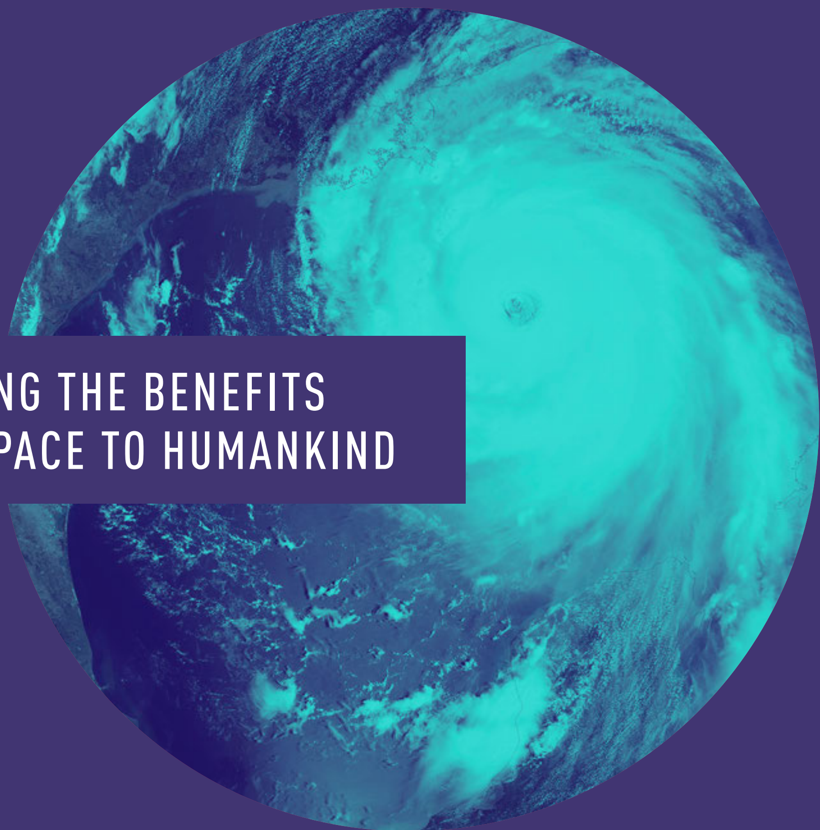

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