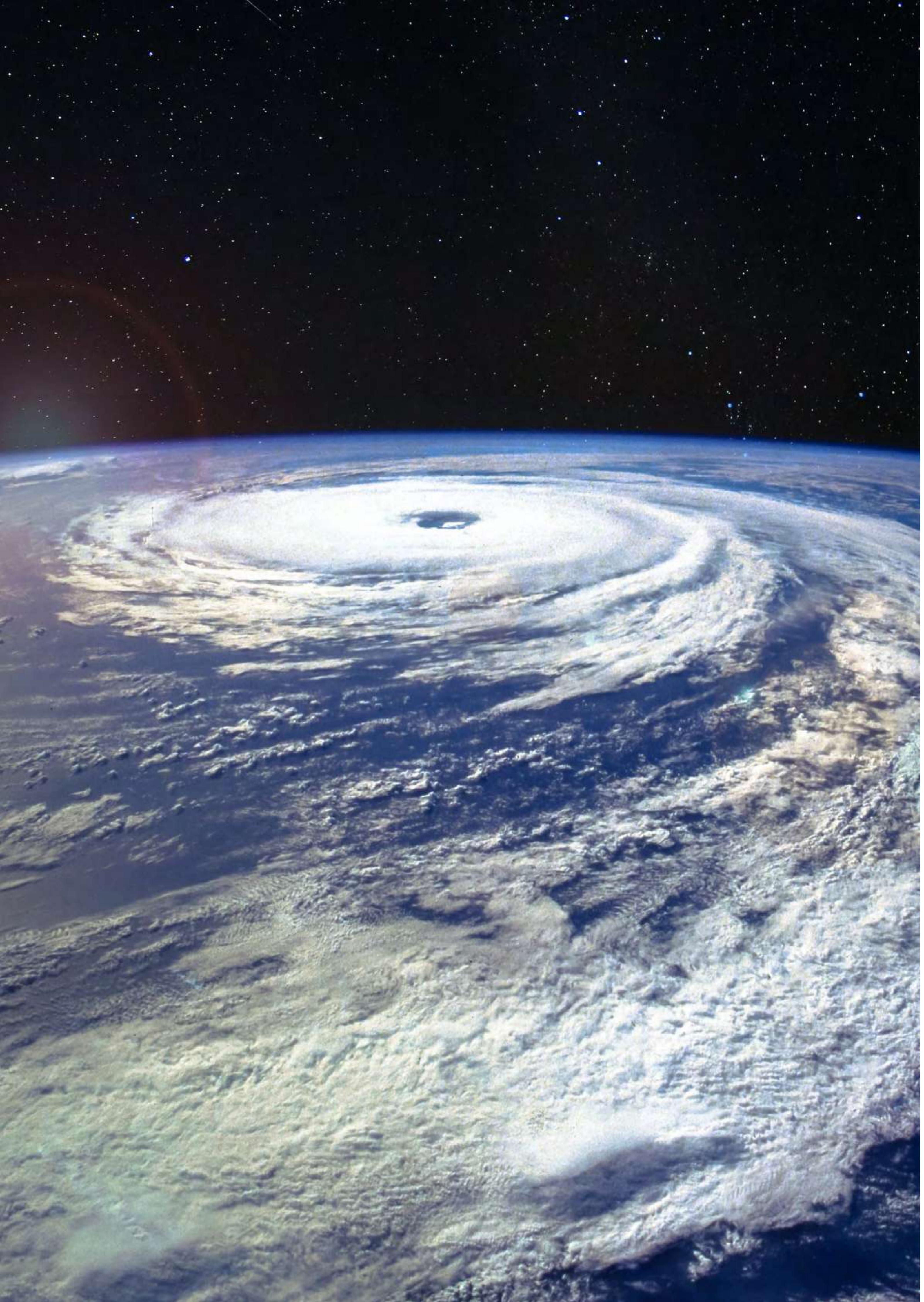
Research Fund

New Tech for *Nat Cat*

Unlocking the Power of Remote Sensing & Artificial Intelligence to Anticipate and Mitigate Natural Disasters



JULIA D'ASTORG

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HEAD OF THE AXA RESEARCH FUND

Foreword

The first months of 2025 have been a reminder of the escalating challenges posed by natural catastrophes globally. Unprecedented wildfires swept through Los Angeles, driven by record-breaking heat and prolonged drought, while a powerful earthquake in Myanmar deepened the humanitarian crisis in an already vulnerable region. In the Philippines, the sudden eruption of the Kanlaon Volcano disrupted lives, agriculture, and infrastructure across the Visayas, and in Iraq, a massive sandstorm turned the skies red, triggering widespread respiratory illnesses. These events are not isolated anomalies anymore. As their frequencies and intensities increase, they are now forming an alarming trend, with far-reaching consequences.

Remote sensing and artificial intelligence (AI) have emerged as transformative tools, offering unprecedented capabilities to monitor environmental changes, model risks and respond to disasters. High-resolution satellite imagery and drone surveillance now provide "real-time" insights into evolving hazards. Meanwhile, AI algorithms process vast and complex datasets to uncover patterns and – when coupled with the human brain – they help in forecasting events, and supporting decision-making before, during, and after crises. Beyond their incredible technical capabilities, these technologies taken together promise to reshape our approach to risk management and disaster risk governance, notably by making it more anticipatory, inclusive, and equitable.

As a leading insurer and responsible private sector player, AXA is committed to addressing these challenges head-on. Through the AXA Research Fund, now part of the AXA Foundation for Human Progress, AXA's global scientific philanthropy initiative supporting risk research, we have supported more than 50 projects at the intersection of remote sensing, AI, and disaster management. These initiatives aim to advance our understanding of natural catastrophes, develop innovative tools for risk mitigation, and foster resilience in the face of an uncertain future.

This publication arrives at a pivotal moment. It brings together the insights and expertise of AXA-supported leading scientists and thought leaders, showcasing how these technologies are already being deployed to address natural hazards — and how much further we can go. It highlights the transformative potential in shifting from reactive to preventive disaster management, while addressing the societal, economic, and policy implications of their adoption.

Introduction

Harnessing *artificial intelligence and remote sensing* for a safer future

With their frequency and intensity escalating due to climate change and human activities, natural catastrophes are among the most pressing challenges of the 21st century. These disasters, ranging from floods, wildfires, and hurricanes to earthquakes and volcanic eruptions, pose significant threats to human lives, ecosystems, and economies. Between 2000 and 2019, over 1.23 million lives were lost, and more than 4 billion people were affected by disasters and $2.97 trillion in economic losses globally. These events have cascading impacts, often amplifying vulnerabilities, disrupting critical infrastructure, food security and livelihoods, particularly in the most exposed and vulnerable regions of the world.

The increasing complexity of these risks calls for a paradigm shift in how we understand, predict, and manage natural catastrophes. Traditional approaches to disaster management, which rely on historical data and reactive measures, are no longer sufficient in the face of unprecedented and rapidly evolving hazards. Instead, there is an urgent need to adopt proactive, data-driven strategies that allow us to anticipate and mitigate risks before they materialize.

Remote sensing and AI have emerged as transformative tools in this context, offering unprecedented capabilities to monitor, model,

and respond to natural disasters.
Remote sensing technologies, including satellite imagery, LiDAR, and drones, provide high-resolution, real-time data on environmental changes, paving the way to a comprehensive understanding of hazards and their drivers. AI, on the other hand, excels in processing and understanding vast and heterogeneous datasets, uncovering trends – and when coupled with human intelligence – allows the generation of actionable insights. Together, these technologies are revolutionizing disaster management by enhancing early warning systems, improving risk assessments, and enabling more targeted and effective interventions.

However, the integration of remote sensing and AI into disaster management does not come without challenges. Data quality, accessibility, and resolution remain significant barriers, particularly in data-scarce regions such as parts of Asia and Africa. Additionally, the development of localized models that account for regional specificities and vulnerabilities is critical to ensure the effectiveness of these technologies. Addressing these challenges requires a concerted effort to invest in research, capacity building, and equitable technology transfer, particularly for the most vulnerable communities.

This report delves into the multifaceted role of remote sensing and AI in addressing natural catastrophes, exploring their applications across various hazards and regions. It highlights the transformative potential of these technologies in shifting from reactive to preventive disaster management, while also addressing the societal, economic, and policy implications of their adoption. By improving our understanding of innovative technologies for natural catastrophes, we can build a more resilient and sustainable future.

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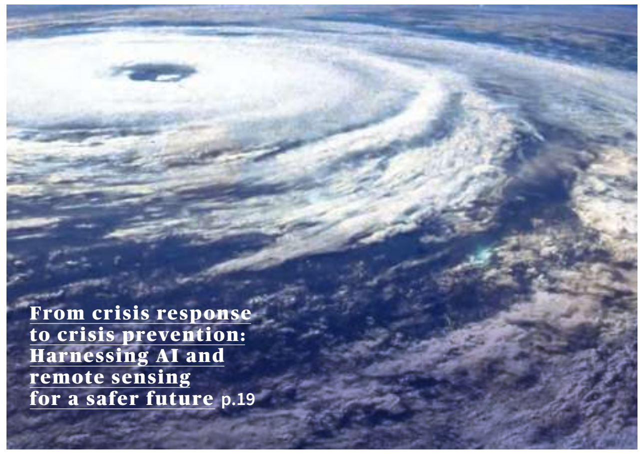

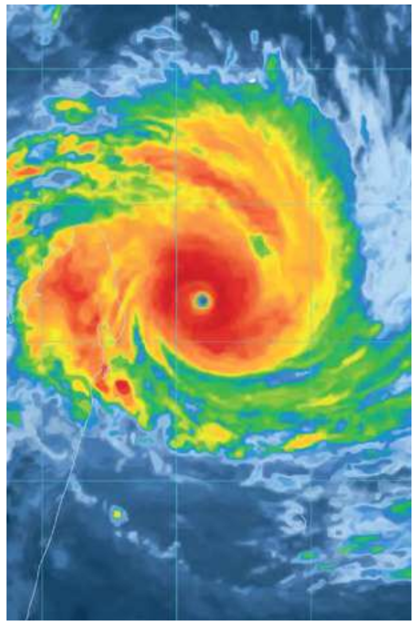

01 How remote sensing and artificial intelligence change the scientific approach to natural risks

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is a Research Director at INRIA in France, specializing in image analysis, remote sensing, machine learning, and artificial intelligence. He has held visiting positions at Stanford University, KTH, NUS, and UCLA, and is an Adjunct Professor at the University of Iceland. He held the AXA Chair in Remote Sensing at the Chinese Academy of Sciences, Aerospace Information Research Institute in Beijing.

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02 The road towards actionable impact forecasting - predicting potential destruction rather than water height or shake magnitude

BRUNO MERZ
is Head of the Hydrology Section at GFZ Helmholtz Centre for Geosciences and a Professor at the University of Potsdam. His research focuses on hydrological extremes, risk management, and climate adaptation. He has pioneered the integration of flood hazard and vulnerability research by combining natural sciences, engineering, and social sciences. He led an AXA Joint Research Initiative on seasonal forecasting of flood frequency.

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03 New approaches to early warning systems

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04 Towards better risk management at a societal level

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is a Senior Researcher at the University Gustave Eiffel and director of the Institute of Earth Sciences of Grenoble. His research focuses on seismic risk analysis in urban areas, primarily relying on observational data or data collected after earthquakes. He led an AXA Joint Research Initiative on strong seismic prone regions.

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04 Towards better risk management at a societal level

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is Head of Claims P&C Retail and Motor Corporate at AXA Belgium since 2021. With extensive experience across various operational domains within AXA, he has held key roles in Retail Banking, Underwriting P&C Retail, and Claims Management. In his current position, he focuses on driving innovation and operational excellence within the claims function by utilizing data, technology, and industry best practices.

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Challenge

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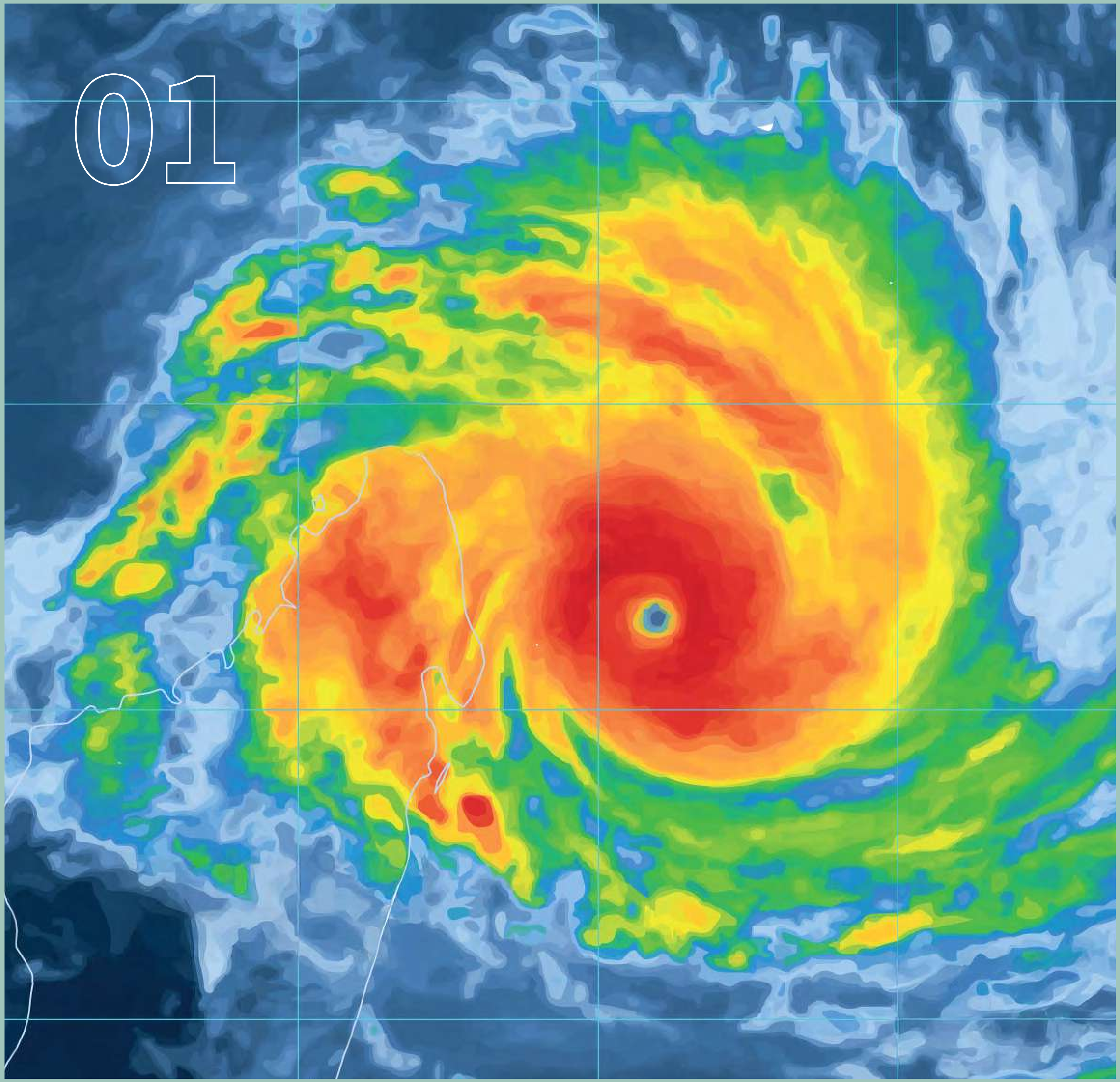


How *remote sensing and artificial intelligence* change the scientific approach to natural risks

ARTICLE

All eyes on the planet

Combatting natural disasters with Earth Observation and artificial intelligence

PROF. JOCELYN CHANUSSOT
INRIA, France and Chinese Academy of Sciences, China

— Natural disasters have a skyrocketing impact on our society

From wildfires, landslides and earthquakes to extreme meteorological events such as droughts, floods and hurricanes, natural disasters are a major threat to our society, with 1.5 million casualties over the past 20 years and skyrocketing economic impacts – trillions USD for the past decade and an increasing trend.
Some of these events are directly triggered by climate change, and most of them see their impact greatly increased because of climate change. For example, the impact of wildfires on arid agricultural land is wide and long lasting: wildfires disrupt the capacity of humans to feed themselves and the very structure of local societies. They can also destroy local biodiversity in areas that are not historically prone to fires and that have not evolved over hundreds of thousands of years to recover from them.

There is hence a strong and pressing need for better risk assessments and for efficient emergency responses. Novel technologies, including remote sensing and artificial intelligence, help us protect ourselves better against natural risks – whether before, during, or after the event. For example, frequent mapping of the ground and sky at high spatial resolution helps us reach a better understanding of local vulnerability and trigger appropriate counter actions; but it also helps us map the damages following the event and thereby contribute to ease the work of first responders.

Understanding the natural and human causes driving natural disasters is also a key issue. Indeed, while labeled 'natural', the alarming frequency of occurrence of natural hazards and their increasingly devastating impacts are to some extent due to the increasing pressure of human activities on the environment. For instance, increasing urban areas reduces the capacity of the ground to absorb water and eventually leads to severe consequences if there is a huge and sudden rainfall – and the fact that very dry soil will not absorb water has similar effects. Better understanding of natural catastrophes and their drivers helps design more resilient infrastructures and draw more sustainable urban planning policies. To do so, we need to observe and monitor of the processes that have been identified as relevant, and they are numerous – vegetation, city sprawling, ground deformation, snow cover and meteorological conditions are just a few of the drivers we need eyes on.

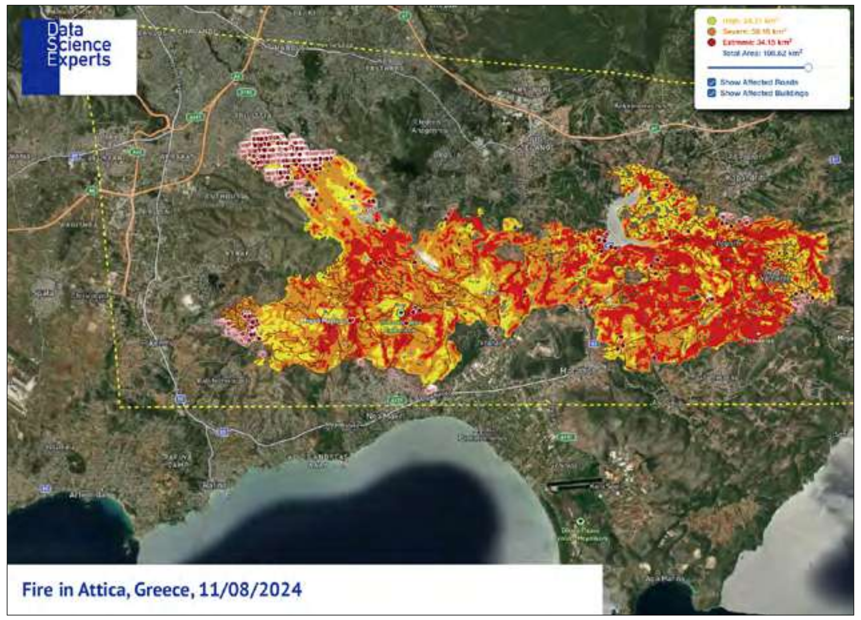
— Remote sensing technologies: our many eyes to monitor the environment

To address these challenges with high societal impact, new resources are increasingly available.
The appearance and flourishing development of very high-resolution sensors has been driving a technical revolution in the field of satellite remote sensing in the last decade.
These sensors allow for the observation of the planet with a wide coverage and a very high spatial resolution, at essentially no cost for the user, and with a very short revisit time. Both radar remote sensing and optical remote sensing (in the visible, near infrared or thermal domain, using multispectral imagers, which record several wavelengths in one shot, or hyperspectral ones, that record more than 100 wavelengths in a shot) benefit from this technological shift. It allows us to access various physical characteristics on the ground. For instance, thermal data can measure the temperature. Hyperspectral data can recognize different minerals. Standard optical data provide information about the land use, including man-made structures, vegetation or agricultural fields. Interferometric radar data can measure small displacements on the ground due to earthquakes or landslides, by analyzing the phase difference of signals received from two different antennas detecting the signal from different directions.
The resolution of remote sensing sensors increases in different ways:

> *'The new generation of remote sensors and satellite constellations allow for a high spatial resolution, high frequency imaging of pretty much everywhere on Earth. Multispectral imaging lets us better identify objects based on the wavelength they reflect.'*

Spatial resolution: Objects that are one-meter large or even less can nowadays be resolved with certain imaging techniques. That opens the door for very accurate geometrical analysis of objects present in scenes of study with unprecedented precision, including for example roads and buildings.

Spectral resolution: The spectral information is instrumental for accurate analysis of the physical components present in one scene. This is of critical importance for several key issues in precision agriculture (to monitor hydric stress, growth status, etc.), mineral exploration and soil composition, detection and monitoring of pollution, including methane in the atmosphere, oil spills etc. After decades of using multispectral remote sensing, most of the major space agencies now have



Map of the Attica wildfire impact, in August 2024 in Greece, based on remote sensing data provided by the Copernicus Sentinel satellites. The data allows scientists to map the extent of the event, and AI helps assess the severity of the damage on each point on the ground (image courtesy of Data Science Experts).

Maps of the Riverine flood impact, in July 2022 in Australia, based on remote sensing data provided by the Copernicus Sentinel satellites. Here again, beyond the mapping of the extent of the event (in purple, left), AI can assess the severity of the flood with an estimation of the water depth for each point on the ground, even in urban areas (right) (Image courtesy of Data Science Experts).

new programs to launch hyperspectral sensors. These record 'reflectance' – that is, light reflected from the Earth's surface – in hundreds of narrow and contiguous spectral bands, which allows them to distinguish between different materials that may have a similar optical signature when detected with older sensors.

Temporal resolution: Due to the launch of satellite constellations and the increasing number of operating systems, the waiting time between two acquisitions over a given scene of interest has dramatically decreased, from the typical duration of 5 days with Sentinel missions down to less than a day for the coming FireSat constellation, that will focus on the management of wildfires.

This opens the door to accurate monitoring of abrupt changes and to efficient response in the case of major disasters such as earthquakes, landslides or the early detection of a starting wildfire. Temporal phenomena with longer scales such as soil erosion, retreat of glaciers, drifting icebergs can also be monitored.

In parallel to the growing availability of satellite-based remote sensing data, airborne-based platforms and light unmanned aerial vehicles (drones) are a tremendous opportunity to provide additional complementary information, with a great flexibility.

Finally, crowdsourcing is another important source of distributed information. The analysis of social media posts and data is an insightful source of very localized information, with very high semantic value. As a result, unprecedented quantities of digital data are available, with heterogeneous scales and modalities.

— AI offers a unique way to exploit the data from our many eyes

Today, due to the complexity of the phenomena that are involved and the size and diversity of the data that are acquired by the new generations of remote sensing sensors, standard data processing techniques sometimes fail.

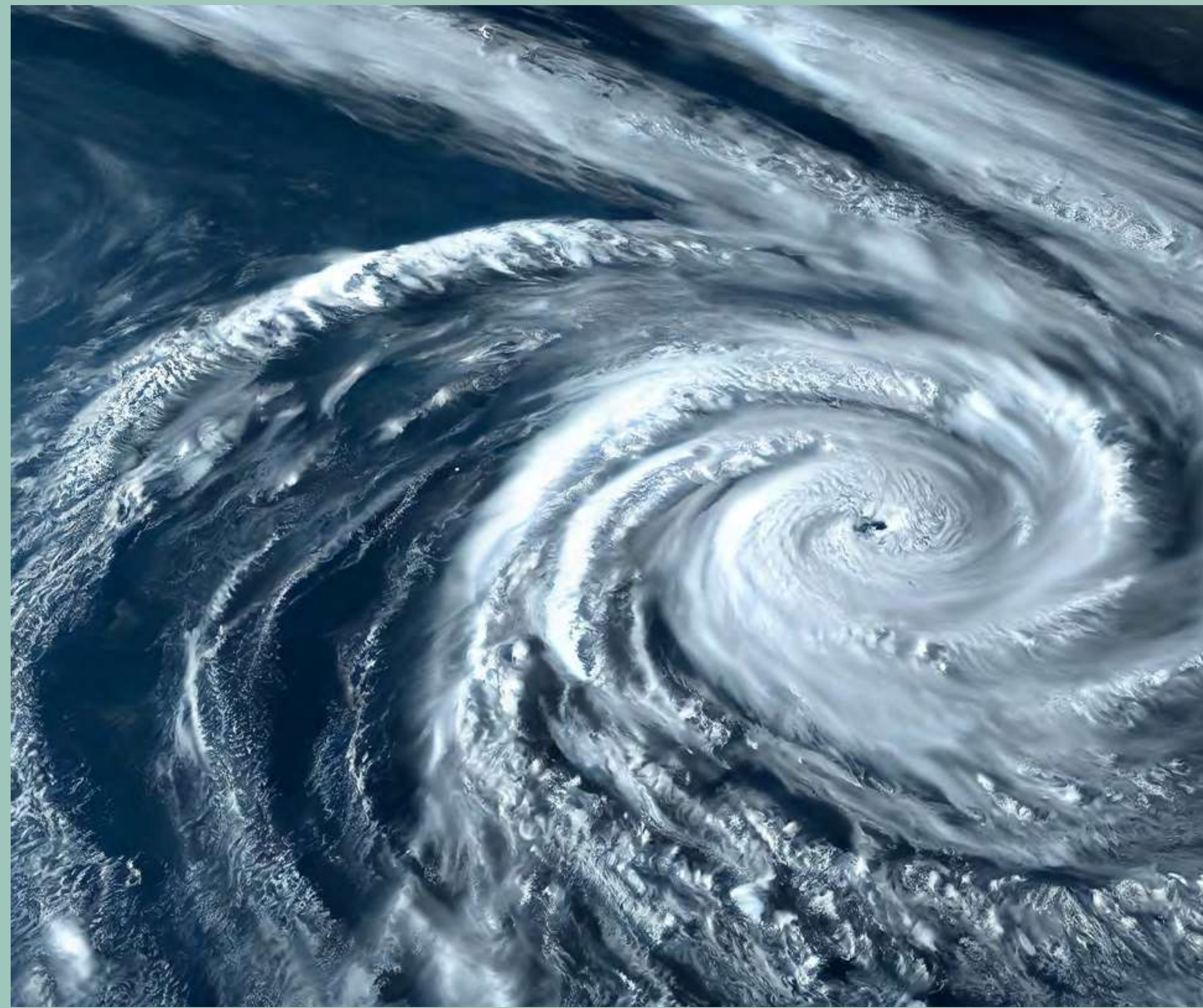
As of now, artificial intelligence systems are the only ones that can handle such heterogeneous and massive sources of information to the required level. Deep learning techniques – including for instance manifold and graph-based representations and data fusion[1] – provide the perfect tool to catch relevant patterns in the data and help us understand and analyze them. For example, data acquired on the same area but at different dates may vary significantly because of the acquisition conditions, and this can lead to wrongful detection of changes on the ground. Using mathematical graphs (manifold representation of the information), we can compensate for the changes of acquisition conditions, hence letting the algorithm understand that the actual situation on the ground has not changed.

While deep learning-based strategies for the analysis of satellite remote sensing data played a critical role in the past decade, they still face a number of challenges, including data quality issues such as noise, missing values (for instance due to cloud coverage), domain shift (from one data to another, one location to another or one sensor to another) or sensor errors (calibration) that can degrade model performance. Also, the process of labeling large datasets for training AI models is time-consuming, expensive and prone to human error, which affects the accuracy and reliability of the models. This points at the emerging importance of self-supervised learning strategies and few-shot learning algorithms. AI algorithms may also inherit biases from the training data, leading to skewed predictions, especially when the data is not representative of diverse geographic or environmental conditions. Finally, specific expertise may be required to ensure the AI systems are trained properly or to correct potential flaws in the AI-derived results, for instance photointerprets in remote sensing imaging. Therefore, while AI systems are very powerful and can help to automate many tasks and perform tasks that we would not be able to master otherwise, it is of utmost importance to 'keep humans in the loop'[2]. For example, in the aftermath of the 2021 earthquake in Haiti, remote volunteers – away from the scene – helped to rapidly map the affected areas to support the aid effort in a remarkable display of crowdsourced teamwork[3].

— AI and remote sensing trends for the near future

In remote sensing technology, the current trend is in developing smaller platforms, named CubeSats, that can be launched in constellations, allowing for a more agile global coverage. Drone-based acquisitions are also used more and more to offer a local highly flexible monitoring solution[4]. Both types of acquisition are needed to face current challenges.
In AI, the current trends are multifold. On the one hand, large generic models named 'foundation models' are trained and made available to tackle more and more specific applications – requiring only fine tuning and a limited amount of new training data, therefore leveraging the genericity of the large pre-trained models[5]. On the other hand, there is also a trend for very small, specialized models allowing AI algorithms to be embedded directly onboard satellites, where the inference calculations can be performed ('edge AI'). These small models can also be used for training and retasking other AI systems[6]. Both AI and remote sensing have reached a level of technical and scientific maturity that allows for unprecedented environmental monitoring – a key step to fight natural disasters.

1 Miller et al., 2024 ; Harb et al., 2017 ; Zhao et al., 2025 – **2** Buscombe, et al., 2022 – **3** Soden et al., 2014 – **4** Prado Osco et al., 2021 – **5** Montillet et al., 2024 – **6** Bui et al., 2024



ARTICLE

Artificial intelligence and remote sensing take exposure, hazard, and vulnerability assessments to another level

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Natural catastrophes can lead to disastrous loss of human life and destruction of the natural environment, private property and public infrastructure. Given the potential magnitude of these losses, it is essential to understand and effectively manage these risks.

Over the past 30 years, the assessment of natural-event-related costs has evolved significantly from simple statistical extrapolations to complex natural catastrophe models. Indeed, losses were initially estimated based on historical data, but the unexpected impact of Hurricane Andrew in the Bahamas and the USA in 1992 – with actual losses tripling the estimates – highlighted the flaws of such strategies and drove a shift in the modeling of natural catastrophes. The approach that emerged at the time has now become the accepted framework of risk assessment: we need to characterize exposure, hazard, and vulnerability as the main risk drivers and look at how they interconnect[1].

However, even with this approach, accurate risk assessments of natural events are challenging. They depend on the quality of exposure data, but also on the complex and evolving nature of extreme events largely influenced by climate change. Vulnerability assessment is a multidimensional challenge in its own right, clouded by much uncertainty, as it reflects the intricate interactions between physical infrastructure, socio-economic adaptive capacities and the dynamic degradation of systems under increasingly unpredictable environmental drivers.

New technologies, and in particular remote sensing and artificial intelligence, now provide ever better data – more qualified, more accurate, timelier – and more powerful ways to leverage this data to enhance our assessments of natural hazard, exposure and vulnerability worldwide.

— Understanding natural hazards using AI and remote sensing

Hazard models simulate the probabilistic landscape of natural events, from rare catastrophic scenarios (such as earthquakes) to frequent occurrences that can generate significant cumulative annual losses (such as severe convective storms and hail events). The point of these simulations is to include all physical events that are theoretically possible but may have never been observed.

However, historical observations do not contain enough rare, impactful extreme events to enable this type of risk assessment. Indeed, most hazard models use traditional statistical methods for risk assessment: they address the lack of data by statistically inflating datasets when such models mostly generate variations of historical events, rather than the entirely new scenarios that are highly probable in a non-stationary and complex climate.

Therefore, the advent of AI-driven models marks a paradigm shift in risk management strategies, notably for meteorological hazards.
For example, AXA and NVIDIA are collaboratively exploring the potential of using an AI weather model for hurricane risk assessment. We generate large ensembles of physically possible but not yet observed hurricanes, exploring what could have happened in the past and what might happen in the future. This includes not only individual storm scenarios but also entire synthetic hurricane seasons, providing a rich dataset for hazard assessment. Similar strategies are being investigated to improve flood hazard assessment by using AI-driven weather models to simulate millions of physically possible but not yet observed precipitation events.

In order to validate the models, observations of what actually occurred on the ground are necessary. Recent advancements in satellite capabilities offer new opportunities to ensure predictions are close to actual observations, in particular in areas previously lacking in-situ observations. For instance, synthetic aperture radar (SAR) constellations provide critical flood data such as flood spatial extent, that is the geographical area affected by flooding, irrespective of the water depth.

EARTH HAZARDS MONITORED THROUGH SATELLITE OBSERVATION

Natural hazard	Useful Satellite Data Types
Floods	**High-resolution optical** imagery to map flood extent. **Elevation data** to identify flood-prone areas. **Radar/SAR** data for flood mapping due to its ability to penetrate clouds and water. Accuracy is limited in urban areas.
Droughts	**Thermal infrared** data for soil moisture and water stress. **Drought indices** derived from satellite data. **Radar/SAR** data for soil moisture.
Sea Level Rise	**Satellite altimetry** data to measure changes in ocean surface height. **Optical and radar** imagery to monitor coastal inundation and shoreline changes.
Tropical Cyclones	**Geostationary** satellite imagery for continuous tracking. **Infrared** data for cloud temperature. **Microwave** data (including radar) for internal storm structure and rainfall intensity.
Earthquakes	**High-resolution optical and radar** imagery to assess damage to buildings and infrastructure after an earthquake. **SAR interferometry** to measure ground deformation.
Wildfires	**Thermal infrared** imagery for active fire detection and temperature measurement. **Optical** imagery to map burned areas and smoke. **Radar/SAR** data for all-weather monitoring and detecting changes in biomass.
Coastal Changes	**High-resolution optical** imagery to monitor coastal erosion and shoreline changes. **Radar/SAR** data for mapping coastal areas and detecting changes. **Elevation data** for vulnerability to sea-level rise.

'Ongoing advancements in satellite technology and AI are expected to significantly strengthen their contribution to data-driven risk management strategies, pushing the ability to manage natural catastrophe risks effectively at individual locations, while simultaneously overseeing sites worldwide on a regular basis.'

These datasets provide resources for rigorous 'backtesting' – probing the model accuracy on past events – and highlighting where hazard models need to be refined[2].

— Exposure – when satellite data gives access to land cover data, from desert to city

Land cover data describe whether the land is covered by forests, agricultural fields, urban areas, property and buildings, and so on. Understanding this precisely at a high spatial resolution helps quantifying how exposed the area is, in the event of a natural hazard – an earthquake hitting a populated area will not lead to the same damage as one hitting an inhabited region.

Exposure is the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas, according to the United Nations Office for Disaster Risk Reduction. Measures of exposure include the number of people or types of assets in the area. To estimate quantitatively the risks associated with a specific hazard in a specific area, measures of exposure are combined with the specific vulnerability and capacity of the exposed elements to a particular hazard.

From the insurers' point of view:
The exposure component contains the insurance portfolio's information: the buildings' locations and their key physical properties (e.g. structure, occupancy, year of construction). Over the past 5 to 10 years, insurers have significantly improved the collection process of information characterizing their clients' exposure. While underwriting-provided information remains one of the primary data sources, satellite data can substantially enhance the completeness and precision of such information and potentially provide additional valuable insights.

For instance, automatic extraction of building footprints from high-resolution imagery can help in a better geolocation of insured sites (see Pierre du Rostu's interview page 69). Multispectral satellite imagery gives access to 'spectral signatures' – that is, signals very specific to an object or material – that facilitate identification of roof materials such as metal, tile, and asphalt. Finally, machine learning algorithms can classify construction materials including wood, concrete, and brick. Construction materials affect how a building would respond in case of a wildfire or hailstorm for example.

— Vulnerability – applying AI to satellite data to better understand the effects on what matters to us

Broadly speaking, vulnerability refers to the connection between a hazard and its potential effects on humans, animals, land and buildings. In natural catastrophe models, we introduce 'vulnerability functions' to mathematically translate hazard intensity (like wind speed) into expected damage percentages for different types of assets. These functions are developed through engineering analysis, historical loss data, satellite data and expert judgment to estimate financial impacts across insurance portfolios. Many studies point out the large differences in vulnerability models – and often ignored uncertainty, that lead to potentially large errors in risk estimations[3].

Systematic data collection of damage information and its associated hazard intensity is therefore vital to characterize the impact of natural hazards on land and buildings. Some research uses AI techniques, in particular Large Language Models (LLM)[4], to develop impact databases that can be used in impact forecasting, early warning, and disaster risk management. The database includes information on deaths, injuries, homelessness, displacements, affected individuals, damaged buildings, and economic damages. It is created using natural language processing techniques and includes data from Wikipedia and open-access research articles.
In addition, AI combined to satellite data can help in better understanding vulnerabilities to specific perils. For example, flood protection standards can be improved using new automated tools, which extract best levee and floodwall heights and widths from high resolution terrain data. The flood protection standards then help in designing and implementing flood defense systems, such as levees, floodwalls and drainage infrastructure[5].

Finally, vegetation encroachment can be assessed using satellite data to detect trees and vegetation near structures, thereby improving the risk of windstorm and wildfire risk respectively.

1 Deroche, 2023 – **2** Bates, 2022 – **3** Wing et al., 2020 – **4** Li et al., 2025 – **5** Zhao et al., 2023

INTERVIEW

—

Natural catastrophes in a changing climate

PROF. MARKUS DONAT
Barcelona Supercomputing Center, Spain

— Many natural catastrophes arise from what meteorologists call weather and climate extremes. European cities suffer from more frequent floods related to extreme precipitation events, such as Valencia in October 2024. In South Ethiopia, devastating landslides followed intense rainfall in July 2024. When they occur in the wrong place, at the wrong time, these extremes can cause devastation and casualties. What controls the occurrence of extreme climate and weather events, such as storms, heatwaves and droughts?

Markus Donat: There are many factors that affect the occurrence of extreme events, and this can get very subtle and complex as processes acting at multiple time scales and spatial scales intertwine. You have for example regional interactions between the atmosphere and the soil, and how they exchange humidity and heat. The weather is also impacted by seasonal or inter-annual, and even longer time-scale, climate variability, such as the 'El Niño' Southern Oscillation. El Niño is a mode of variability in the tropical Pacific Ocean with a cycle typically lasting 4-7 years, but it has impacts in many regions of the globe. For example, a temperature change in certain parts of the ocean can trigger an atmospheric response, which, in turn, impacts weather and climate over land. These influences are geographically remote, which is why we talk of 'teleconnections'. Another example is the Atlantic Multidecadal Variability, a variation in North Atlantic Ocean temperature that affects weather in Europe, North America and parts of Africa.

This means that when we are trying to predict events occurring on a specific time scale, we need to understand and predict how this time scale is affected by various drivers, each acting on their own time scales.

Marine heat waves, for example, are climate extreme events on their own that can last over weeks or even months, with large impacts on biodiversity and fisheries. But they can also have cascading effects, and they can be drivers of other extreme events[1], such as storms fueled by the warm waters with additional vapor and energy. The Derecho storm of 2022 in the Mediterranean wouldn't even have developed to the Derecho threshold without a marine heat wave in the waters below; and neither would have the storm Daniel intensified so massively in September 2023, which brought heavy rainfall and flooding to southeastern Europe and later Libya, where the associated flooding broke dams and led to several thousand deaths.

— How does climate change affect these drivers leading to natural catastrophes?

M. D.: Climate change is not only a global trend of temperature rise: it also affects locally the different drivers of weather and climate extremes.
The longer-term effects of climate change, such as global warming, which is a slow trend that can bring us into different climate regimes and that can even change the specific roles some physical processes play in driving certain events. Indeed, for an extreme event to occur, contributions from other drivers such as the atmospheric circulation can be weaker, because the weather variations happen in a warmer and potentially moister atmosphere.
The better we understand these processes, the more we can use this knowledge to predict what's likely to happen.

— Any weather or climate prediction is probabilistic in nature. However, there are things climate scientists can now predict with good certainty. In the coming years and decades, how can we expect the occurrence of climate and weather extremes that can lead to natural catastrophes to change?

M. D.: Indeed, for producing climate predictions we typically run several simulations with small variations - we call this an 'ensemble' of simulation. These ensembles help us to understand the uncertainties of the predictions, and to quantify the probabilities for specific prediction outcomes or events to occur.

In the coming years and decades, depending on the continued global warming, we will face more frequent and intense heat waves, and less frequent cold waves; and in most regions more intense and frequent precipitation extremes and longer dry periods. The latest IPCC Assessment Report (2021) spells these consequences of global warming very clearly.

'In my opinion, it is when attribution science is integrated with prediction science that it can help answer the more important question: 'should we expect events like this recent heatwave or storm, or extreme weather and climate events more generally, to occur more frequently in the coming years, and to what extent?'

We hear a lot about breaking records – with 2024 yet again the warmest year on record on global average, and 1.5C above the preindustrial reference – and some might conclude that it is too late to do anything.

However, every tenth of a degree of warming still counts. The politically agreed global warming thresholds inform populations and mobilize governments; but the weather and climate extremes continue to be affected by global climate change at every tick above any threshold. This means that even if we exceed 1.5C of global warming in the coming years, there is important value of limiting global warming to as low a level as possible.

— Attribution science seeks to attribute extreme events to anthropogenic climate change and other climate drivers. Why is it useful?

M. D.: Attribution science is important for the public and decision makers to understand the effects of climate change; but it is also useful for scientists to understand the processes at play that govern weather and climate extremes. Attribution science can enable a comprehensive understanding of the roles that all the different drivers play in leading to extreme events and natural catastrophes; anthropogenic climate change being but one of these drivers.

However, in my opinion, it is when attribution science is integrated with prediction science that it can help answer the more important question: *'should we expect events like this recent heatwave or storm, or extreme weather and climate events more generally, to occur more frequently in the coming years, and to what extent?'*

1 González-Alemán et al., 2023

'Very importantly, every tenth of a degree of warming still counts. The politically agreed global warming thresholds inform populations and mobilize governments; but the weather and climate extremes continue to be affected by global climate change at every tick above any threshold.'

— How do current technological progress, such as satellite imaging and artificial intelligence, help answer this question?

M. D.: Both attribution and prediction benefit from better data – with enhanced spatial and temporal coverage and higher resolution, and from better understanding of the physical processes that underlie weather and climate extremes leading to natural catastrophes.

While in situ observations can be very limited in parts of the world, nowadays we have access to huge amounts of data from a variety of sources with good space and time resolutions – like different satellites and validated physical models. There is an incredible potential with this data to better understand climate variations and infer relevant drivers. This improved understanding can then be the basis for better predictions – in our case, whether different types of extreme weather and climate events will occur more or less frequently in the future, potentially leading to natural catastrophes.

However, this large amount of heterogeneous data needs to be turned into something that we can use reliably and consistently, and that fits the purpose of our applications. Combining different types of data is one useful and crucial application of artificial intelligence in that regard.

Artificial intelligence can also be used to make reliable predictions – it already performs very well to predict weather in the coming days and weeks. However, in my opinion, rather than to use it just for better predictions without understanding the physical processes at play, we should use it to generate new knowledge by detecting patterns in the data that we haven't noticed yet, and that can lead to better understanding of the climate system. I am particularly interested in using AI to learn about patterns and processes leading to weather and climate extremes.

However, AI use needs to be extremely careful about the data. When using low-quality or inhomogeneous data, or patching data from different sources, there is a huge risk of generating artifacts such as 'false trends' in the data; or that the AI learns false patterns from compromised data. Poor data used to train AI models could heavily impede further modelling or the conclusions that we draw, as we would get predictions based on data that is unrealistic.

ARTICLE

Our changing coastlines

How remote sensing and artificial intelligence can help mitigate coastal risks

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— The global coastline: home to billions and the world's richest ecosystems

Coastal zones are home to more than 40% of the global population and 75% of the world's largest cities[1]. They also contain some of the world's ecologically richest ecosystems, hosting over one million marine and terrestrial species, including 25% of all marine species[2]. Over the last few decades, 25% of the world's sandy coast has retreated[3] and 5,245 km^2 of mangroves have disappeared – roughly the size of Bali Island in Indonesia[4]. Coastal zones of the world also host a high concentration of critical assets such as ports, airports, highways, energy and communication infrastructure, water and wastewater facilities[5]. If these are compromised, our societies wouldn't be able to function. In the European Union alone, the present-day value of physical assets located within 500 meters of the coast is between €500 billion and €1 trillion[6]. The global value of coastal assets has been projected to increase to USD 35,000 billion [€32.2 billion] by 2070[7].

'Current assessments of coastal climate change impacts are not of a sufficient resolution to inform local scale adaptation measures anywhere in the world. New technologies should enable us to provide detailed high-resolution assessments anywhere in the world.'

— Bracing for the effects of climate change and anthropogenic pressures

Climate change can have many different impacts on coasts, such as coastal flooding and coastline recession, the formation of new tidal inlets (forming new estuaries), or the closure of existing tidal inlets (turning estuaries into lakes). All the factors that drive these impacts are projected to intensify by the middle of this century by the IPCC, with a high level of confidence[8].

From shoreline retreat and coastal flooding to estuaries turning into lakes, we must prepare for huge changes in very populated and highly developed areas. It is no longer a matter of whether the coasts will change, but where exactly, and when. For example, under a very high emissions scenario (RCP8.5), about half of the world's sandy coastline is projected to retreat by 100 meters or more by the end of the 21st century in the absence physical obstructions to shoreline retreat or additional sediment supply to the coast[9]. Even under a moderate emissions scenario (RCP4.5), the global annual damage from coastal flooding is projected to increase from about USD 20 billion [€18,4 billion] per year in 2010 to more than USD 3010 billion [€2770 billion] in 2080[10] (a factor 150 increase), assuming no further protection measures are implemented.
Avoiding such climate change impacts altogether will be a huge challenge due to the combination of the continued human migration to the coast and already committed sea level rise over centuries to come[11].
However, via timely and informed interventions at local and regional scales, impacts and risks could be effectively mitigated.

— Observing the global Earth to better mitigate impacts and risks

To guide action, we need to better understand the hazards to come over the next centuries. This requires numerical modelling of complex processes, as the state of the coastal zone is not only a function of oceanic and weather processes such as mean sea level, tides, waves or storm surges, but also depends on terrestrial processes such as river flows and fluvial sediment supply. When attempting to project what might happen due to climate change, such modeling also needs to account for the inherent uncertainties in climate projections (usually done by performing a number of model simulations under different climate scenarios).

There are extensive efforts to model how the coasts of the world might evolve[12]. However, these models require local scale, high-quality data for model initiation and validation – and this everywhere on Earth. Until about a decade ago, such data were only available via very local scale in-situ measurements, presenting a major obstacle to such efforts.

— Remote sensing is a game changer

With satellites now observing all corners of the Earth night and day, this has changed[13]. Remote sensing products offering models of elevation, terrain, land use or historical shoreline change with good accuracy have become increasingly available in the last decade.
Important data sets that are still not available globally with reasonable accuracy are nearshore bathymetry and land subsidence, although continuous progress is being made in these areas[14].

Another type of critical information that is still missing is the extent of flooding after major flood events – this would be essential for robust validation of detailed flood models. The main limitation so far in this regard is that most satellites do not come back fast enough to the affected area, so that the flood water has long receded by the time the next satellite image is taken. This should however become less of a problem, given how re-visit frequencies are currently increasing.

— From 'everywhere but imprecise' to 'precise anywhere' coastal risks assessments

The rapid expansion and accessibility of remote sensed products have already enabled the assessment of important coastal hazards such as shoreline retreat, beach loss, and coastal flooding 'everywhere' in the world, albeit so far at coarse resolution (that is in the range of a few hundreds of meters to a few tens of kilometers).

However, while such 'everywhere' assessments provide very useful information for hotspot determination and for macro-scale policy development (prioritization of UN loss and damage funding, development banking sector investments, aid organization grants etc.), they are not of a sufficient resolution to inform local scale adaptation measures anywhere in the world.
In addition, despite advances in data availability, the application of physics-based numerical models requires hundreds of individual simulations to account for climate uncertainties. This remains a challenge due to computational resource requirements. Artificial Intelligence (AI) techniques may provide a way around this bottleneck, and several explorations[15] in coastal and ocean engineering spheres have already provided encouraging results.

To date, the so-called Artificial Neural Networks are the most commonly used type of machine learning algorithms in coastal and ocean engineering: they are very versatile and able to model complex relationships. However, algorithms such as Support Vector Machines, Decision Trees, K-Nearest Neighbors and Convolutional Neural Networks[16] are also now increasingly being used for targeted coastal and ocean engineering applications.

'Remote sensing products offering models of elevation, terrain, land use or historical shoreline change with good accuracy have become increasingly available in the last decade.'

— AI models come with inherent challenges

The reliability of the results derived from AI models directly depends on the quality and amount of data used for model training and testing. Therefore, data collection and pre-processing are of vital importance in setting up these models. Although the general thinking is that more data is always better for developing AI models, more data does not necessarily lead to a better model, especially in simpler approaches such as linear regression[17]. In fact, training models with a small amount of high-quality data generally leads to a better outcome than using a large amount of poor-quality data.

In addition, there is no single algorithm that can address all coastal problems. Instead, a good model for the problem at hand needs to be carefully selected, based on previous experience, considering the desired outcome, often following trial-and-error processes. Model selection should ideally take into account factors such as data type, data volume, computational resources, and results interpretability. Finally, AI models trained with data from one location may not be applicable other areas with different features. Using data from diverse locations for model training could enhance the generic applicability of the model[15], although this cannot always be guaranteed.
The proliferation of AI approaches, in combination with the ever-increasing spatio-temporal resolution of remote sensing products, will undoubtably enable us to progress from coarse-resolution assessments of coastal climate change impacts everywhere, to detailed high-resolution assessments anywhere. •

1 United Nations, 2017; Luisetti et al., 2010 – **2** OECD, 2021 – **3** Luijendijk et al., 2018 – **4** UNEP, 2023 – **5** Sadoff et al., 2015 – **6** European Environment Agency, 2019 – **7** Nicholls et al, 2008 – **8** IPCC WG1 Summary for Policymakers, 2021 – **9** Vousdoukas et al., 2020 – **10** Tiggeloven et al., 2020 – **11** IPCC WG1 contribution, Chapter 9, 2021 – **12** Ranasinghe, 2020 – **13** Turner et al., 2021 – **14** Almar et al., 2021; Nicholls and Shirzaei, 2024 – **15** Abouhalima et al., 2024 – **16** Misra et al., 2016; Kim et al., 2017; Magherini et al., 2024 – **17** Goldstein et al., 2019

REGIONAL ZOOM

DR. CHRISTOPHER TRISOS
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Climate change in Africa: risks, realities, and the race for local data

— **Africa has only contributed 2-3% of the greenhouse gases emissions globally from burning fossil fuels, but climate change already exposes Africans to severe drought, floods and extreme heat, to name only the most impacting hazards. Africa is a huge continent, with 54 countries and a population of 1.5 billion – what are the reasons to study and discuss it as an entity?**

Christopher Trisos: Indeed, there's a lot of diversity inside Africa. Nevertheless, there are certain similarities that make climate change impacts and risks more or less severe.

In particular, many countries in Africa have a very high number of people living in poverty, and that makes them highly vulnerable to climate impacts.
It is also a continent that has a very high proportion of people employed in agriculture. Since most of Africa's agriculture is rain-fed and not irrigated, this makes it a very climate-exposed sector; leading many communities and national economies to be vulnerable to changes in precipitation.
For this reason, some continental-level statistics hold true across a wide number of countries in Africa. These can be useful when thinking about risk management.

'Scientists may try to apply to Africa an AI model that has been trained on data acquired elsewhere. However, without local, ground-based observations, it will be hard to tell how well the model is performing in an African context.'

However, local contexts are also very important, in particular in the case of climate change adaptation. The situations differ from country to country, but also from city to city. Indeed, the most rapid urbanization in Africa takes place in secondary cities – that people in Europe or North America might never have heard of, such as Mbale in Uganda and Ibadan in Nigeria. These cities are projected to grow very rapidly in the next few decades – as is the case in some areas in Asia. This is often where some of the highest risks are concentrated, because people are moving into informal settlements that lack basic services and infrastructure.
On the brighter side, it is also where some of the biggest opportunities to provide people with services and adaptation interventions that reduce climate-related risks are concentrated.

— **How does climate change and climate-related natural catastrophes affect lives on the continent?**

C. T.: The IPCC outlines that casualties due to climate change-induced hazards are much greater in high-vulnerability countries than in low-vulnerability countries. Most African countries are in the 'high-vulnerability' group.
More precisely, key development sectors across Africa have already experienced widespread losses and damages attributable to human-caused climate change. For example, droughts have been made more likely by climate change, such as those in Southwest Africa from 2015 to 2017. Climate change has led to reduced growth in crop productivity in Africa – that is, productivity has increased but less than it would have without climate change. This is due to the combined effects of temperature and water shortage, but also to flooding, as a lot of rain can drown the roots of crops and lead to rotting.

Africa has also experienced a lower rate of economic growth than it would have without human-caused climate change. Thus, climate change in Africa is disrupting the common narrative in which GDP per capita is somehow catching up with that in developed countries.

▼ WHAT IS VULNERABILITY?
Vulnerability is the consequence of many different things intersecting.
In human systems, in most cases, a true understanding of the multidimensionality of vulnerability is a mix of quantitative and qualitative factors, including for example local governance systems, histories of inequity and marginalization, socioeconomic development and sustainable land use. All of those might intersect to make a particular group of people or a person more vulnerable.

— Climate change overall increases the probability of natural catastrophes. Is this trend worse in Africa than in other regions of the world?

C. T.: Natural catastrophes in Africa are clearly happening but attributing them to human-caused climate change is a challenge. One of the difficulties is that, in many African countries, we lack regularly-reporting ground weather stations. In Europe for example, there has been widespread coverage of temperature sensors, river gauges, rainfall gauges, and so on, for a long time. These helped to establish a historical baseline and nowadays are crucial to study how climate is changing. In southern Africa, we can attribute heavy precipitation and subsequent flooding to human-caused climate change; but for the rest of the continent, there's still some uncertainty on the attribution of this type of event.

Similarly, for agricultural drought in Southern Africa, West Africa and North Africa, we can now say with some confidence that drought has increased because of human-caused climate change.

— Is this lack of local data why there is interest in remote sensing?

C. T.: Remote sensing definitely helps, but we need local measurements to calibrate remotely sensed data against. For example, scientists may try to apply to Africa an AI model that has been trained on data acquired in Asia. However, without local, ground-based observations, it will be hard to tell how well the model is performing in an African context.

AI and remote sensing also help tackle both hazard and vulnerability mapping, by inducing breakthroughs in the spatial resolution at which we can understand events and their underlying mechanisms – but, again, it needs to be supported by good ground-based data and household surveys.

In addition, there is a trend to shift towards the modeling of impacts – as opposed to 'just' hazards. So we now also need local data regarding impacts. In that respect, we can sometimes use remote sensing and AI to get a better understanding of loss and damage. For example, we can now count individual trees from space – this informs studies of climate change impacts on forests, helps better monitor deforestation, forest health, and the impacts some natural hazards such as droughts or wildfires have on forests.

'If we would like AI to be beneficial to those in most vulnerable contexts for reducing and managing the risks they face, along with spending a lot of money on the data centers and developing new models, we have to be willing to spend significant amounts of money on improving the data coverage with weather station networks and vulnerability data collection through household surveys.'

— How can novel technologies such as remote sensing and AI be most beneficial to vulnerable populations in Africa?

C. T.: If we would like AI to be beneficial to those in most vulnerable contexts for reducing and managing the risks they face, along with spending a lot of money on the data centers and developing new models, we have to be willing to spend significant amounts of money on improving the data coverage with weather station networks and vulnerability data collection through household surveys. All these need to be managed in long-term funded programs. It is interesting to note that between 1990 and 2020, three quarters of the funding for climate change research on Africa went to institutions in Europe and North America, and only about 15% to institutions in Africa. To enable Africa to really benefit from these technology advancements, that ratio must flip around, so that African institutions can build their own capacity to advance these tools and adapt them to their local contexts.

Indeed, when you receive the research funding, you are empowered to shape the research question, and that really is a big part of shaping the answer you get. We know that when the identification of the knowledge gap comes from researchers in developed countries, it might be quite different from the local priority knowledge gap. In addition, from a career advancement perspective, there are still strong incentives to ask cutting-edge research questions, while these might not be the most useful for local decision making. This goes beyond the topics of AI and remote sensing, but it is crucial to understand if we want to help vulnerable populations. Finally, I would like to mention that generative AI already enables people to get answers more rapidly about how to adapt in their local contexts, and more testing of this is needed in the African context. Of course, there is already a lot of information out there provided by public agencies, but I think giving another channel through which people can access information is an important use case for AI.

— How can Africa adapt to climate change? Are there limits to adaptation?

C. T.: We know that there are hard limits to adaptation, which means that even with more financial investment, there would still be loss and damage. For example, hard limits to adaptation have been reached in some coral reef ecosystems, where mass coral bleaching has occurred. The ecosystem thus changed from a coral reef to something else entirely.

Soft limits to adaptation refer to situations when, with a change in society and resources, you could still adapt (for a given level of global warming).
There is some potential to use 'nature-based solutions' to help us both in terms of adaptation and mitigation.
For example, in agriculture, where you could have improved agricultural practices around mulching and irrigation for certain crops. However, these nature-

based solutions only have potential if we stay under some global warming threshold. This is why Africa has a lot of reasons to work towards limiting global warming well below 2C – that is, within the limits of the Paris Agreement.

One cautionary note I would add about adaptation potential is that we are rapidly learning more and more about the complexity of climate risks.
The complexity of climate risks refers to the fact that climate change risks often compound and cascade. For example, heat waves and droughts can occur simultaneously. High precipitation after a drought tends to lead to floods, because the soil has dried. These are compound risks.

We also see cascading impacts of climate change risks. For example, in the Cape Town drought where there was a water shortage in the city, so higher income households go off the grid: they drill boreholes to extract groundwater - that means they no longer buy their water from the city. The water shortage risk for households has cascaded to create a revenue generation risk for the city. And that revenue generation risk for the city then cascades to create a service-delivery risk for low-income households in other parts of the city. Which might in turn cascade to create a political risk where people vote those politicians out of office or protest. This example gives a glimpse of how a climate risk cascades into other risks.

— Most adaptation measures for Africa listed by the IPCC 6th Assessment report face technical barriers – what are these barriers?

C. T.: Technology sharing is an issue of course – although it is not climate-related, the case of inequitable distribution of Covid vaccines illustrates this well. There is a lot to be done around equitable technology sharing regarding agriculture, and also technology sharing in a way that benefits local livelihood, as opposed to makes people dependent on foreign, possibly temporarily present technologies.

But in other contexts, technologies for adaptation still need to be developed. As climate hazards, (heat, drought, flooding) are increasing and compounding and cascading, we need to learn how to blend so-called 'green infrastructures' or nature-based solutions, with 'grey infrastructures' or hard infrastructure. For example, the choice is not just about building a seawall or using mangroves, but about blending those two options together appropriately. These adaptation discussions still require a lot of research and development, in Africa and globally. Another big area of required R&D is low cost, low carbon, energy efficient cooling solutions that can be used and scaled up rapidly, to provide protection under heatwave conditions.

There is a lot of discussion during the COP conferences about private investments. However, many adaptation technologies need a public funding push – low cost, low carbon cooling is a prime example of that. Indeed, the IPCC reports that there were very few, if any, examples of the private sector investing at scale in adaptation for very low-income communities, such as those living in informal settlements. So while there a lot of talk in climate policy about crowding in private sector money for adaptation in developing countries, there is high confidence in the IPCC assessments that this funding will continue to have to come from public sector funds. •

The road towards *actionable impact* forecasting

ARTICLE

From hazard forecasts to impact forecasts

The case of floods

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With climate change, we expect to see more extreme weather events, often ones that have never been observed locally. While societies tend to learn from disasters and improve their risk management systems, this learning is limited for too large events or those too different from what we have experienced so far. Our unpreparedness for such events – made more likely by climate change – can lead to huge damage[1]. For example, while the 2002 Danube River flood caused €4 billion of damage, a similar event in 2013 caused only €2.3 billion of damage. The lower impact in 2013 can be explained by high investments in flood measures and strong improvements in early warning and emergency response. In contrast, the 2021 floods in Western Europe came as a surprise: flood peaks were much higher in many places than what had been observed in recent decades, leading to a catastrophe.

In addition, while river floods are in most cases well predictable, with typical lead times of up to a few days, allowing for disaster management actions such as evacuation; rain-induced flash floods are more difficult to predict. Their much shorter lead times, of up to several hours, and faster water level rises make them a particular challenge for early warning and disaster management.

For example, in March 2024, heavy rainfall caused flash floods and landslides in West Sumatra, Indonesia, with about 30 fatalities and around 80,000 people displaced. In October 2024, torrential rainfall led to catastrophic flash floods in Valencia and the surrounding areas. This was one of the deadliest natural disasters in Spanish history, with over 200 people losing their lives.

Forecasts, early warning systems and rapid information on the unfolding of a disaster are thus essential tools for saving lives and reducing financial losses. The benefits of forecasting are significant: despite an increase in the frequency of flood events, flood fatalities have declined globally in recent decades, reflecting the improvements in flood protection, forecasting and early warning systems. The cost of developing and operating awareness systems is very low relative to the costs of avoided damage. In Europe, the ratio of system cost to avoided damage cost has been estimated to reach 1 to 400[2].

— From forecasting flood hazard to forecasting flood impacts

Flood forecasting systems predict the magnitude, location and timing of potentially damaging situations, such as the expected water level over the next 24 hours at specific river gauges. However, even when this information is timely and accurate, it may not lead to appropriate responses because it can be difficult for the general population and emergency managers to understand potential consequences. For example, the operator of a hospital may not know whether to evacuate if the water level is 6.10 meters high at a gauge 10 kilometers upstream of the hospital.

That is why the new field of 'impact forecasting' aims at extending forecasting systems to provide impact estimates, such as the location of flooded buildings, critical areas in terms of drowning, service disruption or financial loss.

Impact forecasting can provide decision-makers and affected populations with richer information to make informed decisions in emergency situations. In our example, the hospital operator would receive information on whether the hospital would be flooded, how high the water would be and when.

The first challenge researchers meet when going from traditional flood hazard forecasting to impact forecasting is to forecast what areas will be flooded (or inundated), even before including vulnerability considerations regarding buildings and agricultural land for example.

— Recent advances in computing

The traditional hazard forecasting model chain therefore needs to be extended to include models capable of simulating inundation and associated impacts – an issue that has remained out of scope so far due to the long computation times of hydrodynamic models, explaining why such a crucial information is not included yet in forecasts.

The community has started to tackle this challenge thanks to recent advances in high performance computing, including the use of graphics card processing, parallelization and more efficient algorithms.

An additional way to gain computing speed is the use of AI models. AI can produce flood forecasts hundreds to tens of thousands of times faster than hydrodynamic models[3], with only a small loss in accuracy. Instead of relying on complex physics-based calculations, AI learns patterns from existing data to make predictions. Currently, these AI models are trained using large datasets obtained by running hydrodynamic models. However, in the future, they could be trained directly on observed data collected from sources like satellite images, aerial photos, social media posts, and even street-level images. For example, there are an estimated 650,000 CCTV cameras in operation in London alone that could be used to monitor flood situations, which could then be used to train AI models.

> *'The main challenge when going from traditional flood hazard forecasting to impact forecasting is to forecast what areas will be flooded - this has been out of reach so far due to computational limitations.'*

Of course, bypassing the understanding of physical processes at play also has drawbacks, in particular when one seeks to apply an AI-model trained in a specific region onto another region – and even a neighboring catchment can behave quite differently. While physics-based models can be transferred to other catchments or used for extrapolation because the physics underlying the model is the same everywhere, AI models learn from data, and their ability to extrapolate depends on the breadth of the training data. Only when one has access to large and diverse enough datasets, AI models with significant generalizability can be designed. AI based models have successfully transferred the learned patterns and relationships to another area without retraining.

1 Kreibich et al., 2022 – **2** Pappenberger et al., 2015 – **3** Fraehr et al., 2023

'Large language models, such as ChatGPT, could also be integrated with flood databases and models to create intelligent chatbot systems specifically designed to support disaster managers and people affected by floods.'

This approach, known as 'transfer learning'[4], is particularly relevant in the case of data-poor regions[5].
Another advantage of AI based impact forecasting models is their ability to process multimodal data. AI models can simultaneously analyze different types of data, e.g. rainfall intensities or water levels, but also including text and images from social media. This can provide a more comprehensive understanding of flood severity and evolution than models that rely solely on hydrological data, such as water levels. For example, by analysing the geographical distribution and sentiment (emotional tone or attitude expressed) of social media posts, models can map the dynamics and severity of flooding. Natural language processing (NLP) applications have analyzed not only text and photos, but also emoticons to identify emergencies and humanitarian needs during floods (social sensing for emergencies)[6].

Finally, large language models, such as ChatGPT, could also be integrated with flood databases and models to create intelligent chatbot systems specifically designed to support disaster managers and people affected by floods[7]. These chatbots would be able to understand and interpret natural language queries and provide personalized, relevant responses based on the user's specific situation and needs.

The key benefits of NLP-powered chatbots in flood response are 24/7 availability, the ability to handle multiple requests simultaneously, and the personalization of information based on the user's location and specific needs. However, there are possible drawbacks, such as ethical concerns about accountability and responsibility when such as system is used in decision making, or privacy and data security concern when handling private data in emergencies. Moreover, power outages and network disruptions during emergencies could lead to failures when the system is needed most.

— Flood monitoring and forecasting also benefit heavily from remotely sensed data

Satellite-based data products can provide a wealth of spatial information in real time, useful both for rapid assessments of the extreme event and its impacts, and for feeding into flood forecasting models.

Indeed, flood forecasting models require information on precipitation levels but also on the current state of the land surface, for example soil moisture or water levels of rivers and flood plains. Acquiring this information in real time and at the required resolution and quality can be challenging when using ground-based monitoring, because measurement networks are too expensive to cover large, remote or inaccessible areas and because they can fail due to unfavorable environmental conditions during extreme events[8].

Thankfully, remotely sensed data such as snow cover, water levels of lakes or in inundation areas can be assimilated into flood models, improving forecasting skill. Similarly, satellite altimetry can monitor water level variations in rivers and floodplains and can even be converted into discharge estimates[9]. Soil moisture can be derived from microwave, optical, thermal infrared or multispectral remote sensing images. For example, Synthetic Aperture Radar measures the backscatter from the soil surface – it can see through clouds, rain and haze, penetrate vegetation and operate both day and night – which is particularly useful in flood conditions. •

4 Zhou et al., 2023 – 5 Nearing et al., 2024 – 6 Bryan-Smith et al., 2023 – 7 Kumbam, preprint, 2024 – 8 Di Mauro et al., 2021 – 9 Schumann et al., 2023

EMERGENCY MANAGEMENT DURING FLOODS
On 14-15 July 2021, heavy rainfall caused flooding in Western Europe, killing around 240 people and causing almost €50 billion in damage. The Centre for Satellite Based Crisis Information in Germany provided satellite data and aerial images to emergency and rescue teams within hours of notification. Flight campaigns with various camera systems were conducted on 15, 16 and 20 July, providing high-resolution imagery. Satellite SAR imagery was used for continuous surface water monitoring throughout the event. In the immediate aftermath of the flood, several drone-based surveys were conducted in the most severely affected areas. One of the applications was to understand how the road network was affected by the flooding. By comparing pre-disaster and post-disaster images, damaged road sections could be identified. Similarly, the level of damage to buildings was assessed by integrating remote sensing data with AI algorithms. The information obtained was made available to first responders during the event to support emergency management.
In a crisis management system, the quality of information is essential but not enough on its own. Despite high quality data and the extensive emergency efforts deployed during the event, the impacts were devastating, resulting in significant loss of life and widespread destruction.

ARTICLE

Beyond the bang: towards forecasting volcanic impacts rather than just hazards

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Volcanic activity has affected societies for millennia, with impacts ranging from minor nuisances to major destruction and loss of life. Today, over one billion people live within a hundred kilometers of an active volcano, while explosive eruptions are able to affect societies many thousands of kilometers away.

New technologies within the last century have really advanced our understanding of volcanic processes – in particular, remote sensing data from satellites is available since the 1960s, and we can nowadays process and analyze large amounts of data, perform complex and time-consuming computations using artificial intelligence.

These technologies have also increased the number of volcanoes that can be studied, with remote sensing allowing us to observe processes across multiple temporal and spatial scales, reaching even the most remote volcanoes.

However, despite their potential, remote sensing and AI are currently seldom used to evaluate the impacts from volcanic processes, such as damage to infrastructure, buildings, or crops.

— The past is the key to the future

Up to now, our understanding of how future volcanic eruptions will affect society rests on observations of past impacts, supplemented by lab experiments, modeling, and expert judgement.

However, volcanic impact data is rare, in part because of the infrequent nature of eruptions and the complexity of volcanic hazards, which can happen over varying timescales, spatial extents, and intensities, and which can take place consecutively, simultaneously, without an eruption, and/or repeatedly over years or decades, threatening the safety of those in potential impact areas. As a result, there are only four published studies on the impacts of particulates and ash (tephra) falls on buildings[1] for example, contrasting with more than 600 publications discussing earthquake damage to buildings[2].

Despite data on volcanic impacts providing the most accurate constraints on how hazard intensity relates to impact intensity, we simply do not have enough observations today to underpin robust vulnerability models[3].

— Emerging strategies

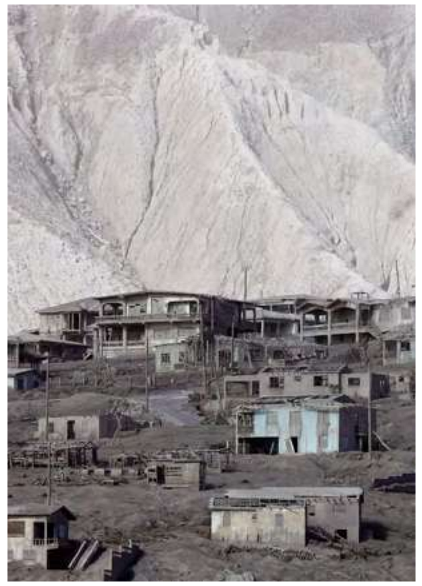
Recent developments in remote sensing are providing opportunities to remotely observe and analyse volcanic impacts. For example, scientists used machine learning with the cloud-based remote sensing platform Google Earth Engine to quantify tephra fall impacts on vegetation following the 2011 eruption of the Cordón Caulle volcano in Chile. As satellites regularly image the area, they were also able to assess the speed at which vegetation recovered[4].

While some studies have used manual inspection of remote sensing data[5], an emerging strategy in volcanic hazard and risk assessment is to couple remote sensing and AI, which can now be used to automate volcanic impact studies, allowing faster and more efficient processing of large data sets. AI is also used to enhance remote sensing applications, including object recognition and building and damage extent classification. For example, following the 2021 eruption of La Soufrière in St Vincent and the Grenadines, models have been trained to locate buildings affected by tephra fall and categorize them into three levels of damage (none, minor, major) using deep learning - a complex form of machine learning that uses so-called 'neural networks' to enable computers to learn with relatively little guidance from human operators[6].
Given these developments, we can for the first time observe impacts around the globe over the course of an eruption, and during the subsequent recovery. In the next years, this novel type of data will vastly increase the evidence base available to us for forecasting future volcanic impacts, leading to improved decision-making in disaster management.

— Looking forward

Future developments in remote sensing and AI are expected to further support improved volcanic impact assessment.

Better sensing: New satellite missions and advanced sensor technologies will provide higher resolution and more accurate data. Integrating remote-sensing data with the Internet of Things (IoT) will enable real-time data collection and analysis; for example, sensors on satellites can regularly monitor large areas while sensors and cameras on IoT devices deployed on the ground can provide continuous detailed local data.



More data: The use of crowdsourcing for data collection will become more sophisticated, allowing for more comprehensive and cost-effective data gathering in the immediate phase during or shortly after impact. For example, where people are present and willing to contribute, smartphones can be used to rapidly gather and transmit photos, locations, and impact descriptions.

Automated data processing: AI will drive the development of automated algorithms for processing large datasets, making it easier and faster to extract valuable insights from data. For example, rapid and objective pattern recognition in large and/or multiple datasets is impractical for humans to carry out manually but possible with AI.

Enhanced data analysis: AI, particularly machine learning and deep learning, will continue to improve the analysis of remote sensing data. This includes better image classification and object detection as a result of higher resolution data and multiple large, labelled volcanic impact datasets that can be used to inform deep learning models, and dynamic land cover mapping that can be updated in near real-time to help monitor recovery.

These advancements will make remote sensing and AI more integral to volcanic impact assessment, but also the wider context of scientific research, disaster management and related applications. •

1 Spence et al., 1991; Blong, 2003; Hayes et al., 2019; Jenkins et al., 2024 – **2** Spence et al., 2011 – **3** Biass et al., 2021 – **4** Lerner et al., 2022 – **5** Biass et al., 2022; Jenkins et al., 2017; Magill et al., 2013; Jenkins et al., 2013; Meredith et al., 2022 – **6** Tennant et al., 2024

INTERVIEW

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Advancing wildfire risk assessment and mitigation strategies

PROF. MARCOS RODRIGUES MIMBRERO
University of Zaragoza, Spain

HUU-AN PHAM
VP Territorial Adaptation and Climate Adaptation Expert, AXA Climate

— Across the world, wildfire occurence has seemed to explode, and not only in the summer months. Is this true statistically?

Marcos Rodrigues Mimbrero: Sadly, data is very sound on the increase of extreme wildfires. One of the most recent examples is the Los Angeles series of fires in winter 2024-2025, which caught people off guard because it was unprecedented at the time of the year, even though these strong wind episodes are common in that season. The economic impact is huge but of course the worst part is when lives are lost. The fire season is also lengthening, and that is even more concerning. Studies find significant increases in the duration of fire seasons all over the world. The fires in Europe in 2022 started in early June – the date itself is not that unusual, but the kind of fires, their sizes, intensities and behaviors were unprecedented for that time of the year.

Similarly, in Chile, fires always occur in the austral summer… but there are now huge firestorms extending over 100,000 hectares, as during the 2016-2017 and 2022-2023 winters for example.

— How does this increase relate to climate change?

Huu-An Pham: We combine two indicators to assess the impact of climate change on wildfires. The first one is called the Fire Weather Index, and it combines several parameters like temperature, precipitation, relative humidity and wind speed – all of which are affected by climate change. The second indicator is tree coverage: this indicates the fuel to burn. This is very specific to wildfires – while studies show that most wildfires are triggered by humans, fuel is required for the fire to extend. Another aspect related to climate change is that there are now wildfires in regions that are not historically prone to wildfire: the Vosges or Brittany in France, northern Germany... This can – understandably – surprise local populations.

— What are the impacts of wildfire?

H.-A. P.: Wildfires have huge impacts because they tend to destroy buildings or infrastructures completely – when some floods or hurricanes might damage them less severely. There are also indirect impacts of wildfires, an important one being air quality. It can lead to fatalities as well, but it is often underestimated. Other important indirect impacts can be very specific and local, for example on crops or even livestock deaths – because crops they normally feed on were burnt in the fire – like in Texas in 2024.

M. R. M.: We mentioned that most wildfires are triggered by humans. This is not solely a responsibility issue. This is important because the kind of assets that are affected by a wildfire are intimately related to the kind of practice that has initiated the fire, for example recreational fires or burning slashes (a farming method that involves the cutting and burning of plants in a forest or woodland to create a field).

There are also unsuspected long-term impacts, for example on the health of professional and volunteer firefighters due to release of pollutants during the fire – this also adds to health effects on the general population of course.

H.-A. P.: Another long-term impact is the carbon dioxide that is released in the atmosphere during the combustion, and that feeds climate change – a study[1] showed that the carbon emissions emitted by Californian wildfires in 2020 exceeded the reduction of emissions the state had managed to achieve over 16 years.

Part of this feedback loop between wildfires and climate change is the change in vegetation. In fire-prone regions, vegetation is normally adapted to fires – some plants even require fire burning of some of their evolutionary stages. Now, this is not the case in other regions, and fires in these regions affect the biodiversity at such a rate that ecosystems do not have the time to adapt.

— Altogether, can we estimate how much money is at stake?

H.-A. P.: The Los Angeles fire is the costliest wildfire event from all perspectives: direct damages, insured losses, uninsured losses, overall economic impact. As of mid-February 2025, overall economic impact is estimated above 250 billion USD (about 232 billion euros); and from the insurance point of view, 80 billion USD (about 74 billion euros). These numbers make this series of fires more costly than major hurricanes.

Here again, urbanization was a huge aggravating factor. While vegetation can act as a fuel, so can wooden houses. Their presence does affect the wildfire propagation.

— The importance urbanization played in devastating some parts of Los Angeles fires points to some prevention measures…

H.-A. P.: Indeed, some individual houses were not burned down, which emphasizes the importance of individual prevention measures, for example using fireproof construction materials.

‘To design better early warning systems, we can mix remote sensing data with AI, but also with human intelligence that can come from social networks, from people in the field.’

In wildfire prevention, such individual prevention measures can add to collective ones like forest management. This is a specificity of wildfire prevention: when you think of flood prevention for example, only collective measures can be implemented.

M. R. M.: In Australia, there are very strict building codes for example, regarding construction materials of course but also – more surprisingly for a European – gardening arrangements, window locations, and so on. All these measures arise from a form of collective learning to co-exist with fires. These measures could be exported to other fire-prone areas in Europe, in the US, in Chile…

— How do early warning systems work?

M. R. M.: Thermal sensors are used for early-warning systems, and they are a good source of information to understand where fires have started and how they progress in real time. We can also combine this information with different algorithms to understand fire behavior and fire progression to pinpoint the next location the fire will reach. One issue is that the sensors detect any thermal anomaly, not just fires, for example metallic roofs getting hot in the sun or agricultural burnings.

1 Jerrett et al., 2022

This can lead to false positives. So, we need to check the information against other ground-based information, including so-called 'citizen information'.

H.-A. P.: Indeed, you can combine sensor information with semantic search on social media, in real time, which gives you geocoded information. This way, using AI, we can mix remote sensing data and human intelligence, sourced from people in the field via social networks.

M. R. M.: This use is interesting because it also raises societal awareness about wildfires. In wildfire prevention, I have often noticed a gap between scientists and decision makers or the general public. Of course, this gap can be a barrier to efficient communication and hence mitigation. Involving citizens as a sort of fire spotter crew could be very useful in bridging this gap between science and society.

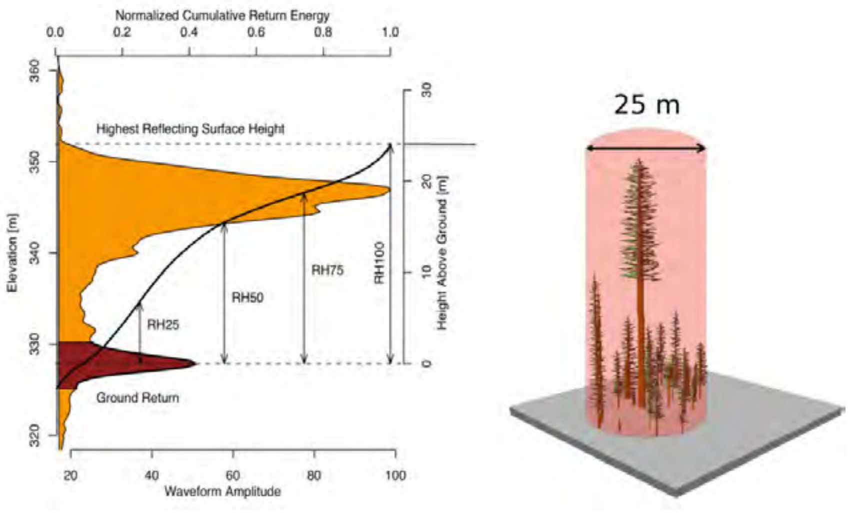
— On what time frames do the fires spread and on what time scale do the algorithms used for modeling wildfire spread work today?

M. R. M.: Fires as hazard have very short time scales, over one or two days, sometimes a week, and in rare occasions several weeks.

However, prevention and mitigation work at other scales. That's why we develop some strategies to understand where fires can occur, where they can spread and produce some sort of impact.
This is another specificity of wildfires: for many other hazards, such as floods and earthquakes, risk regions are better defined. River floods occur on river corridors, although with different intervals depending on the magnitude.
They are confined to a specific region – relative to wildfires, at least. Trying to outline firesheds (that is, delineating areas where fires ignite and are likely to spread to communities and expose buildings or not) is strongly challenging, though necessary.

— So, a big challenge regarding wildfire prediction is location?

M. R. M.: Yes. The triggers can be natural, such as lighting, or man-made, for example accidents and negligence, recreational or agricultural activities. That is a lot of options. So, to understand triggers better and build risk maps, we use a twofold approach. First, we use machine learning techniques to analyze fires that have occurred in the past, to build probability layers or maps that inform the chances of a fire to start in each location. Using that knowledge, we then focus on the regions that are most more prone to trigger a fire and simulate thousands of theoretical fires to understand their propagation.



How to extract canopy structure from Gedi' Lidar data.
Source: Gedi.

Finally, we combine the two pieces of information together to predict which places are more prone to be impacted by a fire. That is what we call the annual burn probability, that is the probability of a fire going through that region in a year. Knowing that burn probability, we can develop mitigation strategies, for example adjust the amount of biomass – or fuel – in the risky areas. This is the kind of approach that we are applying in Chile and in Spain.

We can model the fire behavior with more confidence than before, thanks to recent developments in algorithms for modeling, but also to advances in getting remote sensing information, which we use to calibrate the models. Indeed, global remote sensing products give access to information about the vegetation height, continuity and density that is helping us to learn where the fuel availability is more concerning.

A game changer in that respect has been the GEDI mission. This LIDAR sensor (which determines ranges by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver) located on the International Space Station has been mapping vegetation globally and with a very precise footprint of the structure of the vegetation. That information is being combined with existing products from remote sensing, like Landsat missions and Sentinel missions from the European Space Agency.

— Regarding our understanding of fuel availability, what are the current challenges, and what can we expect from future missions?

M. R. M.: Thanks to the remote sensing products currently available, we know if there is green biomass or no biomass at all; but we have no accurate information on the vegetation vertical development. This information is crucial for wildfire simulation so that we can develop more accurate depictions of the kind of fuels we are looking at and therefore improve the assessment of wildfire exposure and risk mitigation. Hence, future developments are devoted to active sensors (which measure signals transmitted by the sensor that were reflected, refracted or scattered by the Earth's surface or its atmosphere – Lidar being an example of such sensors) that can retrieve information about vertical canopy structures, going beyond the capacities of traditional spectral sensors. These new, active sensors are gradually being put in place, combined with novel techniques for processing the massive information load that is being generated, which is extremely challenging to compute. We need new computational capabilities, mostly cloud-based systems, just to mass process this amount of data.

'A potential future avenue in wildfire risk forecasting would be to couple models working at different scales. In weather forecasting for example, they use regional ensembles and 'downscale' them, i.e. adapt them to more local conditions.'

Finally, we are working on new avenues, algorithms and systems, to improve our modeling approaches.

— When you study a specific region, can you generalize your models to another region? Can this be automated?

M. R. M.: If we are looking at a 'yes or no' question, I would say that no, you cannot apply a model from one region to another, unless you can account for the specifics of the new region or if you are very certain that the region is similar.
For instance, I have exported models from Spain to Portugal successfully, but these are neighboring regions. But if you try to apply the model from Spain to California, while these regions do share some commonalities, there might be differences that are key for risk mitigation, and you absolutely do not want to overlook these! That said, we have a saying in geography, which says that 'a change in scale is a change in the problem' – in other words, it deserves proper attention and proper methods. So, when we develop models, we always have in mind that they could be reproduced or contribute to the understanding of a similar phenomenon in a different region. That means that we can try and build models with key components that are common to other regions, so that the model itself can be exported – but we need to calibrate it to for the specifics.

For instance, take the Fire Weather Index Huu-An Pham mentioned earlier. This index includes information on the amount of moisture that the fuels may contain, because it is a key factor in most Mediterranean regions, but not in Chile, where it is less important. It's not that it's not important at all in Chile, but fuel moisture content is always low when the fires start there – so more concerning for that area are human factors, like the presence of power lines or the vicinity to urban settlements. This example illustrates how difficult it can be, from a modeler perspective, to build models in a way that they may be useful elsewhere.

Actually, this also opens a new question for me: can global models (that explain the global phenomenon) be employed to understand the local aspects of the phenomenon in a specific region?

I mention this because I think that could be an avenue in wildfire risk forecasting to couple models working at different scales. In weather forecasting for example, they use regional ensembles and 'downscale' them, i.e. adapt them to more local conditions.

Now that we are entering a new era of resources in terms of informational and computational capabilities, I would like to explore this 'downscaling' approach and see if it could help us with wildfire prediction and mitigation. •

REGIONAL ZOOM

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Predicting and monitoring explosive storms in a densely populated climate-change hotspot

— Why is the Mediterranean basin one of the climate change hotspots?

Emmanouil Flaounas: We call it a hotspot because it's getting warmer at a faster pace than the rest of the planet – typically 20% faster. This includes both the temperature of the air on the ground and sea surface temperature. There are local effects adding to that, with different consequences, but altogether, the Mediterranean basin is quite unique because it is a narrow, small and closed area, almost like a lagoon.

'The Mediterranean basin is warming faster than the rest of the planet - typically 20% faster.'

— How does climate change affect the Mediterranean weather?

E.F.: We expect less total precipitation (accumulated over the year), leading to dryer conditions, but we also expect days with more extreme precipitation. A dry environment with extreme precipitation is a recipe for disaster. It implies increased risks of forest fires, erosion, and floods. And this is compounded by further vulnerability factors, including crops suffering from droughts, hail, and storms, and tourism dropping.

Giulia Panegrossi: Climate change also leads to higher temperatures overall, with warmer summers in the Mediterranean basin. A massive heat wave reached up to nearly 49 °C in Sicily for example in 2021.

The global increase in temperature also feeds storms, among which Mediterranean cyclones. For example, in September 2023, storm Daniel hit Libya and Greece. That was one of the deadliest storms in the region recently, because of the impacts on land, notably huge damage on a dam, that caused thousands of casualties in the city of Derna (Libya).

E.F.: Storms can intensify due to different reasons. For instance, cloud development can be a source of intensification. Therefore, a warmer sea favors evaporation from its surface, 'fueling' clouds because of more abundant water vapor in the atmosphere.

In the Mediterranean, this mechanism is not exactly the same, but it is comparable to that of tropical cyclones. The issue with global warming is similar: we have warming sea surface temperatures; this favors the development of stronger storms… of the kind that delivers more precipitation.

Heini Wernli: We are talking of storms that are about 500 kilometers wide, and that go from weak to super strong in only a day or two. That's what we call an 'explosive storm': one that becomes very intense very quickly.

— What are "medicanes" and why the recent interest?

E.F.: The word itself is the contraction of Mediterranean and hurricane. It's a subgroup of intense cyclones in the Mediterranean, that look like tropical cyclones from satellites pictures, meaning that they exhibit spiral shapes, whereas less intense cyclones in the Mediterranean region look like an arch, or a comma.

G.P.: In the early stages of their development, medicanes and the other extratropical cyclones look similar, but the medicanes eventually develop further to finally assume tropical-like characteristics such as the spiral shape clouds rotating around an eye-like feature. Some of them also exhibit thermodynamical properties that are typical of tropical cyclones, such as a warm temperature anomaly (a warm core) in the center. There are different types of medicanes, depending on their formation mechanisms.

— How do we detect cyclone formation in the Mediterranean and track these cyclones today?

G.P.: Emmanouil and I lead a project funded by the European Space Agency on the use of satellite observations to improve medicanes understanding, monitoring and forecasting.

First, we needed to define these intriguing objects, as they are quite unusual, becoming very strong in a rather 'small' sea. We need to understand the processes that lead to the formation of medicanes, and to improve our capacities to tracking them during their early development, in the phase when they still look like extratropical cyclones (typically lasting from 2 to 5 days, the coast limits the evolution), before becoming tropical-like. There are many tools to detect and track tropical cyclones, many of which are developed in the United States, and nowadays automated tools allow for near real-time tracking and intensity estimation.

However, we need to adapt these existing tools for the Mediterranean. This requires knowledge on local conditions and local intensities – which is why we are using imagery from geostationary satellites that provide high-resolution measurements and lower-orbiting platforms that provide measurements to characterize thermodynamics processes and precipitation structure.
Field campaigns would likewise be very useful, also from research aircrafts.

The medicane Ianos in the Ionian Sea in September 2020, as seen by the Copernicus Sentinel-3 mission (Source: ESA) .

'There are many tools to detect and track tropical cyclones, many of which are developed in the United States, and nowadays automated tools allow for near real-time tracking and intensity estimation. However, we need to adapt these existing tools for the Mediterranean. This requires more local knowledge.'

These measurements can help to calibrate our remote-sensing tools, as we deal with 'low intensity' cyclones (relatively speaking, we are still talking about near-surface winds exceeding 100- 120 kilometers per hour) compared to tropical cyclones for which most satellite-based tools have been developed. So far, we only rely on ground-based measurements on the coast or on islands. For example, for 2020 medicane Ianos, which was classified as intense as a category 1 tropical cyclone – a very unique event in the Mediterranean – persistent winds up to 158 kilometers per hour, with gusts up to 194 kilometers per hour, were recorded in the Island of Cephalonia.

We then need to develop custom AI tools to identify and follow features of the medicane. The advantage of using machine learning is that it learns from large amounts of data, and that the synergy between sensors from different satellites can be exploited. AI tools should also be able to extract specific features and tell us if we are facing a medicane or not, automate the identification of the storm eye (as a center of rotation exists already in the early phase) and follow its trajectory.

— Can the intensity estimations be automated?

G.P.: This is actually a question as well regarding tropical cyclones, U.S. agencies such as the NOAA National Hurricane Center work with satellite-based tools estimating tropical cyclone intensity. Here again, we cannot always use the tools that have been developed for tropical cyclones, because intensity estimations from remote sensors (measuring for example warm temperature anomalies) are calibrated against measurements from field experiments.

— Now shifting to cyclones prediction – before they start forming: is it particularly difficult to predict cyclones in the Mediterranean region and why?

H.W.: Nowadays, we can predict cyclones[1] – both tropical and extratropical – using meteorological models. This is done typically a few days in advance, with a reasonable accuracy. We use an ensemble prediction system to predict, for instance, probabilities of where and how strongly the storms hit a certain part of the coast.

In exceptional cases, however, forecasts still go wrong. For example, missing the early phases of cyclone genesis leads to errors on how it will evolve, how rapidly it will intensify and where it will move. In the Mediterranean, we have a small basin and enormous population centers, so small errors in forecasting can have huge impacts on the economy and on humans, compared to cyclones in the middle of the Atlantic for example.

In addition, some Mediterranean coastal regions can be hit by a medicane that didn't even exist two days before – these are very dynamic objects with rather short lifetimes, and this makes predictive work harder. The Mediterranean Sea is quite unique because it is almost enclosed: while the triggering of cyclones arises from the large-scale circulation of the atmosphere – at much larger length scales than the Mediterranean Sea itself – the development of a cyclone 'stuck' in the Mediterranean basin is quite specific. Cyclones in this region have been under-researched in the past, but the community is now catching up in understanding how they form and evolve.

— Are forecasts reliable today? What are the sources of uncertainty?

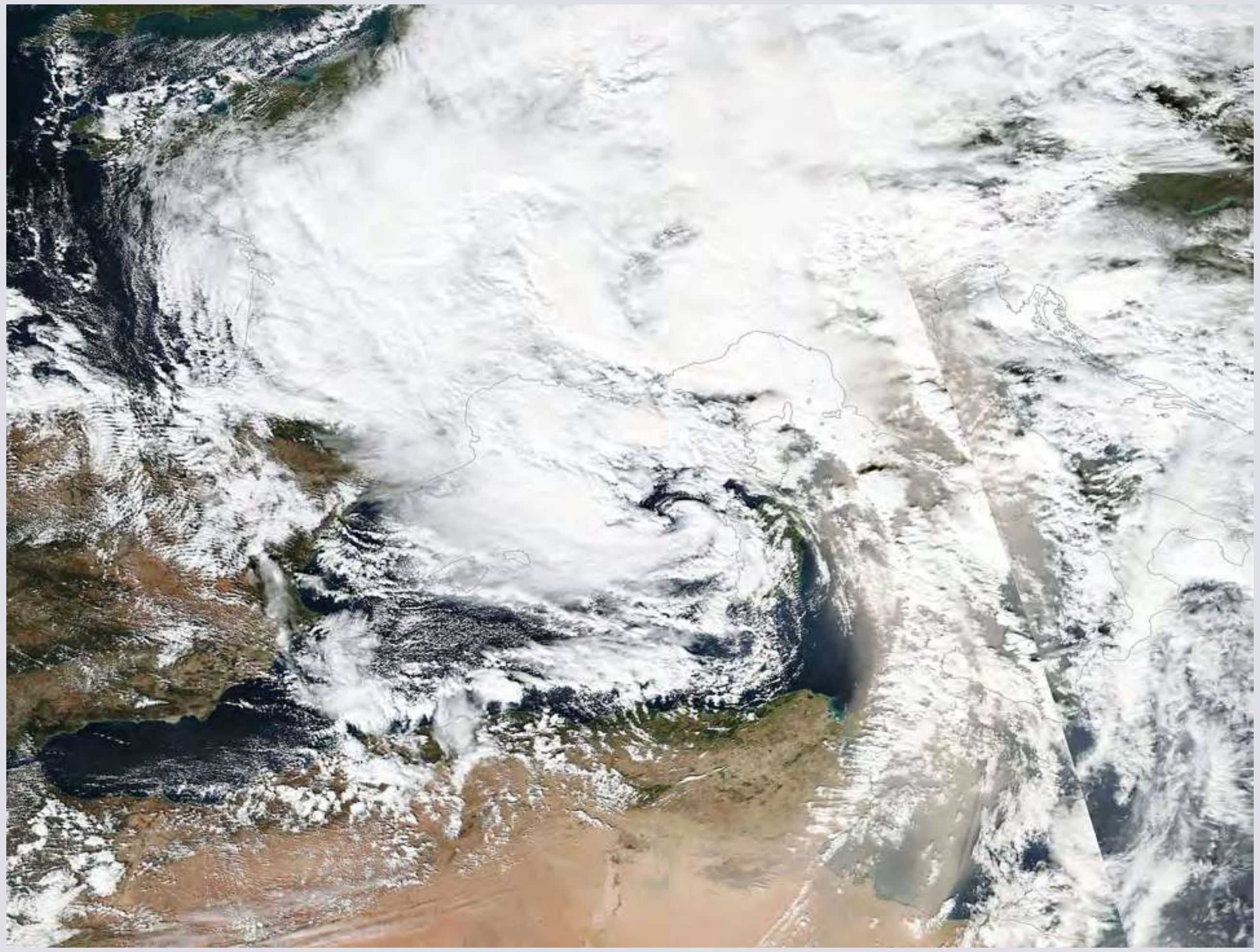
H.W.: We now have very good weather prediction systems, which were developed over the last two decades. So we can generally predict the weather with good accuracy, including the evolution of cyclones, but there is sometimes still a gap in decision making. The Mediterranean region is very diverse, each country has a different organization of the warning chain. However, the scientific community is working more and more with impact experts and stakeholders, and I'm optimistic that with current numerical weather predictions and working more towards impact forecasts and warnings, we can improve on that even more in the next few years.

E.F.: In some regions of the world, for example Florida, everyone knows that eventually, in the long-term, they will be hit by a storm (tropical cyclone), and therefore populations, governments, local authorities, and insurance companies are ready for that, to a larger extent at least than we currently are around the Mediterranean. In Libya for instance, there was a humanitarian catastrophe because of the storm Daniel in 2023. Now that you think of it, it is quite obvious that the infrastructure was not ready to accept the intensity of such an event; but this event was rather unprecedented and it is thus hard to expect anyone to have a 'modus operandi', i.e. handy rules that say what we should do in such a case. And this is where climate change becomes such a game changer, in the sense that each time we experience an unprecedented event, we could run into a catastrophe. It's hard to prepare for events that have never been experienced in a specific location.

— In the context of climate change, where events that have never occurred at a location start to occur – how can scientists predict extremely rare events with little historical data to get information from?

G.P.: This is a challenge when we use data driven methodologies to forecast extreme events, because we rely on the representativeness of the data set that we used to create the model. For example, in machine learning algorithms, the data set used for training is the main basis of the algorithms that predict the target variable. So, when we do not have any of these extremes in the training data set – or even if they exist but are underrepresented – then your machine learning algorithms can fail. Essentially, if we do not have enough data representing this situation, it is difficult to depict a specific feature, especially if it's a small scale and a rapidly evolving event, like some explosive storms.

H.W.: On the other hand, when you work with meteorological models to make your predictions, it's easier, because even though the climate is changing, the physics that drives the evolution of the weather is still the same. We understand the physics very well



The storm Adrian over the western Mediterranean in October 2018, as pictured in the NASA Worldview (Source: NASA).

and we have very precise information from observations that help us constrain the initial conditions. From that point of view, we can also do a good job for extreme events, even when they are unprecedented in a specific region.

E.F.: So nowadays there are research efforts that focus on combining data-driven models that are not too expensive to run – i.e. they are rather fast without needing extensive computing resources – with actual physical models that could potentially reproduce rare weather events since their underlying physics are fairly well modeled.

'In the Mediterranean, we have a small basin and enormous population centers, so small errors in forecasting can have huge impacts on the economy and on humans, compared to cyclones in the middle of the Atlantic for example. Cyclones in this region have been under-researched in the past, but the community is now catching up in understanding how they form and evolve.'

— What type of data can be used to get more reliable and timely forecasts?

G.P.: Nowadays, meteorological satellites are improving their capabilities in terms of resolution. Over Europe and Africa, we now have Meteosat Third Generation, which is the geostationary satellite with sensors at the highest temporal and spatial resolution that we ever had for these regions, and it includes many sensors. We can really use this varied, well-resolved data sets to improve near real-time monitoring and forecasts. There are also constellations of low orbit satellites that are used to characterize several elements, such as near-surface winds and their peak intensity and precipitation, helping us define the severity and potential impacts of the cyclones.

The challenge today is to exploit this huge amount of data. In my opinion, it is still currently being underexploited, both for near real-time monitoring of these catastrophic weather systems and for forecasting their impacts on populations in the Mediterranean basin. •

1 Bauer et al., 2015

New approaches to early warning systems

INTERVIEW

Towards the advancement of tsunami early warning systems

DR. MICHELA RAVANELLI
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— Most tsunamis occur on coasts directly facing large earthquakes, 80% of them around the Pacific Ring of Fire. Some lead to numerous casualties and extensive destruction, as was the case in 2004 with a tsunami that struck the many coasts of the Indian Ocean and caused more than 220,000 casualties in Indonesia, Sri Lanka, India and Thailand. In 2011, the Tōhoku earthquake generated tsunamis across the Pacific, hitting Japan first, with dramatic damages, including long-lasting impacts on nuclear reactors. To avoid such catastrophic losses, what are the typical mitigation measures for tsunamis today?

Michela Ravanelli: On the long term, mitigation measures include maps of risk assessments and so-called 'coastal defenses', such as sea walls built in Japan as early as 1934. There is also a lot of work on public awareness, and this has grown significantly since the 2004 tsunami in the Indian Ocean.

However, once an event occurs that may trigger a tsunami – an earthquake or a volcanic event at sea, Tsunami Early Warning Systems (TEWS) are among the most important mitigations tool left. EWS tell people in the risk zone to evacuate or protect themselves. While earthquake EWS have little time before the shake, minutes at most, in the case on tsunamis, there is potentially a lot of time to prepare - depending on how far from the coast the tsunami was generated.

For example, in 2004, the tsunami hit the Sri Lanka coast from 90 to 120 minutes after being triggered by an earthquake in the Indian Ocean. The Japan Meteorological Agency (JMA) monitors seismic activity 24 hours a day, 7 days a week; once an earthquake occurs, the JMA reports the recorded seismic intensities in about 2 minutes, and the estimated location (latitude, longitude and depth) and size (magnitude) of the earthquake, as well as the possibility of a tsunami within 3-5 minutes. One issue, of course, is that these warnings need to actually reach the local populations – in Japan, warnings are provided immediately to local residents via TV and radio, mobile phone, email, cell broadcasts and the emergency alert system (J-ALERT) with its nationwide network of loudspeakers.

— Can you tell us a bit more on how these Early Warning Systems work?

Currently, EWS for tsunamis are based on seismic signals measured by seismometers across the monitored zone. Scientists and agencies can rapidly compute the magnitude of the earthquake, determine if it is 'tsunamic-genic' and map its potential route across the ocean. They then use local detectors on the sea to confirm sea level measurements – and thus decide to go forward with a warning, or to cancel it. The issue with this system is that is rather patchy, as it depends on how well various regions are equipped.

Only recently have earthquake and tsunami warning systems begun using GNSS (Global Navigation Satellite System) data, a specific kind of remote sensing data. Unlike traditional sensors, GNSS can track ground movement without becoming overwhelmed during massive events like the 2011 Tohoku earthquake, providing crucial data for faster and more reliable warnings. Remote sensing allows global coverage at essentially no cost for the user, contrarily to laying hundreds of kilometers of cables across the sea floor for example.

— You focus on developing a new kind of early warning system for tsunamis. How does it work?

M. R.: I also use GNSS remote sensing, but in a very unusual way. Most of the time, remote sensing is used to look at the Earth, whereas I use it to look at the atmosphere.

Earthquakes and tsunamis can generate acoustic and gravity waves through the atmosphere, because they change the pressure and gravity locally. These waves travel up, and they perturb the electron content of the upper and ionized part of the atmosphere (which is called the 'ionosphere'). Because the signals from the GNSS satellites cross the atmosphere before they reach detectors on the ground, these variations can give us information about vertical displacements of the sea floor and even track the propagation of the tsunami wave itself. The processing of this GNSS ionospheric sounding data is done within minutes. Currently, we can detect the start of the atmospheric perturbation due to the earthquake in 8 to 10 minutes.

We can also track the tsunami wave propagation far from the coast. The current limitations with this method today are that we do the computation after the fact (we know where and when a tsunami occurred), and that there is a detection threshold – we can detect earthquakes of magnitude 6.5 or above.

I am working on a prototype that processes these signals in real time, when events occur, to see if we can integrate our method into existing EWS. The goal is that the different methods complement each other and give robust and reliable warning systems.

— Your method also helps in detecting tsunamis that traditional systems do not catch?

M. R.: Yes. Some tsunamis are generated by volcanoes and seismic networks are struggling to detect these signals. For example, the 2022 Tonga volcano eruption generated two separate tsunamis – one due to pressure waves, the second generated by the collapse of the volcano. Since it started in water, the first one was faster than ordinary tsunamis, and unexpected. These two tsunamis were so big that we could see both their signatures very clearly in the ionospheric signal.

As a comparison, it was more challenging to clearly identify the 2020 Samos earthquake and tsunami. Since the event was smaller, the ionospheric signal was hidden in all the other variations of the ionosphere – for example those due to solar activity, that also affect the electronic content of the upper atmosphere.

— Are scientists looking to make more progress to deliver the early warning sooner, or to improve the accuracy and reliability of early warnings?

M. R.: One key issue is to provide timely information of course, but there is a big challenge surrounding early warning reliability, to avoid false alarms. In 2010 for example, there were two earthquakes and resulting tsunamis in Indonesia. The waves looked very similar, but for the crucial fact that one was a tsunami… and the other wasn't. Unfortunately, the alarm for the tsunamigenic wave was cancelled –

and there were fatalities. The other wave was a false positive: it generated an alarm without cause. This event highlights the need for more robust tsunami warning systems to ensure reliable alerts. Ensuring robust and reliable tsunami warnings is critical for public trust, timely evacuations, and effective decision-making by authorities. Accurate warnings prevent unnecessary disruptions and casualties, reduce economic losses, and help protect infrastructure. They also drive scientific advancements, improve international coordination, and enhance overall disaster preparedness, ensuring that warnings are trusted and lead to effective action. A key issue is that unreliable or inconsistent warnings can erode public trust in early warning systems. If warnings are issued and later canceled – or if a tsunami occurs despite no warning – people may become skeptical about the system's accuracy. This could lead to delayed or no response in future events, increasing casualties and damage.

A well-functioning system must not only provide accurate and timely alerts but also maintain public confidence to ensure effective evacuation and response.

— How will tsunami EWS develop in the future?

M. R.: In the future, we hope to be able to deploy tsunami EWS across the globe. Indeed, following the tragic Indian Ocean tsunami of 26 December 2004, UNESCO was given the mandate to establish global tsunami warning services operating in different ocean basins, each coordinated by a regional Intergovernmental Coordination Groups.

Early Warnings for All is a groundbreaking initiative launched in 2022 by the United Nations Secretary-General, António Guterres, to ensure that everyone on Earth is protected from hazardous weather, water (including tsunami) or climate events through life-saving early warning systems by the end of 2027. This is challenging because some systems use seismic signals, but also hydrophones or cables along the sea floor. This makes for heterogenous data and results in a very spotty coverage, with Japan and California much more equipped that other regions of the world. Therefore, GNSS Ionospheric sounding is a valuable tool for enhancing coverage in Tsunami Early Warning Systems. There are of course technical challenges. Even just from GNSS, we receive huge amounts of data. We are currently developing new artificial intelligence tools to process this data, to be able to detect the relevant signal automatically and, potentially, very quickly. We could do this without AI… but AI is very powerful for this type of use. However, it is also a very blind tool, and we really need to watch out for data quality to ensure that early warnings are reliable.

I am also working on a very current issue called 'explainability'. This means that many AI algorithms work as black boxes, which hinders their usefulness for EWS development. For example, understanding how AI systems end up with their conclusions is key to determine how confident we are with the automated detection – here again, to avoid false alarms, whether missing real tsunamis or alerting people when there is no actual danger. •

ARTICLE

Enhancing dust storm early warning systems with remote sensing and artificial intelligence

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With the participation of:
EMANUELE EMILI, JERÓNIMO ESCRIBANO and HERVÉ PETETIN.

Dust storms occur when strong winds loft vast amounts of dust into the atmosphere, sometimes carrying particles over thousands of kilometers. They are most severe in the global dust belt, which spans North Africa's Sahara and Sahel, the Middle East, and Central and East Asia – regions where arid landscapes and powerful winds create ideal conditions for frequent, large-scale dust events.

These storms degrade air quality, disrupt transportation, damage infrastructure, and threaten agriculture and water supplies. Despite these wide-ranging impacts, forecasting these events remains a significant challenge.

— Dust Storm Early Warning Systems and Their Current Limitations

Dust storm nowcasting is crucial for tracking and predicting dust storms as they develop, particularly in the case of haboobs – intense dust storms triggered by thunderstorm downdrafts, which can intensify within minutes. Geostationary satellites are particularly well-suited for this task, as they provide high-frequency imagery that enables early detection of dust mobilization and transport. Notably, the Meteosat series covers Europe, Africa, and the Atlantic/Indian Ocean sectors[1]; GOES-16/17 monitor the Americas[2]; Himawari-8/9 covers East Asia and the Western Pacific[3]; and China's Fengyun-4 satellites observe Asia[4]. These satellites span the visible, near-infrared, and thermal infrared wavelength ranges, providing images every 10 or even 5 minutes in rapid-scan modes.

Based on these images, meteorological agencies have developed composite imagery specifically for dust monitoring. For instance, Dust RGB products combine thermal infrared channels to highlight airborne dust in a distinctive magenta color, distinguishing it from clouds and the surface. Such RGB products, available on Meteosat, Himawari, and GOES satellites, are widely used by forecasters and have greatly enhanced qualitative dust detection and situational awareness.

However, despite their strengths, geostationary satellites often face challenges in detecting and quantifying dust over bright desert surfaces, especially at night, when the absence of visible bands and land surface cooling reduce thermal contrast, weakening the dust signal in infrared channels. Additionally, despite their high-frequency observations and high spatial resolution, operational nowcasts of dust storms remain limited, with interpretation and short-term predictions still relying heavily on manual analysis and subjective assessments.

Dust storm forecasting heavily depends on dust models integrated into numerical weather prediction models, which simulate dust emission, transport, and deposition processes[5]. The initial dust conditions in these forecasts are typically constrained through data assimilation, incorporating observations from polar-orbiting satellites which provide global coverage but only revisit the same location once or twice a day[6].

The World Meteorological Organization's Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS) integrates multiple dust model forecasts, offering a coordinated approach to providing global and regional dust predictions.

— The issue with haboobs

While these models perform reasonably well for large-scale dust outbreaks driven by broad synoptic (large-scale) disturbances, such as cold fronts, they struggle to capture sudden, localized dust surges like haboobs.

Accurately representing haboobs requires model resolutions finer than 3–5 kilometers to capture critical small-scale dynamics. Running such high-resolution simulations across vast regions like the Sahara and Arabian Peninsula is computationally expensive, particularly when employing ensemble forecasting – a technique that runs multiple simulations with slightly different initial conditions or model parameters to estimate uncertainty and improve forecast reliability. However, the ensemble forecasting approach is particularly valuable for haboob prediction, given their inherently stochastic and rapidly evolving nature.

▼

Dust Storm Early Warning Systems are designed to detect, predict, and issue alerts about approaching dust storms to minimize risks. Similar to other weather-related hazards, the detection and prediction of dust storms operate on different timescales and serve distinct purposes. Distinguishing between forecasting and nowcasting is fundamental for structuring effective dust storm monitoring and prediction strategies.

Dust storm nowcasting focuses on real-time monitoring and very short-term predictions, typically within hours or even minutes before and during an event. This is essential for immediate response measures, such as issuing warnings for transportation safety and emergency services.

Dust storm forecasting, on the other hand, involves predicting these storms before they begin, usually ranging from a day to a week in advance. This capability is critical for sectors such as aviation, agriculture, and public health, where preparedness and mitigation strategies are vital.

— AI-Enhanced Dust Storm Nowcasting

At present, nowcasting for dust storms using geostationary satellites still relies heavily on human forecasters interpreting semi-automated products. Artificial intelligence presents a promising avenue for automating nowcasting. Indeed, studies have shown that machine learning approaches can significantly enhance dust storm detection compared to traditional methods.

For instance, a machine learning model was able to accurately identify dust plumes at night – a task that is particularly challenging using manual techniques[7]. Deep learning models often surpass classical ML approaches in capturing complex textures and temporal evolution, and research is increasingly moving in this direction[8]. These recent advancements suggest that AI could reliably automate tasks that previously required expert analysis, ultimately improving situational awareness and short-term dust storm predictions. However, fully automated AI-driven nowcasting systems remain in the research phase and require further refinement before operational deployment.

▼ **IN BRIEF**

Dust storms, especially fast-evolving haboobs, remain challenging to nowcast and forecast due to limitations in numerical weather prediction models and high computational costs. While geostationary satellites provide real-time monitoring, their effectiveness depends on improved detection, quantification and AI integration. AI-driven solutions, such as deep learning and hybrid models for nowcasting and forecasting, offer promise but require additional research, validation and robust implementation.

A dedicated geostationary aerosol mission for North Africa and the Middle East would greatly enhance dust monitoring and forecasting, but in the meantime, refining existing satellite products and incorporating AI remains essential for advancing early warning systems.

— AI-Enhanced Dust Storm Forecasting

Dust forecasts have traditionally relied on numerical weather prediction models and polar-orbiting satellite data. Efforts to enhance dust forecasts should increasingly focus on integrating more frequent observations, particularly from geostationary satellites. Although geostationary retrievals can provide near-real-time updates of aerosol fields, deriving quantitative dust properties over bright desert surfaces remains challenging and requires further improvement. New satellite missions, including GEMS (2021), Meteosat Third Generation (2023), and TEMPO (2024), offer improved spectral capabilities in specific regions, which could enhance dust quantification. Sentinel-4, designed for advanced air quality and aerosol monitoring and scheduled for launch in summer 2025, will provide high-quality quantitative aerosol data. However, its coverage will be limited to Europe and the northernmost part of Africa, leaving major Saharan and Middle Eastern dust hotspots without adequate geostationary monitoring.

One promising development is the emergence of high-resolution reanalysis datasets[9], which blend diverse observations – including satellite and ground-based measurements – into continuous, gridded records of weather and aerosol parameters. These reanalyses provide comprehensive datasets for training AI models, allowing convolutional or recurrent neural networks to learn dust dynamics from large repositories of past data.

Hybrid AI-physics models also present exciting opportunities. They include a conventional numerical weather prediction model that simulates dust emission and transport, and an AI layer that corrects biases or downscales coarse outputs to capture small-scale phenomena like haboobs.

Advanced strategies, akin to the large foundation models seen in other AI fields that use massive unlabeled datasets for training, could employ self-supervised learning on vast meteorological and dust archives to infer dust processes without relying purely on labeled data. Of course, here, ensuring physical realism is crucial. If validated and implemented operationally, these AI-driven approaches could significantly enhance dust forecasts, improving predictions for both haboobs and large-scale dust storms. •

1 Martinez et al., 2009 – **2** Fuell et al., 2016 – **3** Bessho et al., 2016 – **4** Yang et al., 2023 – **5** Klose et al., 2021 – **6** Di Tomaso et al., 2017; Escribano et al., 2021 – **7** Berndt et al., 2021 – **8** Hermes et al., 2025 – **9** Di Tomaso et al., 2022

REGIONAL ZOOM

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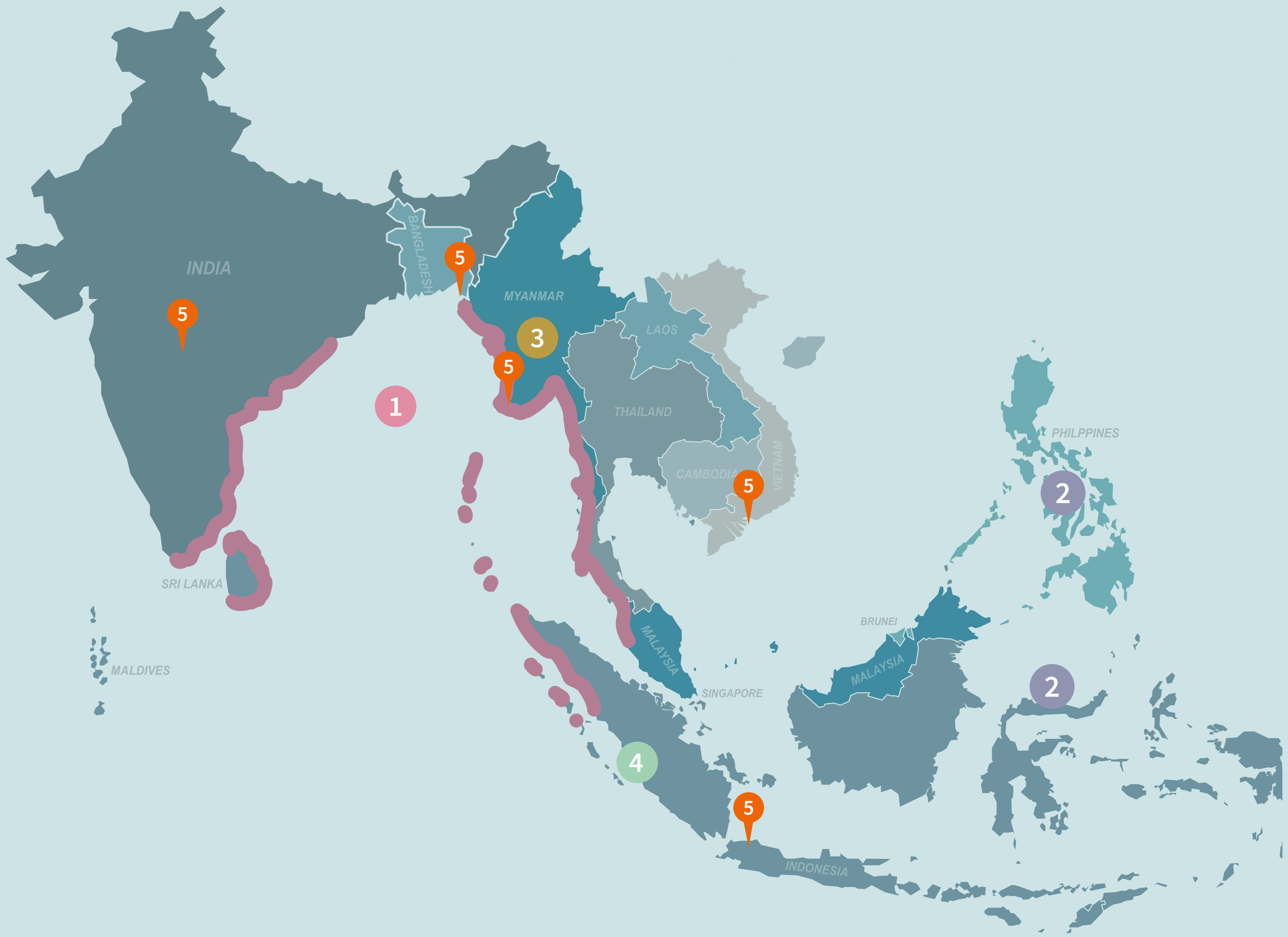
Mobilizing remote sensing and artificial intelligence against natural hazards and disasters



— We have always lived on a restless planet

Complex geological and climate forces generate natural hazards, such as earthquakes and tsunamis, volcanic eruptions, typhoons and sea-level rise, that can impact our societies in both the short and long term if we are not prepared for, cannot respond to and recover appropriately from them. By working together, scientists, governments, the civil society and other stakeholders have made great strides in better understanding the hazards communities are facing and have put in place strategies to reduce disaster risk for these communities.
But big challenges remain. For example, we still cannot say when the next earthquake will occur. We can detect signs prior to volcanic eruptions but reliable eruption forecasting is still challenging. We can project the track of a category five typhoon but there are serious knowledge, information and communication gaps with stakeholders.

Other challenges lie in the interactions between different hazards. What if an earthquake triggers a landslide in a volcanic area? What if a volcanic eruption happens at the same time as a typhoon, the magnitude of which is impacted by climate change? These compounded and cascading hazards are still poorly understood. We have not yet unravelled the complexity and interactions of the different Earth systems, which prevents our models from consistently producing reliable and timely forecasts. The challenge of compounded and cascading hazards would perhaps not be as urgent to address if we did not see the exposure of populations and infrastructure and the ever-increasing threat of the climate crisis.

— Southeast Asia Ring of Fire

Southeast Asia is a case in point where millions of people and billions of dollars are exposed and vulnerable to the wrath of a range of natural hazards. We have seen the devastation from large earthquakes triggering tsunamis (in the case of the 2004 Indian Ocean event) and landslides (with the 2022 Cianjur event). We have also witnessed the destruction caused by volcanic eruptions triggering landslides and tsunamis (the 2018 Krakatau eruption), and typhoons triggering floods and landslides (the 2013 Typhoon Haiyan).

While science has made great strides at identifying patterns and signals that help assess the hazards to a certain extent, much is still to be uncovered to both help communities prepare for and recover from the hazards. We need more data about the hazards and communities living with them, we need to improve the models to produce forecasts for preparedness, and information used for disaster response and recovery, and the way we communicate with societies in a timely manner.

— Using AI: yes, but let's do it right

But within the rise of AI, the push for data sharing, and the possibility to conduct research on natural hazards and disasters from anywhere lie several potential ethical challenges. For example, to better understand the hazards and identify appropriate mitigation and adaptation strategies, we need a lot of data that are usually collected near hazardous regions by local institutions. These data are crucial to validate the Earth Observatory of Singapore (EOS) maps: indeed, rigorous validation processes ensure that damage proxy maps are accurate and reliable, allowing for informed decision-making during disaster response and recovery. EOS is transparent about the data and methods used. It also uses a range of independent data, such as online content from social media and traditional media, to validate their maps. For example, the team compares images of damaged areas with the results of their damage proxy maps for the same location, which gives confidence in their results.

Local data is also absolutely necessary to ensure models used for forecasting are not biased towards other regions where more data are available, such as the Global North. And for the researchers collecting the data to not be left out and considered data collectors only, foreign institutions need to find ways to work collaboratively with them. It is the ethical thing to do, and it is crucial for the interpretation of the results too. Local researchers are familiar with the context, the hazards and what could have led to certain data points.

Another ethical consideration for the use of AI relates to the need for more data about the intersectionality of populations exposed to the hazards. Indeed, while we are making great strides to improve the characterization of the hazards, it is only a component of risk. For appropriately reducing disaster risk for people, more and regularly updated information about the populations exposed and vulnerable to the hazards will help develop appropriate and targeted strategies that respond to the needs of these communities.

1 The 2004 great Indian ocean earthquake and tsunami

Following the 2004 Indian Ocean event that claimed the lives of more than 230,000 people around the Indian Ocean, there was a clear push to better understand the likelihood of such events in the future. For example, new sensors were installed on the ground to monitor the movements of the tectonic plates and provide insight into which regions might be prone to earthquakes. The EOS was setup a few years after the event, and over the last 16 years, has worked collaboratively with Indonesian scientists and agencies to install and maintain more than 40 stations along the fault that generated the 2004 event.

Remote sensing techniques are essential to map ground deformation over large areas for example. Combined with data from ground stations, such as GPS stations, these help scientists to monitor how fast and in which directions the tectonic plates move. We have for example identified a portion of the fault that has curiously not ruptured in more than 200 years, despite the accumulated strain – the Mentawai Seismic Gap, located south of the island of Siberut in the Mentawai Islands. While no one can currently forecast *when* the next big earthquake and tsunami will be, the Mentawai Seismic Gap could be a potential location for future earthquakes[1].

Altogether, remotely-sensed deformation together with GPS and seismic data represent a wealth of data that contain precious information about future earthquake and tsunami risks. AI in this case is an essential tool to study these big datasets together, to extract patterns that can unravel how earthquakes work and tend to repeat themselves.

1 Sarkawi et al, 2025

2 A novel database for caldera eruptions

Southeast Asia is home to more than 750 active and potentially active volcanoes, mostly located in Indonesia and the Philippines. The two largest caldera eruptions in human history occurred in this region; the Krakatau eruption in 1883 and the Tambora of 1815. These eruptions can have global, regional and local impacts, causing cascading hazards because of the volume of ash they eject in the atmosphere, which can travel thousands of kilometers away.

For example, the ash from the Tambora eruption column dispersed around the world and lowered global temperatures in an event sometimes known as the Year Without a Summer in 1816. This brief period of significant climate change triggered extreme weather and harvest failures in many areas around the world.

The calderas of Southeast Asia are being studied via a range of techniques. For example, monitoring stations record seismicity, deformation and gas emissions. Many clues about the caldera behavior (such as where the magma is) are also contained in the rocks from past eruptions themselves. From these rocks, petrologists can extract timescales for magma ascent, as well as temperature and pressure conditions within the volcano. These represent large amounts of very inhomogeneous datasets.

To better assess where and when the next big caldera eruption could occur, our EOS team is developing a novel database linking storage depths, erupted volumes, geochemistry and tectonics. Such a database enables the application of both machine learning (to handle databases with a variety of datasets and to identify patterns) and physics-based models (to ensure the physics are accurate) to explore volcanic processes – it promises to provide a forward-looking approach to volcanic hazard and better forecasting.

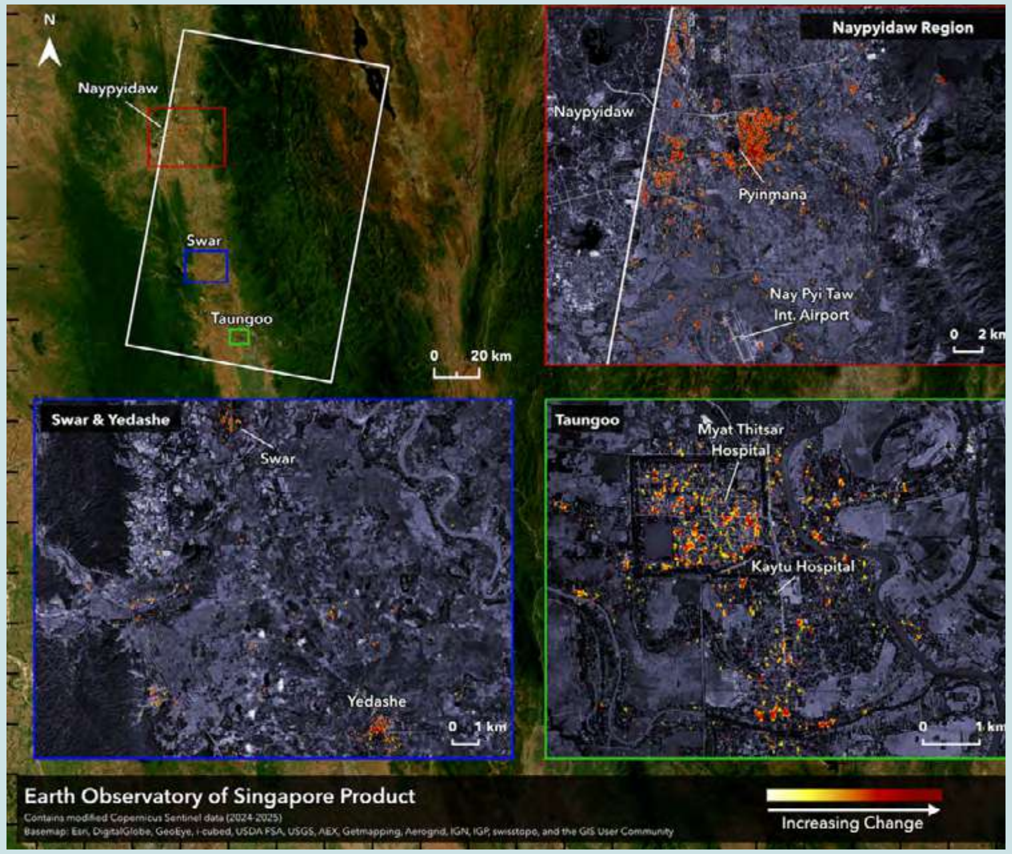
3 Myanmar 2025: a most recent example of how machine learning can help

The EOS Remote Sensing Lab produces disaster-proxy maps, which show ground surface change before and after the event, which can help identify damaged areas – hence their 'damage-proxy' denomination.

For example, the map below was produced following the M7.7 earthquake that struck Myanmar at the end of March 2025. It was shared with appropriate stakeholders on the ground to support rescue and humanitarian efforts.

As this technique uses radar waves which penetrate most weather clouds and are equally effective in darkness, it is particularly useful in tropical regions.

In this area, machine learning will be useful for distinguishing actual damage from other changes in the Earth's surface, by identifying their distinctive spatial and temporal characteristics – the other changes in the Earth's surface could be due to weather or human activities for example. AI is a key tool to this effort, and the EOS Remote Sensing Lab is working on designing a new AI architecture to improve the quality of disaster proxy maps, both in terms of accuracy and latency (i.e. the waiting time for the map to be produced).



This preliminary Damage Proxy Map, created by EOS, highlights likely damaged areas near Naypyidaw, Myanmar, following the 28 March Mw7.7 earthquake and aftershocks. Derived from Copernicus Sentinel-1 SAR data (Dec 2024–Mar 2025), it uses 30-meter colored pixels to indicate damage intensity and is validated with news, ground, and satellite imagery. Note: Accuracy may vary in vegetated or mountainous regions. (Source: Earth Observatory of Singapore, contains modified Copernicus Sentinel data (2024-2025).

4 Landslides following the 2022 West Java earthquake

The Mw 5.6 earthquake that struck West Java on 21 November 2022 was smaller than many other earthquakes happening along the tectonic plate boundaries offshore the Java Island. But this earthquake was quite shallow and close to local populations. Many buildings were damaged by strong shaking and there were landslides in the region of Cugenang and Cianjur.

In that instance too, the EOS Remote Sensing Lab produced a damage-proxy map that shows how much the surface of the Earth had changed between two satellite images acquired before and after the earthquake. These changes can arise from damages to buildings or from land changes, such as landslides or liquefaction induced by the earthquake – and of course to other changes during the time span of satellite data but not related to the earthquake. Our maps show that many areas around Cianjur and Cugenang had changed in rather small spots.

Some of these changes were due to the landslides – secondary hazards that commonly occur in the region around earthquake epicenters, especially in areas with steep topography and if associated with rainfalls.

5 Sinking cities

With climate change action picking up, the subject of sea-level rise has rightfully gotten much attention – but its lesser known twin, land subsidence, has also been emerging as an urgent challenge for many coastal cities. However, since subsidence rates can vary quickly across small areas, land-based measurements often do not capture the true scale of the problem. Therefore, EOS used satellite data, namely InSAR, to provide accurate measurements of coastal sinking to a tenth of a millimeter.

We found that 42 out of 48 of the world's most populous coastal cities are sinking[2]. Land subsidence is also more variable across the 48 cities (-16.2 to 1.1 24 mm/year) than the latest estimations of vertical land motion (-5.2 to 4.9 mm/year) from the Intergovernmental Panel on Climate Change.

Many of these cities are located in Southeast Asia, including Ho Chi Minh City, Tianjin, Chittagong, Yangon, Jakarta and Ahmedabad. The scientists found coastal cities to subside as quickly as 43 millimeters per year, which is 10 times more than the current global mean sea-level rise from melting of the ice sheets and warming of the ocean of 3.7 millimeters per year. Local land subsidence mostly happens in rapidly expanding megacities, where an increased demand for groundwater and rapid urban development cause soil compaction. As subsidence leads to higher flood risk, it is crucial for local communities and policymakers to identify which areas are at particular risk. Preventive action includes slowing the rate of groundwater extraction to a sustainable level.

2 Tay et al., 2022

Towards *better risk* management at a societal level

ARTICLE

A new vision for seismic risk, towards better risk management

DR. PHILIPPE GUÉGUEN
University Gustave Eiffel and Université Grenoble Alpes, France

Stakeholders must ground seismic risk mitigation policies on the most precise possible understanding of hazard, exposure, vulnerability, and consequences. Hazard studies characterize potential earthquakes and their frequency. Exposure and associated vulnerabilities tie to the density of population and assets in the risk zone, including for example the type of construction and their seismic resistance or the degree of preparedness of local populations.

The expected consequences of an earthquake taken into account are usually economic and human but could in principle be expanded to consequences for biodiversity for example. Two key postulates guide current scientific research to design seismic risk policies: losses result from damage to structures, infrastructures, and other types of property; and this damage is the result of ground vibrations, called seismic waves. Analyzing the consequences of past earthquakes reveals the importance of actions for prevention, protection and risk transfer.

However, earthquakes are rare events and there is still much to learn about the physical and social processes that influence each of the components of risk – hazard, exposure, vulnerability, consequences – including for example, the loading state of faults for time-dependent hazard assessment and the site-city interaction in urban area. Scientists therefore have always played a key role in characterizing them as accurately as possible, and hence in designing better risk mitigation policies.

— L'Aquila earthquake, a gamechanger in establishing liability after a natural catastrophe

The case of the L'Aquila earthquake, which struck Central Italy on the 6th of April, 2009 and killed 309 persons, clearly illustrates that the actions or inactions of authorities or stakeholders involved in risk management must be considered when evaluating the consequences of a natural disaster.

Indeed, in that case, the relatives of some of the victims filed a lawsuit against six geoscientists and the deputy head of Italy's civil protection. The accused had met six days before the earthquake and reassured the public by stating that no major earthquake was imminent.

This subsequent trial has been highly controversial due to the unpredictability of earthquakes. The scientific incompetence of the deputy head of Italy's civil protection regarding the seismic sequence before the main shock was a central point of discussion during the trial. The resulting six-year sentences for the seven members of the advisory committee were overturned on appeal and ultimately annulled by the Italian Supreme Court in November 2018. Only the deputy head, in his political capacity to ensure civil protection, had his conviction upheld, although it was reduced to a two-year suspended prison sentence.

This example shows that society now considers that public stakeholders, such as the state, government, local authorities, civil protection, etc., are key in altering the scale of the consequences of a natural disaster and thereby hold a responsibility towards the population.

If, as societies, we accept that, although hazards are natural and difficult to predict, the disasters themselves are defined by their consequences on human society – themselves influenced by actions, decisions and lack thereof – we must consider that public stakeholders could be held responsible for disastrous consequences.

— Enhancing seismic science with AI and remote sensing to design better risk maps and reduce uncertainties on losses assessment

Seismic risk is evaluated based on the probabilities of occurrence of an earthquake and the uncertainties tied to them. It is then translated into a language suited for decision-making (as opposed to everyday language, which remains vague and imprecise). This approach captures all the uncertainties associated with each step of the evaluation process. Ultimately, these uncertainties reflect the lack of knowledge regarding the complex processes at play, from the characterization of the seismic source to the assessment of the consequences. They can be reduced or better defined through the collection of high-quality, large-scale data, which can help provide a more accurate predictive representation.

Understanding seismic hazard
In earthquake science, hazard is defined through a probabilistic process integrating all geological and tectonic knowledge, whose goal is to characterize source zones, seismicity, and ground motion. Predicting ground motion involves compiling data from in-situ sensor networks (seismometer, accelerometers…) to derive models of how the ground will

IN BRIEF
Although the number of natural disasters is increasing globally since the early 21st century[1], largely due to climate change, their consequences relative to the exposure growth tend to decrease for human populations and assets. This is the result of risk management policies and tools, such as warning systems and protective infrastructure, which rely on the scientific understanding of hazards, exposure and vulnerability of populations and assets.

However, the increase in disasters and the judicialization of societies are increasingly leading to a search for liability when disasters are caused by natural hazards. Major legal cases illustrate this evolution. In the case of seismic risk, L'Aquila trial has shown that liability is not sought in the hazard as such, but in the consequences of the disaster, linked to the action or inaction of the authorities responsible for risk prevention. In this respect, a proper definition of seismic risk should now include the action or inaction of stakeholders, combined with the notions of hazard, exposure and vulnerability.

Novel technologies such as remote sensing and AI and attribution science help further our understanding of seismic risks, design better mitigation strategies, and locate where more effective actions can lead to better protection.

1 Dollet et al., 2022

move for each possible magnitude and distance to the earthquake epicenter. Variability around these models relates for example to the aleatory uncertainties associated to the natural phenomenon.

Earthquakes follow a cycle dictated by tectonics that conditions return periods and occurrences of these events: knowing where we are in this cycle would help estimate the time until the next rupture. The use of GPS stations and satellite images to track Earth's surface deformation, combined with advanced data analysis, is key to understanding earthquake cycles. In particular, it helps to describe how friction on the fault evolves over time – which is particularly important in understanding earthquake mechanics – as well as fault stability and the nucleation of seismic events. It also helps improve the accuracy of earthquake risk predictions by refining the models that estimate where and how earthquakes may occur[2].

Quantifying exposure of populations and property

Characterizing exposure first involves identifying vulnerable property and populations. The risk is then derived from understanding the interaction between hazard and exposure, and effective risk management relies on a comprehensive approach to both components. The inclusion of data collected by citizens and post-seismic damage surveys provides an effective solution to globally assess exposure and expected consequences for a given scenario, based on the intensity or frequency of a seismic hazard. For example, we were able to assess and predict damage at a global scale (urban or country) with a better and faster solution[3] than what had been achieved before. To do so, we used a machine learning algorithm, which was trained on a building portfolio that included basic building features (such as number of stories, roof shape, localization, extracted either from crowd-sourced data or satellite images) and the damages observed on the buildings after past earthquakes. Subsequently, the algorithm was used to predict the damages at a larger scale. This type of strategy could be used to derive maps of potential impacts in seismic regions.

2 Donniol et al., 2024 – 3 Ghimire et al., 2022

▼ States have long had a duty to protect their citizens from risks, whether natural or not

Informed decisions and actions can be taken only once the potential consequences of disasters are scientifically understood, and once stakeholders wish to align their policies and strategies within the existing regulatory framework. Regarding risk reduction actions, the European Convention on Human Rights (ECHR) stipulates, for example, the obligation of member states to protect the lives of individuals and property requiring measures that ensure a high level of protection, such as seismic regulations aimed at saving lives or emergency and post-seismic management plans. Regarding risk transfer actions, the Solvency II framework defines rules for insurance companies in the European space to ensure adequate capital to meet their long-term obligations to beneficiaries, thus allowing them to face probable events with a 200-year return period (i.e., events with low probability and long return periods, but with high consequences), accelerating the economic resilience of the affected region.
The occurrence of a natural disaster thus serves as a crucial test for the performance of stakeholders, whether states, governments, civil protection or others. While no one can be held responsible for the natural hazard itself, citizens evaluate the responsibility of stakeholders based on how effectively they manage the disaster. Natural disasters are now considered abnormal events, and the search for responsibility and guilt is increasingly likely to be dealt with by courts, particularly in litigation related to compensation claims and liability towards victims.

▼ In our climate-change era, science is taking an additional role in mitigating natural catastrophes

In the last decade, a climate-science field called 'attribution science' has been used in legal cases to broaden the obligation of governments, businesses, and other actors to limit the foreseeable consequences of climate-induced catastrophes.
Indeed, while attribution science was initially developed to differentiate extreme natural events caused by anthropogenic climate change from those attributed to natural climate variability, it ultimately aligns with the strict definition of causality, which can be likened to the 'but-for' legal causality test: that is, the disaster could not have occurred without the presence of the causal factor, such as the inaction of states.

Several landmark legal sequences in recent years illustrate individuals' commitment to holding states legally accountable for their climate inaction. In 2019, Urgenda Fondation's lawsuit led to the condemnation of the Netherlands by the Council of State for climate inaction and became a reference in the matter. In 2020, the Duarte Agostinho case was brought against Portugal and 32 EU member states before the European Court of Human Rights for climate inaction that caused an increase in forest fires since 2017 in the European space, citing the failure of states to meet the obligations set by the European Convention for Human Rights. In 2021, the administrative court of Paris condemned the state for failing to meet its greenhouse gas reduction commitments between 2015-2018, after the mobilization of four NGOs supported by more than 2 million people signing the 'Case of the Century' (L'Affaire du siècle). Finally, the case of the 'Swiss older women for the climate' – KlimaSeniorinnen – who have been fighting since 2016 to recognize Switzerland's responsibility for climate inaction, illustrates the introduction of attribution science into courts of justice.

All these examples illustrate that the role of scientists is evolving, towards providing a rational explanation of natural events – an explanation that allows greater understanding of the relationship between the damaging event and the authorities' actions or inaction.

ARTICLE

Artificial intelligence to the rescue: designing flood and cyclone forecasts in line with the needs of humanitarians on the ground

ANDREA FICCHÌ
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With the participation of:
ANDREA CASTELLETTI, ELISABETH STEPHENS, JANIO DAMBO and VALDEMIRO SULTANE.

Over the past decade, natural catastrophes led to an annual average of 24 million displaced people globally, peaking in 2022, with nearly 32 million displacements within countries caused by weather-related hazards, according to the United Nations. There is an urgent need to accelerate efforts to improve early warnings and early actions to reduce human losses in many parts of the world, especially in developing countries. Humanitarian organizations need precise information and a large enough time window to act – often on a budget. In this regard, AI can help design more useful forecasts to reduce human losses. Recent advancements in AI have led to an acceleration in the progress of hydro-meteorological forecasting. AI-based models are now competing with or in some cases outperforming state-of-the-art physics-based numerical weather prediction and hydrological forecasting systems[1,2]. Thanks to the greater quantity and quality of environmental data, especially from remote sensing, AI offers unprecedented opportunities to enhance the accuracy and timeliness of forecasts of extreme events such as tropical cyclones and floods. This potential can be exploited to support timelier and more effective humanitarian forecast-based action, which aims to provide life-saving assistance to at-risk communities ahead of a predicted catastrophic event, for example by providing shelter, health and hygiene kits or securing evacuation routes.

— The transformative potential of AI

Despite decades of continuous progress in physics-based models[3], forecast accuracy and skillful lead times (how far in advance a forecast remains more reliable than a reference) for extreme weather events are still a limitation, restricting time for early warnings and early actions. The quality of forecast systems can be measured in terms of the so-called *skill*, which refers to metrics telling users how much better a forecast is at predicting events or aspects of interest with respect to a reference or basic prediction. The skill of hydro-meteorological forecasts has steadily improved, but with no significant jumps until when AI came into play, and there is room for improvement. There are still large biases, such as systematic errors, in predicting the correct magnitude and location of catastrophic events that limit forecast utility for rapid and cost-effective early action. For example, in global coastal regions exposed to tropical cyclones, early action is limited by the current errors of weather models in accurately predicting the tracks and impacts of cyclones with sufficient lead-time.

Even with the most advanced forecasting systems, tropical cyclones track errors are still larger than 200 kilometers beyond 3-day lead times[4], while a larger window of time would be often needed to reach all at-risk communities. AI can help bridge these gaps at a faster pace than working only on traditional models. We categorize here 5 distinct advantages that AI-based approaches offer for advancing operational early warning systems and impact-based forecasts:

1. Faster computation and reduced costs: Once trained to predict specific events using historical data, AI models are significantly faster than physics-based models, enabling real-time generation of forecasts with reduced computational resources. This efficiency translates to cost savings, which is particularly important for applications in areas with pressing resource constraints.

2. Enhanced probabilistic forecasts: Thanks to their speed, AI models can generate large ensembles of future scenarios at a fraction of the computational cost of traditional methods. This capability allows for more accurate probabilistic forecasts, providing better risk estimates.

3. More flexible integration of diverse observational data: AI tools can more readily assimilate heterogeneous data from satellites, as well as ground stations like weather and river gauges, improving forecast calibration and flexibility. This capacity is especially valuable for regions with sparse conventional observation networks, like most parts of Africa.

4. More locally-relevant climate services through bias adjustment and downscaling: AI-driven post-processing can refine forecasts and simulations, enabling bias correction – in other words, reducing errors – and downscaling – increasing the level of detail, for example translating coarse regional models into localized predictions. These refinements provide more accurate and higher-resolution, locally-relevant services, with forecasts tailored to specific regions and decision-makers.

5. User-oriented improvements in forecast skill: By guiding the training of AI models following user needs and criteria, AI tools can enhance forecast accuracy and skill, in ways directly relevant to decision-making, offering tailored services for local stakeholders and specific applications.

— From the theory to the practice: a route to harvesting the opportunities of AI for disaster risk management

All these AI-based advancements can contribute to democratize access to advanced forecasting tools, empowering developing countries to adopt low-cost, high-impact solutions. However, realizing this vision requires coordinated international efforts to address challenges such as accessibility to data and computing infrastructures for AI tools and capacity building. In particular, local trust in AI-based models and interdisciplinary collaborations involving scientists and practitioners need to be fostered.

To do so, we organized a workshop in Maputo in October 2024, focusing on AI applications for climate services and forecasting with local researchers and practitioners from national hydro-meteorological services and humanitarian organizations. This workshop contributed not only to enhancing local capacity building initiatives but also to spread the message of our research which was well received by local professionals, who seek effective solutions for acting ahead of cyclones or floods in Mozambique. Disaster managers and humanitarians are interested in applying AI to improve forecasts to support anticipatory actions. They are ready to embrace the changes that AI is bringing in hydro-meteorological forecasting, working together with scientists, hydrometeorologists and forecasters, to advance towards more proactive risk management and enhance life-saving actions. •

— In 2024, at least 12,000 people lost their lives due to climate-related hazards. (United Nations Office for the Coordination of Humanitarian Affairs)

— In Africa alone, more than 100,000 people died because of disasters between 2013 and 2022. (Sendai Framework Monitor data)

1 Nearing et al., 2024 – **2** Price et al., 2025 – **3** Bauer et al., 2015 – **4** Emerton et al., 2020

CASE STUDIES

How AI-based enhancements respond to the needs of humanitarians: 3 case studies

1 IMPROVING CYCLONE RAINFALL AND FLOOD FORECASTS FOR EARLY ACTION IN MOZAMBIQUE

In the PRINTFLOODS and CLINT projects, we developed two AI-based post-processing schemes for advancing operational forecasts of cyclones and floods. They illustrate advantages 4 and 5: moving towards more locally-relevant and user-oriented services.

For tropical cyclones, we developed an AI-based post-processing model for extreme rainfall forecasts[1]. Our model significantly improved the skill of the operational gold-standard numerical weather prediction system, extending the skillful forecast horizon in which actions can be implemented[1].

In Mozambique, our improved forecasts better meet critical performance thresholds, reducing false alarms and increasing hit rates (how often a forecast correctly predicts an actual event) of crucial interest for humanitarians like the Mozambique Red Cross (Cruz Vermelha Moçambique, CVM).

This translates into an increase of approximately two days in the time window to act, moving from 3 days (of current contingency plans) to 5 days, enabling a more effective implementation of all the anticipatory actions by CVM and the government institution responsible for coordinating the disaster risk reduction actions. These actions include early deployment of personnel and resources to expected impact areas, dissemination of timely alerts, advising the population to leave at-risk areas, allowing more efficient evacuations, and pre-positioning relief and emergency supplies to support life-saving interventions (for example, distributing shelter kits, water purifiers, buckets to transport and store water, mosquito nets and hygiene kits). The potential of AI for improving existing services is also being explored for flood forecasts.

We use an operational system, the Global Flood Awareness System, of the European Commission's Copernicus Emergency Management Service, used in some Early Action Protocols of the Red Cross Red Crescent across the world. Its current skill limitations prevent a more widespread operational use, especially in African regions like in Mozambique. For example, the Mozambique early action protocol for floods is currently limited to a lead time of 3 days[1], within which CVM can act before a flood, and to only four main river basins. The trigger is currently mostly based on measured water levels at upstream river gauge stations, providing CVM with approximately 3 days of lead time to reach at-risk communities downstream. We were able to post-process the data from the Global Flood Awareness System in the Zambezi River Basin and coastal areas of Mozambique, using an AI-based correction.

This approach here also extends the actionable lead time, significantly reduces false alarms and increases hit rates, offering the opportunity to extend the lead times for early action and the spatial coverage of at-risk areas.

In Mozambique, where floods are recurrent and devastating, like after tropical cyclone Idai in 2019[2], the additional warning time allows humanitarian agents and disaster managers to efficiently manage precarious access roads from warehouses to impact sites, in order to reach and assist the most marginalized and vulnerable communities, evacuating at-risk population when necessary, reinforcing houses and protecting critical infrastructure. Our reduction of false alarms helps ensure a reduction in costs from unnecessary actions and a better use of resources to reduce human and economic losses.

1 Nearing et al., 2024 – **2** Price et al., 2025

2 FASTER COMPUTATION AND LARGER ENSEMBLES OF STORM SURGE PREDICTIONS

In another application from the PRINTFLOODS project, we developed an AI-based surrogate model for storm surge predictions, leveraging on AI to deliver faster predictions at reduced costs (advantage 1), while better representing uncertainties (advantage 2) compared to a physics-based model. The surrogate AI model complements the computationally demanding physics-based Global Tide and Surge Model, by offering a faster generation of large ensembles of scenarios to better represent uncertainties over different time scales and provide more informative risk estimates for end-users. Our AI model can be deployed over any local area of interest, requiring less data than global models, making it easier to run and tailor to the needs of local users. We evaluated the accuracy of this approach for projecting storm surge extremes over future scenarios, demonstrating its benefits for

a case study in the New York City coastal area[1]. The same approach can be applied to any global coastal regions using available open-source input datasets, for both short-range forecasts and long-range projections.

Several end-users, including humanitarians, disaster managers and insurers could benefit from such faster and less costly ensembles of storm-surge predictions to estimate coastal flood risks.

3 ADVANCING RIVERINE FLOOD FORECASTS WITH PURELY AI-BASED AND HYBRID APPROACHES

Beyond the use of AI in forecast post-processing and surrogate modelling (which can be seen as hybrid approaches, relying on the combined use of AI and traditional physics-based models), purely AI-based models are increasingly demonstrating reduced costs and better integration of multiple observational datasets (advantages 1 and 3) for producing actionable flood forecasts.

For example, in the last few years Google Research has contributed scaling up flood forecasting capabilities at the global scale, developing AI-based models. This work led to the launch of the Flood Hub platform in 2022, providing real-time flood forecasts worldwide.

These forecasts bring a significant improvement also in data-scarce regions[1] with respect to current state-of-the-art physics-based models (that still rely not only on physics-based equations, but also on data for their calibration), extending capabilities in vulnerable areas with little available observations. Where available, local historical and real-time data can be used to improve the forecasts, as done in Bangladesh, where data from the Bangladesh Water Development Board help ensure more accurate and timely predictions, and use them operationally.

Finally, the INFLOW project (co-led by the University of Reading and ICPAC) leverages the ability of AI methods to integrate diverse observational data to produce forecasts of flooding in South Sudan. Indeed, record high levels in Lake Victoria upstream in 2020 drove unprecedented flooding around the wetlands of South Sudan from 2020-2022, aggravating an already complex humanitarian situation. INFLOW_AI is a new operational hybrid forecasting approach which uses an artificial neural network to forecast the evolution of flood extent based on satellite observations of the current flood extent, upstream lake levels and rainfall, while it can integrate forecasts from numerical weather prediction models.

INTERVIEW

—

How the insurance sector seizes artificial intelligence and remote sensing tools for natural disasters

PIERRE DU ROSTU
CEO of AXA's Digital Commercial Platform

— A major challenge today is to ensure that the planet remains insurable, despite increasing natural risks and vulnerability of populations, particularly as a result of climate change and human settlements in high-risk areas. How is AXA Digital Commercial Platform (DCP) contributing to this challenge?

Pierre du Rostu: We face a new world for the insurance industry, because of climate change and how it increases natural risks, but also with other kinds of risk arising, such as cyber or geopolitical ones. Regarding climate change, over the last 20-30 years, we have seen a massive acceleration in terms of frequency and intensity of events – this leads to a critical challenge for the insurance industry, which we call the insurance gap.
This refers to the gap between what the industry can offer as level of warranties and what is actually needed – and this gap is growing everywhere on earth and for all types of catastrophes. For example, some insurers – although not AXA – have been essentially withdrawing themselves from the markets by offering premiums that are so costly than no one will buy them.

'We have this strong conviction that because of those new risks, becoming involved only after an event is not sustainable anymore. This is why we want to bring prevention at scale to our clients. We are shifting the relationship between the customer and the insurance company from curative medicine to preventive medicine.'

There are different ways of bridging this gap. One is to look at public-private partnerships, such as the one that exists in France where the state mandates that all insured contribute to a natural catastrophe reinsurance fund that helps cover costs in case of events so devastating that they are labeled 'natural catastrophe state'. Other countries and the European Union are now starting to consider this type of options.

Another part of the answer is to become better at prevention – and this is where AXA DCP comes in. We have this strong conviction that because of those new risks, becoming involved only *after* an event is not sustainable anymore.
This is why we want to bring prevention at scale to our clients. We are shifting the relationship between the customer and the insurance company from curative medicine to preventive medicine.
So we bring new solutions to help our clients understand where their assets are, where the risks lie, what they should be doing in terms of prevention, what is happening in real time, and how they should react, as fast as possible, to mitigate the impact of the event.
This is what AXA DCP is about: we combine hardcore risk expertise from all-across AXA together with new technologies to create new solutions to help our clients face those challenges.

— In the case of 'natural' disasters, how does prevention work in practice?

P. D. R.: If we talk about wildfires for example, the issue is that our risk maps are becoming obsolete: they have been built by looking at the past 50 or 100 years. When climate changes, you cannot draw information from what happened before anymore. We have to invent new ways of understanding risks so that we can take decisions. AXA Climate for example works on forecasting the evolution of wildfire risk in 20 or 30 years. At AXA DCP, we have built, together with Kayrros, a French startup, an innovative model using satellite pictures. We derive risk scores in real time, by looking at the presence of vegetation, its density, its typology and blending this information with plenty of other factors such as topography or temperature.

We use satellite pictures so we can do this at scale, but we also have prevention engineers using these tools and their expertise able to provide specific advice locally – pinpointing high-risk buildings and showing clients how the vegetation next to the building is an aggravating factor and how they can clear the vegetation to reduce exposure. Clients can judge if they want a digital-only approach – which might be enough for some of their sites – or if they need a deeper recommendation for high-risk sites for example. In the case of floods, there are also mitigating factors that can be targeted in a prevention approach: flood walls, river dredging (that is, removing sediments from riverbeds), or simply placing stocks or computers one meter high. Since we can tell more and more precisely to clients how they are exposed to flooding, we can help them reduce exposure – sometimes by helping them to pick a site for a new factory.
It's a win-win situation.

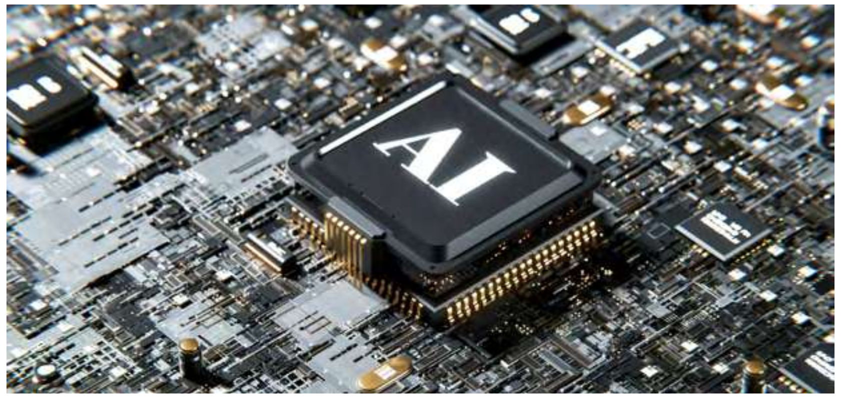
'We now have to invent new ways of understanding risks, so that we can take decisions. To do this, at AXA DCP, we build innovative models using satellite pictures, to derive risk scores in real time - this is a shift in an insurer's business model.'

We have also made available to our users some of the AXA unique risk models to cover more and more perils. As an illustration, users can access our hail model, which uses an AI system reading through satellite pictures to assess whether any solar panels or glass roofs might be exposed to high hail risks.

— How does this change the relationship with customers in the insurance sector?

P. D. R.: It changes everything. Historically, the relationship between customers and their insurers hasn't been always agreeable – but now we are working together, with aligned interests. Our agents do not only discuss claims or price, but about acting together to practically reduce risks. However, the adoption of prevention measures should evolve positively not as a punitive strategy towards insuring people. Of course, there has always been a link between the level of preparedness of a client towards specific risks and the price of insurance contracts that are offered to them, but we want to create and maintain a strong alignment of interest and foster prevention adoption at scale. So, this is a shift in the business model, and this is why DCP is a Group strategic ambition. We believe that, in the future, prevention is why clients will come to the insurance sector.

Another interesting point is that although we originally focus on B2B (SMEs to very large companies), we have more and more municipalities or public authorities coming to us. For instance, our wildfire model has been bought by a firefighters' organization. Over the past two years, we have seen a clear change on public bodies seeking advice. I think this may be related to public pressure on States regarding natural catastrophes – and from the fact that, at the end of the day, we all know that we must act collectively on this one.



'The shift due to novel technologies is massive. Beyond prevention, it will impact almost the entire value chain of the insurance industry, in our ability to understand risks, underwrite and price risks, and manage claims after an event happens.'

— What role do remote sensing and AI tools play in decision-making and pricing?

P. D. R.: I think we are living through a paradigm shift with remote sensing data for the insurance industry. So far, we must admit that our knowledge level can be very poor – sometimes even our clients don't know precisely where all their buildings are; they could know for 80% of their 10,000 sites portfolio for example. In this case, how can you model risk and do prevention?

Now we have tools and data, that enable us to solve part of this problem at scale – across the entire planet, and in real time too. During the floods in Valencia in the fall of 2024 and also the Los Angeles wildfires at the start of 2025, we used a lot of satellite pictures to understand how things were evolving in real time.

So, we use remote sensing and AI to understand where the assets are, how they are structured. For instance, we can identify whether there are AC units on the roof of the building that might fly off in case of a hurricane, or if they are wooden pallets next to a building that could catch fire. We use very varied data too, from public satellite fleets and private constellations depending on the use cases: one of them for example, Iceye, has radar sensors that can measure the depth of water – for us, that is a very interesting insight. By buying different types of data, we get the information we need to cover all forms of natural risks.

Remote sensing is also extremely useful because it gives a consistent approach globally. Insurers have different risk models for the US, for Western Europe or Australia, all separated, based on different data. Now we start to have global ways of looking at risk.

The shift due to novel technologies is massive. Beyond prevention, it will impact the entire value chain of the insurance industry, in our ability to understand risks, underwrite and price risks, and manage claims after an event happens.

AI is accelerating significantly. Of course, some of our models have been using machine learning for 10 or 15 years; but the adoption curve is impressive. For example, over the past five years we have improved significantly in computer vision – the ability for a computer to read through an image and identify objects thanks to deep learning is really impressive.

Generative AI is also providing a huge technological acceleration. We are starting to use it to create much faster interfaces with our clients, so information is easier to interact with. In particular, Geo-LLM can extract geospatial knowledge using large-language model coupled with map data, so clients can read through images more easily or interact with maps for example. We also use generative AI to train our computer vision models or to help our developers. It's not just about generative AI but about blending it with other types of models so that we are faster and more efficient. Finally, I'd like to mention IoT, the Internet-of-Things that is, which connects sensors across assets. We use IoT to track in real time the vessels of our clients, to inform them about natural catastrophes or risky zones. IoT also allows us to monitor the inside of buildings, and allows us to blend this information with views from space using remote sensing, to bring in early versions of digital twins – or at least going in that direction. This could be useful in providing predictive maintenance advice, for example noticing peak electricity usage related to defective devices that could have led to fires or to identify flooding early.

— What technical challenges are you facing currently in terms of AI and remote sensing - what tools will be available in the future?

P. D. R.: One of the first challenge sounds pretty basic, but it is crucial. We have a lot of different types of data, and we need to be able to aggregate them in a meaningful and useful way. For instance, when you locate a building, you have an address, cadastral data giving you the shape of the site but not where buildings are, satellite pictures and data maps giving you buildings or perhaps vegetation type – and all these need to be stitched together. That's where the DCP acronym comes from: we are a 'digital commercial platform', so that we are able to aggregate plenty of different data sources from different places and make sense out of it. Another challenge is to keep up to speed with all the innovations that exist out there. The pace of technical progress is incredible. This is very exciting, but also a big challenge.

Finally, a less technical challenge, but still critical, is how we can help our stakeholders better understand and effectively use the data. Sometimes, clients have experts internally with whom we can co-innovate, and sometimes, there is a lot of change management to be done in our relation to risk and to risk prevention. •

ARTICLE

Leveraging the potential of remote sensing and artificial intelligence to help keep the world insurable

ALEXANDER VOLLERT
AXA Group COO
& AXA Group Operations CEO

Remote sensing and AI continue to reshape how insurers address natural catastrophes and other environmental risks. Although challenges persist — ranging from high resolution data-acquisition costs to labeling complexity – continuous research and innovation are unlocking new possibilities. In the insurers' world, these technologies improve underwriting, expedite claims management and anticipate future risks. As such, they help maintain and broaden insurability in our ever-changing world, ultimately contributing to greater societal resilience.

In an era of increasing natural catastrophes, leveraging technology to enhance risk assessment is crucial for maintaining insurability — that is, the ability to provide insurance coverage at a feasible premium — for risks that can be accurately measured or modeled.

Remote sensing and AI play a pivotal role in achieving this goal. Satellites and other aerial data sources now help insurers observe damages from climate change, including hurricanes, droughts and floods, as well as human-driven factors, like deforestation or agricultural practices. AI models contribute to qualify and quantify these phenomena, allowing for better risk understanding and even better forecasting. This enables insurers to mitigate losses with informed preventive measures and better disaster response. However, current challenges include:

- ***Data quality and resolution:*** Cloud cover and limited revisit times can hamper timely analysis, despite recent progress made with novel satellite sensors and constellations.
- ***Cost and accessibility:*** Acquiring high-resolution data can be expensive and specialized expertise is needed to process it.
- ***Labeling complexity:*** Many tasks require extensive data labeling to enable AI systems to exploit the data, slowing down model development.
- ***Regulatory constraints:*** Privacy laws and data protection regulations can limit the use of certain types of imagery.

Despite these hurdles, remote sensing and AI are already enhancing overall risk profiling, improving loss prevention and accelerating claims processing. By fostering better risk-sharing and enabling new types of insurance coverage, they already contribute to maintaining insurability for both individuals and businesses.

These technologies also ultimately support the mission of insurers like AXA to protect what matters to customers and to society. Reduced claims frequency and severity, optimized resource allocation and more competitive products are just a few of the ways AI-driven analysis of remote sensing data helps achieve sustainable development and societal well-being.

— Remote sensing and AI are already operational for better prevention and enhanced risk management

On the business side: AXA's Digital Commercial Platform

AXA's Digital Commercial Platform already leverages advanced computer vision models to quickly detect risk factors on commercial properties, including for example oil tanks, large cooling towers, and surrounding vegetation.
Early identification of potential risk factors helps clients take preventive measures, reducing disruptions or damages.
In addition, more accurate property insights enable more refined underwriting decisions and strengthen risk engineering overall. Finally, Earth Observation data can also provide near real-time damage assessments following natural catastrophes, facilitating quicker response and more precise reserving.

If applied broadly, these technical capabilities could also serve in other scenarios beyond commercial property underwriting – such as monitoring critical infrastructure in disaster-prone areas or accelerating claims support after catastrophic events – ensuring that response teams have accurate and timely information.

On the tech side: deep learning for object detection

A key challenge in remote sensing is to quickly recognize objects of interests, such as property or vulnerability factors like large fuel or gas tanks on recently acquired images. Identifying these vulnerability factors accurately is essential to getting a comprehensive risk awareness of insured assets. Training such detection models is time-consuming and requires a large number of annotated images, where specialized domain expertise is required. So far, AXA's models can detect seven types of vulnerability factors. They are being deployed in Digital Commercial Platform. They will support XL Risk Consulting, XL commercial underwriters, and, in a subsequent phase, the risk officers of our corporate customers. By automating object identification, AXA can enhance risk assessment and underwriting processes, providing more proactive and accurate insights.

— A broader vision for integrating AI and remote sensing to natural catastrophe risk management

Our broader vision encompasses a future where insurers proactively anticipate and tackle emerging risks. By systematically integrating remote sensing and AI, insurers can shift from a reactive stance to more predictive and preventive model, enhancing resilience for businesses and communities.

On the business side

- Improved underwriting
By leveraging satellite observations of evolving hazards – such as the presence of industrial risks on sites, insurers gain more accurate risk awareness, enabling more precise and tailored insurance underwriting.
- More frequent risk maps recalibration
Regularly updating risk maps thanks to new satellite data and AI analysis allows for better policy pricing and underwriting decisions.
- Parametric policies for agriculture
Parametric policies based on remote sensing data (e.g., drought monitoring), can provide automatic payoffs to farmers if the crop yields fall below a level specified in their contract, which could be detected by remote sensing.

On the tech side

- Few-shot learning, or the ability for AI to recognize objects that it has seldom seen before
Collecting labels for new categories of objects or risks is labor-intensive. Few-shot learning enables models to recognize new categories from just a few labeled examples. AXA's research team has proposed new techniques in this field[1], and several start-ups are also tackling this challenge.

1 Chevalley et al., 2023

Successful scaling to production would let underwriters and risk engineers themselves performing data labeling and continuously refine detection models, allowing insurers to expand detection capabilities and more targeted risk coverage.

- Multi-spectral imaging for more accurate detection

Objects indistinguishable by standard RGB cameras often reveal unique signatures under infrared or other spectral bands. AXA's research team has explored using advanced imaging methods for wildfire detection, vegetation health monitoring and roof condition assessments. By capturing broader image bands, multi-spectral imagery opens the door to deeper insights and more targeted risk evaluations.

— Expanding further the boundaries of risk detection

- Open World GeoSatLM – using AI to understand satellite images in plain language

AXA GO leads a research initiative that uses a generative AI-powered foundation model to analyze remotely sensed imagery.
Indeed, deep learning models excel at detecting known targets in images, but they usually recognize only predefined categories. Adding new objects or risks typically requires collecting annotated examples and retraining – a time-consuming process.

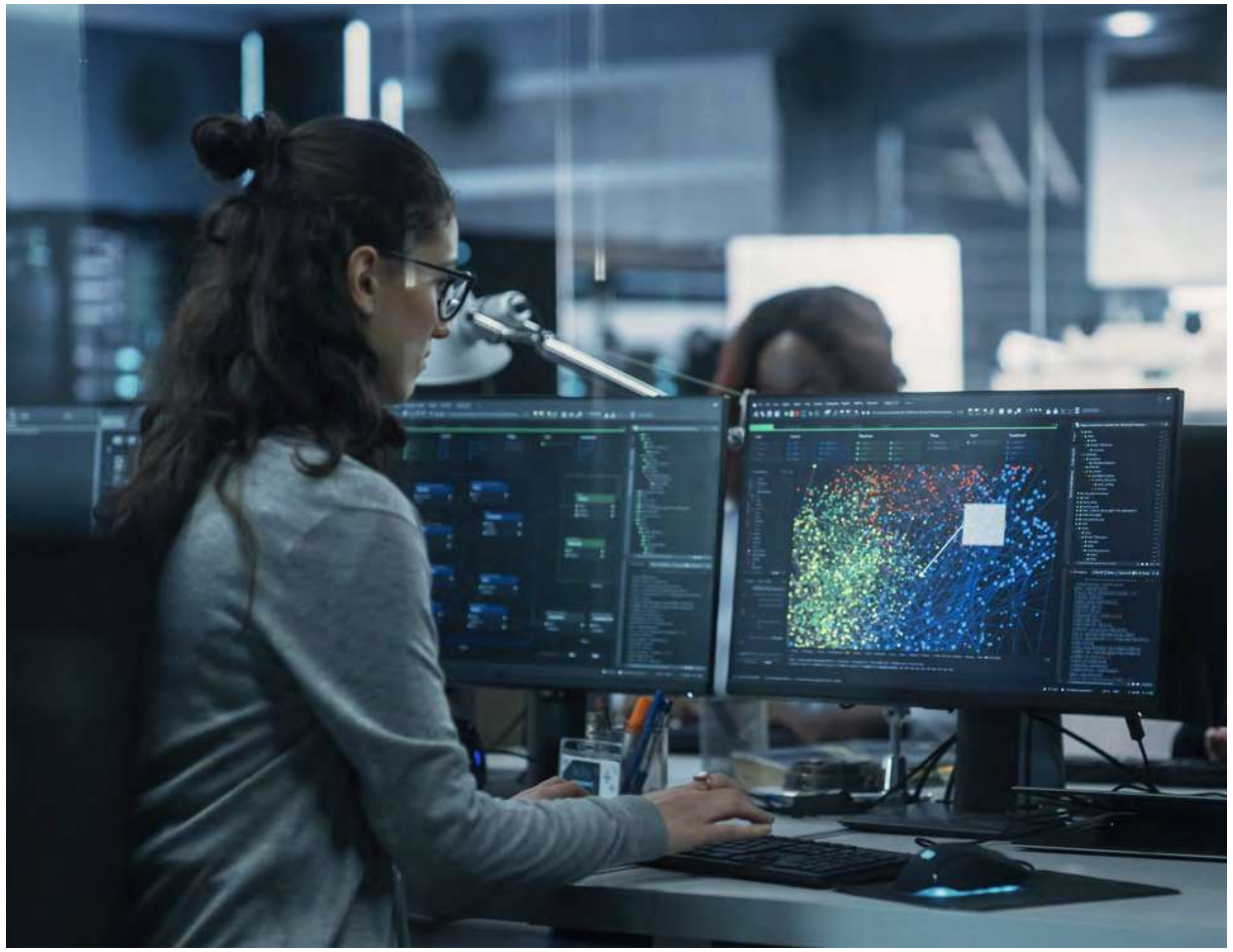
Generative AI offers a breakthrough, as models pre-trained on massive datasets can interpret prompts describing never-before-seen objects. AXA's research team is combining these universal language capabilities with remote sensing technologies to detect new categories purely from textual descriptions, accelerating the roll out of new risk-detection use-cases and responses to emerging threats.

Change Detection by Design

As detailed above, detecting objects from a predefined list is possible. Open World GeoSatLM opens the

'AXA's vision encompasses a future where insurers proactively anticipate and tackle emerging risks. By systematically integrating remote sensing and AI, insurers can further shift from a reactive stance to more predictive and preventive model, enhancing resilience for businesses and communities.'

possibility of detecting anything, skipping predefined lists and lowering the time to market of detecting new risks. However, insurers are often focused on significant changes over time. High-resolution, high-revisit imagery now enables us to track evolving risks and promptly detect anomalies. AXA's research team is developing robust change detection models for remote sensing data, to distinguish normal seasonal shifts from unexpected events, enhancing insurers' ability to respond to new risks, manage losses, and keep coverage relevant. •



REGIONAL ZOOM

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CASE STUDY

—

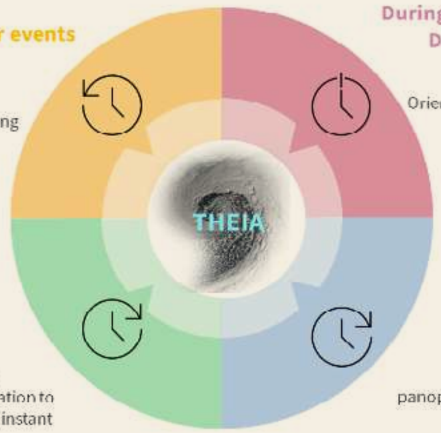
Transforming Claims Management with Remote Sensing and Artificial intelligence

Traditional insurance claims processes often require clients to initiate contact with brokers, who then relay information to their insurer. This approach can be time-consuming, particularly during large-scale climate events such as storms and floods. With the increasing frequency and intensity of natural catastrophes, the need for a more proactive and automated claims management system has become critical.

— A Game-Changing Solution: THEIA

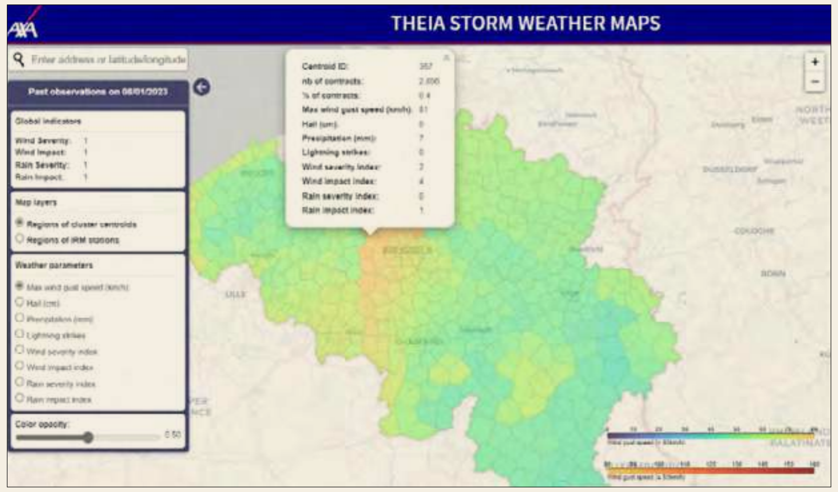
AXA Belgium has introduced THEIA, a cutting-edge, data-driven tool that has redefined how the company responds to natural catastrophes, especially storm events. THEIA integrates weather data – such as wind gust speeds, precipitation, hail, and lightning strikes – with geo-localized information about insured properties.

This innovative solution underscores the shift toward more localized and customer-centric services. By embedding THEIA's storm maps into tools used by brokers, customers, and claims handlers (e.g., e-claims and Guidewire's ClaimCenter), AXA Belgium has significantly streamlined the claims declaration process and improved decision-making for interventions. This enables swift action, reducing response times during major climate events.



— Staying Ahead with Proactive Preparedness

THEIA equips AXA Belgium with precise weather alerts for affected regions, which are promptly shared with claims and assistance teams to ensure readiness. Given the unpredictable nature of summer storms, alerts are issued for broader areas rather than narrowly defined zones. This proactive strategy includes providing clients with prevention tips and clear guidance on how to declare claims and access assistance quickly.



— Harnessing the Power of Satellite Technology

Beyond weather data, AXA Belgium has integrated satellite imagery from the Copernicus Emergency Management Service to monitor extensive flooding events. This capability allows the company to map flooded areas and identify impacted customers. The satellite data enhances AXA Belgium's ability to notify claims management and assistance teams, engage brokers, and dispatch experts to assess affected zones efficiently.

THE IMPACT: FASTER, SMARTER, AND MORE CUSTOMER-FOCUSED

Strengthened Collaboration with Brokers:
THEIA fosters seamless communication and coordination between AXA Belgium and brokers, ensuring timely support for affected customers.
Enhanced Customer Experience:
Customers benefit from expedited claims processing and clear, actionable guidance, alleviating stress during challenging times.
Accelerated Claims Handling:
THEIA's automated approach enables AXA Belgium to swiftly identify and assist customers impacted by storm events, resulting in more efficient claims management.

The challenges of miniaturization in low earth orbit satellites

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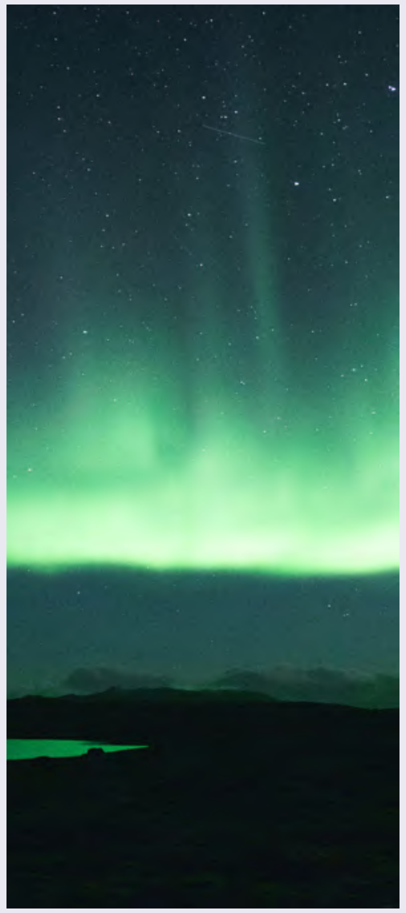
— *As space exploration* evolves, the trend toward miniaturization and simplification of satellites in Low Earth Orbit (LEO) grows, introducing vulnerabilities with significant implications for satellite operations. It also plays *a crucial role* in advancing remote sensing for natural catastrophes, as these miniaturized satellites provide critical data for disaster monitoring and response.

1 Cost-Effective Access to Space

The reduction in launch costs has been a primary driver of this trend. The emergence of new small launch vehicles by private companies has significantly decreased the mass of payloads sent into orbit, particularly in the LEO region. This has coincided with a burgeoning market for small satellites, with numerous manufacturers springing up, first in the United States and now expanding throughout Europe and Asia. Technological advancements have also played a vital role, allowing for the deployment of lightweight payloads – especially for Earth Observation satellites equipped with optical (panchromatic, multispectral, hyperspectral) and radar technologies. These small satellites, named nanosats, can be of different sizes and serve diverse applications, from agricultural monitoring to tracking vessels and observing methane emissions, and they have proven invaluable during natural disasters.

A notable aspect of this miniaturization is the utilization of Commercial Off-The-Shelf (COTS) components, originally designed for other industries such as electronics and automotive. This strategy reduces development and production costs, but it poses risks when these components need to be requalified for space use.



2 Increased Risk of Failure

— Space weather impacts

One of the most pressing concerns with smaller satellites (largely sent to Low Earth Orbit) is their heightened risk of failure. Space weather poses a significant threat, as these satellites are generally equipped with less shielding and redundancy compared to their larger counterparts.

For example, many cubesats operate with a single onboard computer, while larger satellites typically incorporate dual systems to maintain functionality in the event of a failure. Moreover, radiation testing is often minimal, leading to potential flaws in the requalification process for COTS components.

The newer generation of geostationary satellites are designed for flexible coverage allowing them to reconfigure their mission from the ground, for example starting a TV broadcast service over Europe and being reconfigured for an internet service over Africa after few years in-orbit. To do so, they have increased electronic complexity, making them more susceptible to solar energetic particles and galactic cosmic radiation.

The consequences of this vulnerability can manifest in several ways, depending on the altitude of the satellite and the environment in which it is traveling:

- ***Single Event Effect:***
A particle can penetrate the satellite's structure and damage electronic circuitry. Without redundancy, the satellite may fail to fulfill its mission. Damages are therefore classified into two categories: 'destructive' disturbances (causing permanent damage) and 'non-destructive' disturbances (causing disturbances without serious consequences).

- ***Charge/Discharge Phenomenon:***
Internal or Surface charging may occur. Internal charging results from the charged particles that accumulate within the satellite and, when discharged, create internal electrostatic discharges that damage insulation and electronic components. Surface charging results from the accumulation of charge on the surface of the satellite which moves into the surrounding plasma.

- ***Atmospheric Drag:***
Variations in thermospheric conditions due to space weather can increase the density of lower atmospheric layers, causing satellites in very low orbits (typically below 500 km) to experience drag. If their propulsion systems are inadequate or nonexistent, these satellites may descend prematurely, re-entering the atmosphere sooner than expected.

- ***Total Ionizing Dose/ Total Non Ionizing Dose:***
Caused by the accumulation of energy inside the satellite, which is continuously exposed to space radiation throughout its mission. This results in the ionization of the elementary particles making up the satellite's materials and the displacement of atoms in the crystalline lattices of the components. The satellite's components are degraded at an early stage.

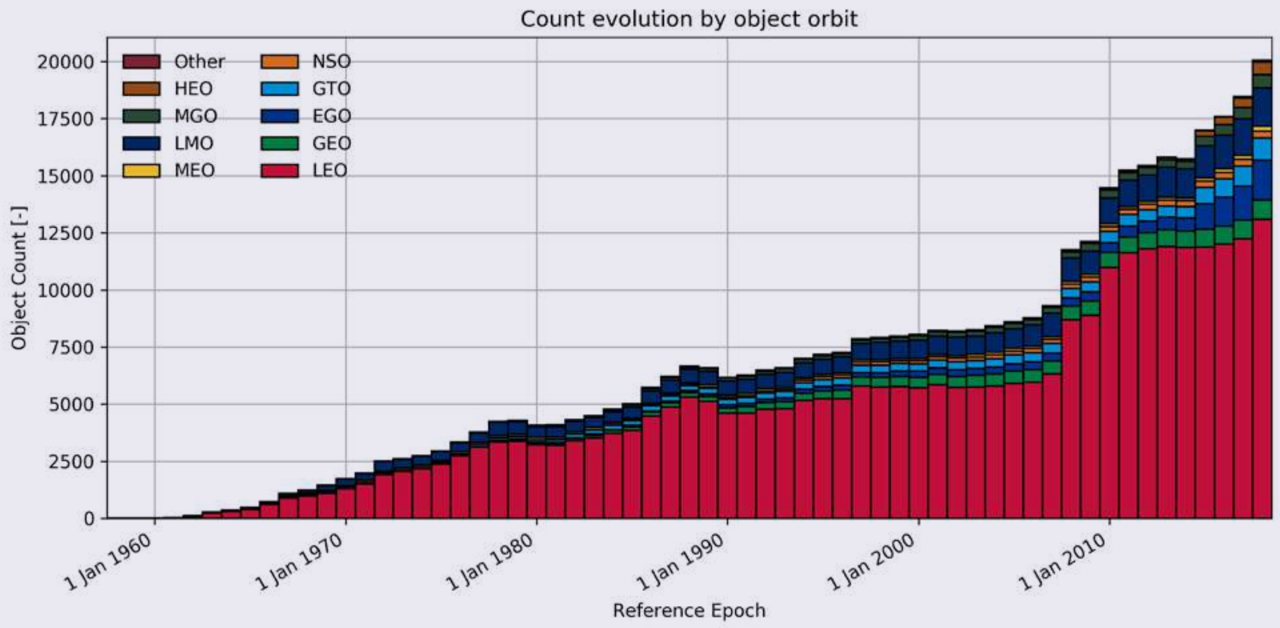
These different impacts can affect satellites temporarily or permanently, and must be closely monitored by satellite operators to ensure the sustainability of their missions. Furthermore, these risks are important to take into account because the number of objects in recent years has followed an exponential curve (see Figure 3) which can become space debris.

— Collision Risks

The increasing number of satellites being launched has led to congestion in certain orbital paths, raising the risk of collisions – a situation exacerbated by tests conducted by major powers demonstrating anti-satellite capabilities, which have resulted in an increase in debris. This phenomenon, known as the Kessler Syndrome, suggests that even if satellite launches were halted, the number of orbital objects would continue to grow due to collisions.

While systems for collision alerts are in place, driven by US detection capabilities and private initiatives, many satellites lack propulsion systems that would allow for avoidance maneuvers. Furthermore, the cubesats become smaller and smaller and pass below the radar detection threshold, which can become very problematic.

EVOLUTION IN ALL ORBITS



Evolution of number of space objects over time (Source: ESA)

3 Cybersecurity Concerns

Like any communicating computer system, satellites are exposed to the risk of cyberattacks carried out by private or government-affiliated hackers.
Cyber risks also pose a significant challenge, with varying levels of security measures in place across different types of satellites. Military satellites and high-value civilian satellites typically employ advanced security protections against hacking. However, some agencies and companies organize competitions on specific satellites, such as the US Air Force's Hack-A-Sat, to uncover potential vulnerabilities and Starlink's Bug Bounty initiative.
In contrast, nanosats often have more vulnerable security protocols. A flaw in the nanosat's onboard software can be exploited by hackers to compromise its mission or to take control, resulting in permanent hijacking and loss of ownership. Moreover, in the event of maneuvers triggered by hackers, the original owner of the nanosat could even be held liable for damages to other satellites in the event of a collision.

Another threat involves jamming of ground-to-satellite communications, which can prevent telecommands and software updates being transmitted to the nanosat. Spoofing of the onboard time system (which may be provided by a GNSS receiver or a telecommand from a ground teleport) can lead to delayed or premature onboard operations (transmissions, imaging, maneuvers, etc.), severely affecting the nanosat's mission.

4 Future Improvements

To mitigate these risks, continued investment in research related to space weather is essential. This includes the identification of precursor signs, enhancing predictive models (potentially with the help of artificial intelligence), establishing an international bulletin system for collision risks, and improving feedback sharing of in-orbit anomalies. Additionally, enhancing onboard protection through redundancy, shielding, and ground testing can significantly bolster satellite resilience. On the debris front, existing guidelines from the Inter-Agency Space Debris Coordination Committee (IADC) need to be enforced to ensure "clean" deorbiting and quicker identification of satellites post-launch. Standardizing satellite design to include propulsion systems for collision avoidance and employing structures that are standardized to be compatible with future in-orbit servicing and that generate minimal debris in the event of a collision are also critical steps. Implementing a reliable and accessible Space Traffic Management system, along with a rating system based on debris generation probability, will be vital for assessing the long-term impact of space systems. Regulatory frameworks are evolving, with new French legislation requiring that all satellites above 600 km must include a propulsion system. Similarly, cybersecurity regulations are tightening, mandating that launch operators implement robust cybersecurity measures to protect against malicious cyber activity. As the landscape of space exploration continues to shift, addressing these vulnerabilities will be crucial for the sustainable operation of satellites in an increasingly crowded and complex orbital environment.

About the AXA *research fund*

Now part of the AXA Foundation for Human Progress, the AXA Research Fund is AXA Group's global initiative for scientific philanthropy. Since its inception in 2008, it addresses the most pressing issues facing our planet, supporting human progress by funding research in key areas related to risk and informing science-based decision-making. As the cornerstone of the Science Pillar of the AXA Foundation for Human Progress — launched on June 30th, 2025, to mark AXA's 40th anniversary — the Fund has so far committed over €250 million to support 750 projects across climate and environment, health, and socio-economic risks in 39 countries.

The AXA Foundation for Human Progress brings together the main philanthropic actions of the AXA Group and AXA Mutuelles d'Assurances, both in France and in over 50 countries worldwide. With an endowment of €60 million, it aims to amplify support for impactful projects in AXA's four historical areas of support: science and health; planet protection; solidarity, inclusion, and education; and arts, culture, and heritage. Aligned with AXA's mission — *"Acting for human progress by protecting what matters"* — the AXA Foundation for Human Progress embodies its broader vision of protection; which extends to the resilience of societies and the reduction of inequalities, today and for future generations.

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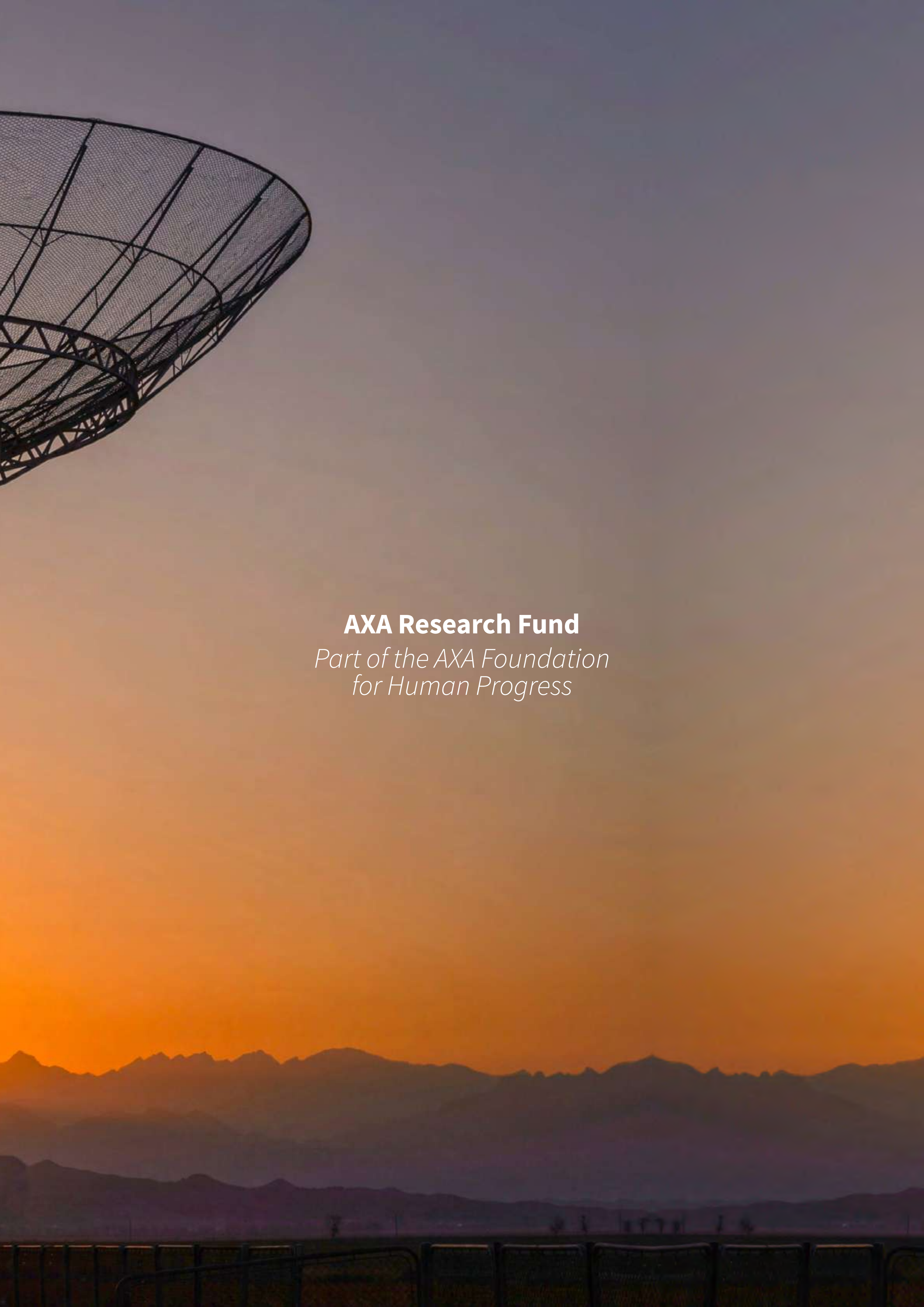

AXA Research Fund

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