United in Science 2024

A multi-organization high-level compilation of the latest weather, climate, water and related environmental and social sciences for the future

WORLD METEOROLOGICAL ORGANIZATION
UNITED NATIONS Office for Outer Space Affairs
International Science Council
UN environment programme
Early Warnings for All
GLOBAL CARBON project
ECMWF
Met Office
ITU
United Nations Convention to Combat Desertification

This report has been compiled by the World Meteorological Organization (WMO) under the direction of the United Nations Secretary-General to bring together the latest climate science-related updates from key global partner organizations. Aligned with the 2024 United Nations Summit of the Future, this report provides an update on the state of climate science and the latest weather, climate, water and related environmental and social sciences for the future. Contributing partners include: WMO, Met Office UK, the Official Children and Youth Constituency of the United Nations Framework Convention on Climate Change (YOUNGO), WMO Global Atmosphere Watch (GAW), WMO World Weather Research Programme (WWRP), World Climate Research Programme (WCRP), Global Carbon Project (GCP), United Nations Environment Programme (UNEP), European Centre for Medium-Range Weather Forecasts (ECMWF), United Nations Office for Outer Space Affairs (UNOOSA), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), International Telecommunication Union (ITU), United Nations Convention to Combat Desertification (UNCCD), International Science Council (ISC), United Nations Office for Disaster Risk Reduction (UNDRR), International Federation of Red Cross and Red Crescent Societies (IFRC) and Future Earth.

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Foreword by Prof. Celeste Saulo, Secretary-General of the World Meteorological Organization

The science is clear – greenhouse gas emissions are rising, global temperatures are shattering records and extreme weather is wreaking havoc with our lives and our economies. Urgent and ambitious action is needed to support sustainable development, climate action and disaster risk reduction. The decisions we make today could mean the difference between a future of breakdown or a breakthrough to a better world for people and the planet.

Natural and social sciences, technology and innovation hold tremendous potential to help us achieve these global goals. Rapid advances in artificial intelligence and machine learning are revolutionizing weather forecasting. Innovations in space-based Earth observations can help us better monitor greenhouse gas sources and sinks. Technologies such as digital twins and virtual reality can be applied in innovative contexts to help us achieve sustainable development and enhance disaster preparedness.

However, science and technology alone are not enough. In an increasingly complex world, we must embrace diverse knowledge, experiences and perspectives to co-create solutions together. The United Nations Secretary-General's groundbreaking Early Warnings for All initiative highlights how we can work together to utilize advances in natural and social science, technology and transdisciplinary approaches to save lives and safeguard sustainable development gains.

The Summit of the Future provides an opportunity to rethink, reimagine and reboot our actions, leverage diverse knowledge and experience, and strengthen governance mechanisms and trust in our institutions. We must ensure that the benefits of science and technology are accessible to all if we are to achieve global goals.

I thank the many partner organizations and experts involved in creating this report to highlight the future of weather, climate, water and related environmental and social sciences in accelerating progress to achieve a better world today and for future generations to come.

Prof. C. Saulo
Secretary-General, WMO

Executive summary

The Summit of the Future provides a once-in-a-generation opportunity to demonstrate how we can collectively achieve global goals, such as the Paris Agreement, Sendai Framework for Disaster Risk Reduction and 2030 Agenda for Sustainable Development. With global temperatures reaching record highs and the impacts of climate change and hazardous weather events reversing development gains, a sustainable future for all is at risk. However, harnessing the power of natural and social sciences, technology and innovation provides an unprecedented opportunity to get back on track to achieve global goals and a better world for present and future generations.

United in Science 2024 emphasizes the transformative impact of new technologies and innovative approaches across weather, climate, water and related environmental and social sciences. From artificial intelligence (AI) to cutting-edge satellite technologies and virtual realities that bridge the physical and digital worlds, scientific and technological advances are enhancing weather, climate, water and related environmental applications as well as informing strategies for responding to global challenges such as climate change and sustainable development. The report also underscores the necessity of transdisciplinary approaches that help apply science and technology in local contexts and boost their impact by embracing diverse knowledge, perspectives and experiences to co-develop and implement solutions. While significant gaps and challenges remain, enhanced collaboration across scales is essential to harness the full potential of weather, climate, water and related environmental and social sciences to ensure that their benefits are accessible to all.

The science is clear – we are far off track from achieving global climate goals, threatening a sustainable future for all

Human-caused climate change has resulted in widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere, affecting many weather and climate extremes. Global greenhouse gas (GHG) emissions rose by 1.2% from 2021 to 2022, reaching 57.4 billion tons of carbon dioxide (CO_2) equivalent. Globally averaged surface concentrations of CO_2, methane (CH_4) and nitrous oxide (N_2O) also reached new highs. The year 2023 was the warmest on record by a large margin, with ocean heat content also reaching record highs, while Arctic and Antarctic sea-ice extent reached record lows. The first half of 2024 witnessed exceptionally high global temperatures and many extreme weather events, from scorching heat waves across large parts of Asia and drought in Southern Africa to record-breaking floods in southern Brazil and the unprecedented Category 5 Hurricane *Beryl* in the Caribbean. The increasing frequency of extreme and hazardous weather events and their devastating impacts across society underscore the need for urgent and ambitious climate action.

Looking ahead, there is an 86% chance of at least one year in the next five years exceeding 2023 as the warmest year on record and an 80% chance that the global mean near-surface temperature will temporarily exceed 1.5 °C above pre-industrial levels at least one of the next five years. Although progress has been made in mitigating global GHG emissions, the emissions gap remains high. If current policies are continued, it is estimated (with 66% probability) that global warming will be kept to a maximum of 3 °C throughout the century. To reach levels consistent with limiting global warming to below 2 °C and 1.5 °C, global GHG emissions in 2030 must be reduced by 28% and 42%, respectively, from the emission levels that current policies are projected to deliver. Additionally, the complex and escalating nature of climate risks underscores the need for robust adaptation that is grounded in diverse knowledge and promotes inclusive engagement. As a result, ambitious adaptation action can help reduce the adverse impacts of climate change across ecosystems and societies, minimize losses and damages and safeguard sustainable development gains.

Advances in weather, climate, water and related environmental and social sciences can enhance our understanding of the Earth system and boost progress towards achieving a sustainable future for all

AI and machine learning (ML) have emerged as potentially transformative technologies that are revolutionizing weather forecasting and could equip society with better tools to drive progress towards climate change adaptation, disaster risk reduction and sustainable development. With rapid progress being made, AI and ML can make skillful weather modelling faster, cheaper and more accessible to lower-income countries with limited computational capacities. Additionally, innovations in satellite-based Earth observations can open new frontiers to advance weather, climate, water and related environmental applications. By leveraging public–private partnerships and international collaboration, innovations in space-based Earth observations can pave the way for improved weather prediction, enhanced understanding of our climate system and more robust environmental monitoring. Additionally, immersive technologies are providing innovative solutions to address compounding socioeconomic and climate change impacts on water and land resources. For example, digital twins, virtual reality and the metaverse can revolutionize land and water management by offering immersive, interactive and data-driven solutions that bridge the physical and digital worlds. When enabled by sustainable funding mechanisms and effective governance frameworks, these technologies can enhance decision-making and the engagement of diverse actors.

Box 1. Harnessing the power of data through international cooperation and robust governance

Weather and climate have no borders or boundaries, highlighting the need for international cooperation to close global data gaps and foster exchange of weather data to inform timely decision-making. Advances in science and technology are resulting in an exponential increase in data volumes and an explosive demand for data to support essential services across society. While there is tremendous potential to harness the power of data to deliver benefits across society, the growing data divide can lead to inequitable distribution of benefits and the misuse and misinterpretation of data.

One example of international collaboration is the Systematic Observations Financing Facility (SOFF), which aims to support and accelerate the sustained collection and international exchange of essential surface-based weather and climate observations by providing financial support to implement the internationally agreed Global Basic Observing Network, especially in least developed countries and small island developing States. Additionally, the WMO Unified Data Policy recognizes the need for robust data governance based on the core principles of free and unrestricted data exchange. The policy guides the exchange of data between WMO Member countries to strengthen and sustain monitoring and prediction of all Earth system components and provides an essential framework to harness the spectacular developments in AI/ML for weather and climate prediction. These initiatives support better delivery of weather, climate, water and related environmental data and services, which can accelerate progress towards the achievement of the Sustainable Development Goals (SDGs) and contribute to the objectives outlined in the Global Digital Compact through the enhancement of data interoperability and accessibility.

However, global challenges such as climate change and sustainable development cannot be addressed by science and technology alone – they require a transdisciplinary approach to co-create and implement solutions

Addressing complex global challenges such as climate change, disaster risk reduction and sustainable development requires an enhanced rethinking and reimagining of how diverse perspectives, knowledge and experiences can help us co-create knowledge and implement solutions. Transdisciplinary approaches are increasingly being used to unite diverse actors – such as scientists, policymakers, practitioners and civil society, including local and Indigenous communities – and to apply natural and social sciences in local contexts. These approaches can amplify the impact of perspectives offered by weather, climate, water and related environmental and social sciences and enhance trust in various actors and institutions, including National Meteorological and Hydrological Services (NMHSs). Additionally, increasing the diversity of engaged actors, political commitment and global efforts to address climate action can accelerate sustainable development and disaster risk reduction, leading to stronger, more resilient communities in the face of evolving global challenges.

The Early Warnings for All (EW4All) initiative exemplifies how integrating global efforts across natural and social sciences, technological advances and transdisciplinary approaches can protect lives, livelihoods and the environment from natural hazards

The EW4All initiative is a groundbreaking effort that aims to ensure everyone on Earth is protected from hazardous weather, water or climate events through life-saving early warning systems by the end of 2027. Natural and social sciences, technological advances and transdisciplinary approaches, alongside robust partnerships, adequate resources and enhanced capacities, underpin effective multi-hazard early warning systems (MHEWS). Advancements in AI, space-based Earth observations and immersive technologies can contribute to this critical initiative by advancing weather forecasting, contextualizing and communicating complex information for decision-making, and creating interactive, educational simulations to visualize different hazard scenarios and potential impacts to support anticipatory action. Additionally, transdisciplinary approaches, including participatory engagement methods such as citizen science, enhance the effectiveness of NMHSs through the co-development of knowledge and solutions that are relevant to local contexts.

Collaboration across scales is essential to address gaps and challenges and harness the full potential of weather, climate, water and related environmental and social sciences to ensure that their benefits are accessible to all

Advances in weather, climate, water and related environmental and social sciences offer huge potential to support the full achievement of global goals, including the Paris Agreement, 2030 Agenda, Sendai Framework for Disaster Risk Reduction and EW4All. However, data gaps, limited financial resources, inadequate capacity to utilize emerging technologies, as well as governance challenges limit the realization of the full potential of these advances and risk further exacerbating the digital divide. Moving forward, global partnerships between governments, the private sector, international organizations, civil society, academia, youth and local communities will be essential to address these challenges and ensure that the benefits of natural and social sciences, technologies and innovations are accessible to all.

Box 2. Embracing youth and early career researchers

Young people and early career researchers (ECRs) belong to the generation of the present and the future, hence it is crucial to engage them in scientific endeavours, policymaking and climate action. As agents of change, young people often bring fresh perspectives, innovative approaches and a willingness to challenge the status quo, leading to breakthroughs in understanding and solving complex global problems. Their adaptability to new technologies and digital tools enhances the dissemination and application of diverse knowledge in our rapidly evolving society. Moreover, involving young people ensures the continuity of scientific inquiry and problem-solving, fostering a sense of responsibility and ownership over scientific and societal challenges which is essential for long-term impact. Thirteen ECRs were actively engaged in the development of *United in Science 2024*, which incorporates their perspectives and innovative ideas throughout. The involvement of ECRs exemplifies the commitment of WMO and partner organizations involved in this report to embrace the crucial role that young people play in shaping a sustainable and resilient future for generations to come.

Photo: UNDP Cambodia

Recommendations

- **Enhance the quality, availability, accessibility, and interoperability of data.** Reliable, transparent and easily accessible data, including Earth observation data, lie at the heart of scientific and technological transformation and can bridge global technological disparities. International cooperation can help close data gaps, improving the availability and quality of data, while robust governance mechanisms can enhance access to data by enabling the free and unrestricted exchange of data (Box 1). Additionally, the seamless integration of data from different public and private sources can improve data interoperability and empower diverse actors to leverage real-time insights in an effort to drive substantial progress towards global goals.

- **Boost investments in and access to emerging science and technology.** Advances in science and technology hold tremendous potential to revolutionize environmental monitoring, inform decision-making and support effective climate change mitigation and adaptation; however, further research and analysis are needed to address outstanding scientific questions and better understand potential risks and opportunities associated with these technologies. Innovative financing models, public–private partnerships and strong governance at all levels can create an enabling environment to scale up and accelerate research, innovation and transdisciplinary approaches and ensure the benefits are accessible to all.

- **Scale up education, training and capacity development, particularly in developing countries.** Education, training and capacity development are essential to seize the opportunities presented by science, technology and innovation and prepare the next generation to address the challenges of the future (Box 2). In particular, education and training in transdisciplinary approaches should be encouraged to boost the impact of perspectives offered by weather, climate, water and related environmental and social sciences by embracing diverse knowledge and solutions. Additionally, accelerating the transfer of technologies can help close the digital divide while also driving climate action and supporting sustainable development at all levels.


Photo: Freepik

CHAPTER 1

State of climate science: the need for urgent and ambitious climate action

The science is clear – rising greenhouse gas emissions and atmospheric concentrations are leading to changes in key climate indicators and affecting extreme events, contributing to devastating impacts globally and underscoring the need for urgent and ambitious action to achieve a sustainable future.

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Key messages

- **Total global greenhouse gas (GHG) emissions increased by 1.2% from 2021 to 2022, setting a record of 57.4 billion tons of carbon dioxide equivalent.**
- **The year 2023 was the warmest on record by a large margin, and during the first half of 2024 the world has experienced exceptionally high global temperatures and many extreme weather events with devastating impacts to society.**
- **If current mitigation policies are continued, it is estimated (with 66% probability) that global warming will be kept to a maximum of 3 °C throughout the century.**

Greenhouse gas (GHG) emissions and concentrations

Over the 2011–2020 decade, human activities associated with the emissions of GHGs have unequivocally caused global warming, with global surface temperature reaching 1.1 °C above 1850–1900 (IPCC, 2023). GHG emissions increased by 1.2% from 2021 to 2022, reaching a record of 57.4 billion tons of carbon dioxide equivalent ($GtCO_2e$). Emissions of methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, which have higher global warming potentials and account for about one quarter of current GHG emissions, are also increasing rapidly. Fluorinated gas emissions grew in 2022 by 5.5%, followed by CH_4 at 1.8% and N_2O at 0.9% (UNEP, 2023a).

As emissions rise, so do atmospheric concentrations of GHGs. The latest analysis of observations from the WMO Global Atmosphere Watch in situ observational network shows that the globally averaged surface concentrations[1] for CO_2, CH_4 and N_2O reached new highs in 2022, with CO_2 at 417.9 ± 0.2 ppm, CH_4 at 1 923 ± 2 ppb and N_2O at 335.8 ± 0.1 ppb (***WMO Greenhouse Gas Bulletin (GHG Bulletin), No. 19***). These values constitute, respectively, 150%, 264% and 124% of pre-industrial (before 1750) levels. The increase in CO_2 from 2021 to 2022 was slightly lower than the increase observed from 2020 to 2021 and slightly lower than the average annual growth rate over the last decade; this was most likely partly caused by natural variability, as CO_2 emissions have continued to increase. For CH_4, the increase from 2021 to 2022 was slightly lower than that observed from 2020 to 2021 but considerably higher than the average annual growth rate over the last decade. For N_2O, the increase from 2021 to 2022 was higher than that observed any time before in our modern time record. However, atmospheric concentrations of GHGs are driven by both anthropogenic emissions as well as natural emissions and sinks, such as ecosystems that absorb CO_2, which are extremely sensitive to climate variability and change.

Current and historical GHG emissions vary significantly across regions, countries and groups of countries, reflecting patterns of global inequality and varying progress on climate action. For example, globally, the 10% of the population with the highest income accounted for nearly half (48%) of emissions, with two thirds of this group living in developed countries, while the bottom 50% of the world population contributed only 12% of total emissions. Additionally, nearly 80% of historical cumulative fossil and land use, land-use change and forestry CO_2 emissions came from G20 countries, with the largest contributions from China, the United States of America and the European Union, while least developed countries contributed only 4% (UNEP, 2023a). As national and regional inequalities in GHG emissions continue to grow, scientific reporting of these emissions is becoming increasingly important to support effective decarbonization pathways and track mitigation targets, as highlighted in Box 1.

Photo: Freepik

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1. The scientifically correct term for the abundance in the atmosphere of compounds such as carbon dioxide and other GHGs is dry air mole fraction, expressed as the number of moles of each gas per mole of dry air, often with units of ppm[2] or ppb[3].
2. ppm – parts per million, that is, the number of molecules of a gas per million (10^6) molecules of dry air
3. ppb – parts per billion, that is, the number of molecules of a gas per billion (10^9) molecules of dry air

Box 1. Regional and national GHG budget analysis

The Global Carbon Project's REgional Carbon Cycle Assessment and Processes (RECCAP2) conducts CO_2, CH_4 and N_2O budget analyses with higher spatial resolution, regionally relevant sources and sinks, and more detailed attribution to processes to better track the human and natural perturbations in atmospheric concentrations (Canadell et al., 2022; Friedlingstein et al., 2023; Saunois et al., 2024; Tian et al., 2024). In Australia, for example, fossil fuels are the largest source of CO_2 emissions from human activities, with an average of 403 million tons of CO_2 per year (2010–2019) (Figure 1). CO_2 emissions from natural wildfires and prescribed burning (human-caused) account for an even higher amount at an average of 568 million tons of CO_2 per year. Unlike fossil fuel emissions, however, fire emissions are largely offset by vegetation regrowth, leading to an average net CO_2 accumulation in the atmosphere of 36 million tons per year (Villalobos et al., 2023). Factoring in the natural CO_2 sinks, the net carbon balance of Australia was a source to the atmosphere of 140 million tons of CO_2 per year during 2010–2019. Surprisingly, analysis has shown that Australia can be a large net source of CO_2 one year and a large net CO_2 sink the next, making it hard to detect long-term trends and understand if natural carbon sinks are growing or decreasing.

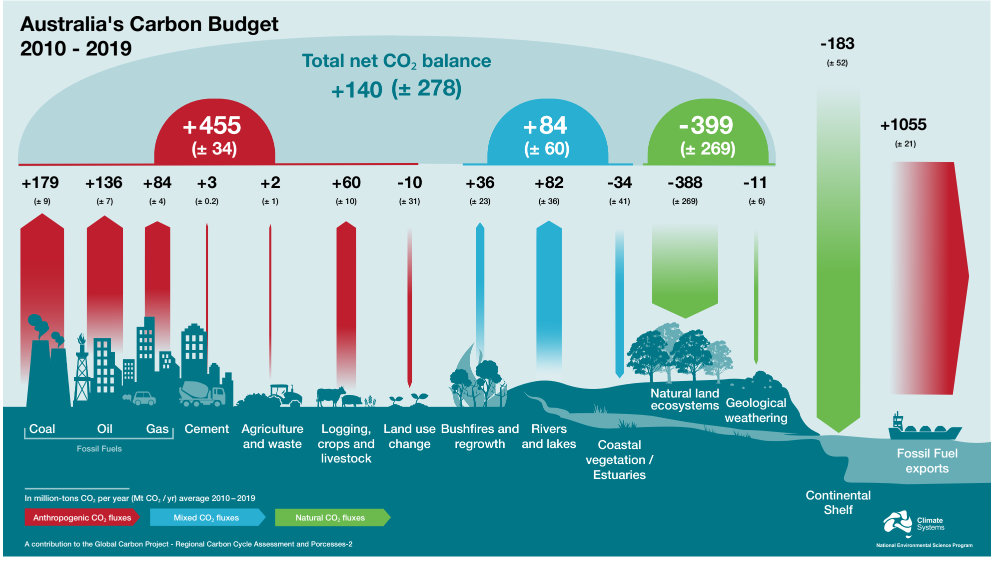
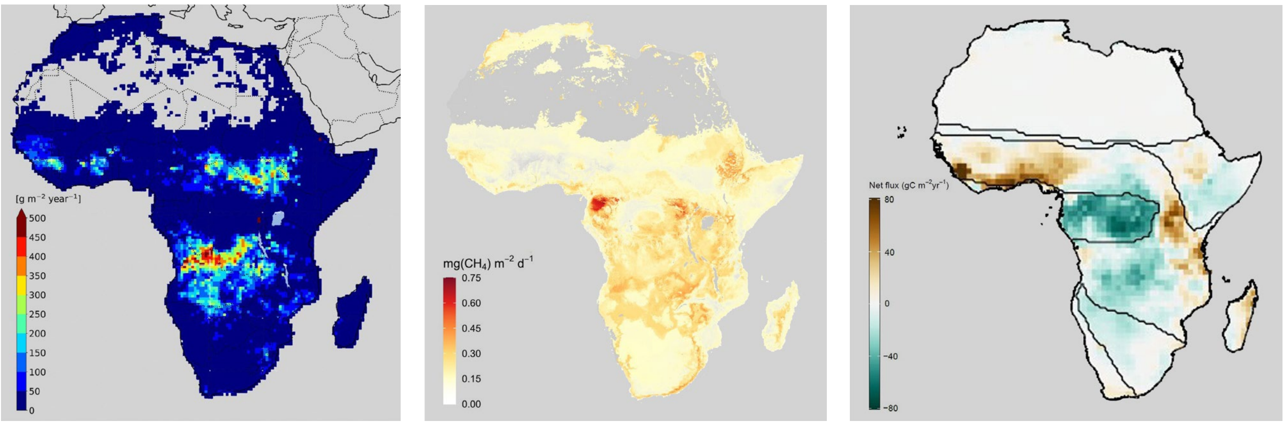


Figure 1. Australia's carbon budget with the mean annual anthropogenic and natural sources and sinks of carbon dioxide for 2010–2019 (million tons CO_2 per year). Source: **National Environmental Science Program – Climate Systems Hub**

At the regional level, the African continent includes a complex system of anthropogenic and natural sources and sinks of GHGs (Ernst et al., 2024). Emissions from land use change – an average of 1.7 billion tons of CO_2 -equivalent per year (2010–2019) – are similar in magnitude to the emissions from fossil fuels at 1.74 billion tons of CO_2-equivalent. Terrestrial ecosystems, in particular, support a large CO_2 sink of an average of 0.8 billion tons of carbon, representing 20% of the global land CO_2 sink. As anthropogenic emissions from land use change and fossil fuels continue to grow, however, the continent has become a net carbon source to the atmosphere (Figure 2).



Fire carbon emissions **Termite CH_4 emissions** **Net carbon sequestration**

Figure 2. Components of the greenhouse gas budget of Africa for 2010–2019: fire CO_2 emissions, termite methane emissions and biospheric net carbon sequestration. *Source:* Ernst et al., 2024

Global climate indicators

Human-caused climate change has resulted in widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere, affecting many weather and climate extremes (IPCC, 2023). The WMO State of the Global Climate reports provide a summary of the state of global climate indicators (Trewin et al., 2021), including global temperature, ocean heat and cryosphere indicators, among others.

Global temperature

The years from 2015 to 2023 were the nine warmest on record, and it is likely that the years 2015 to 2024 will be the ten warmest. The 2020–2024 global mean temperature average (based on data up to July 2024) is estimated to be 1.31 ± 0.12 °C above the 1850–1900 average. It is the warmest five-year period on record according to all data sets surveyed (Figure 3). Although La Niña conditions persisted from late 2020 to early 2023, a rapid transition to El Niño saw a 13-month string of exceptionally high global temperatures with June 2023 through June 2024 each setting a new monthly record. El Niño gives a short-term boost to global temperatures, whereas years affected by La Niña are typically a little cooler.

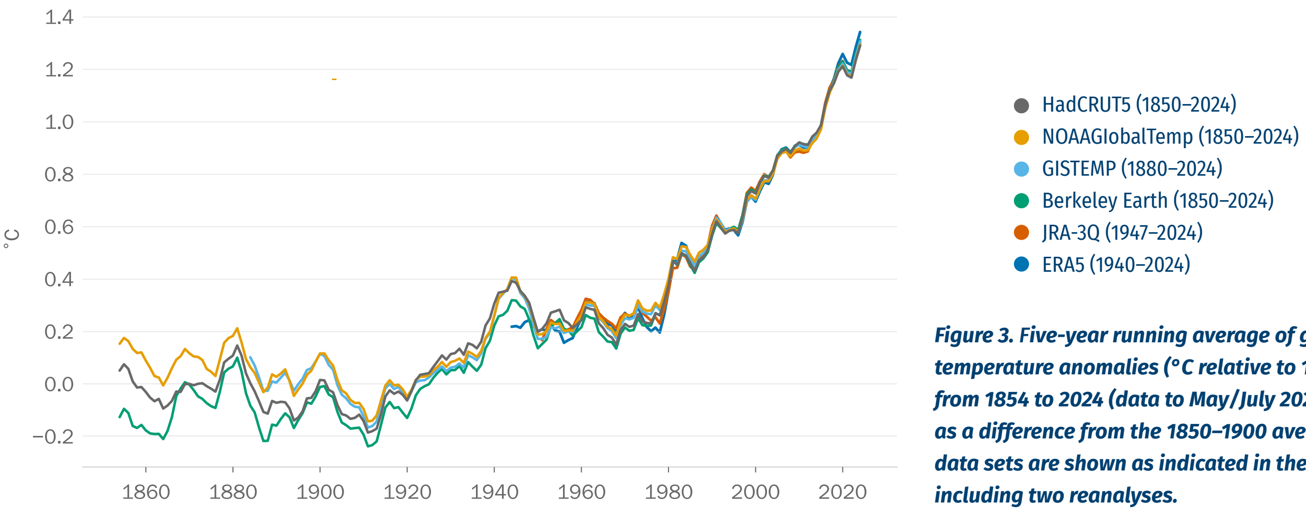


Figure 3. Five-year running average of global temperature anomalies (°C relative to 1850–1900) from 1854 to 2024 (data to May/July 2024) shown as a difference from the 1850–1900 average. Six data sets are shown as indicated in the legend, including two reanalyses.

Ocean heat content

Around 90% of the excess energy that accumulates in the Earth system due to increasing concentrations of GHGs in the atmosphere is taken up by the ocean. This added energy warms the ocean, and the consequent thermal expansion of the water leads to sea-level rise. Figure 4 shows the global ocean heat content, a measure of the heat that has accumulated in the ocean, at 0–2 000 m from 1960 to 2023. The upper 2 000 m of the ocean continued to warm in 2023, reaching the highest heat content on record. It is expected that it will continue to rise in the future – a change which is irreversible on centennial to millennial timescales (Cheng et al., 2017; IPCC, 2019).

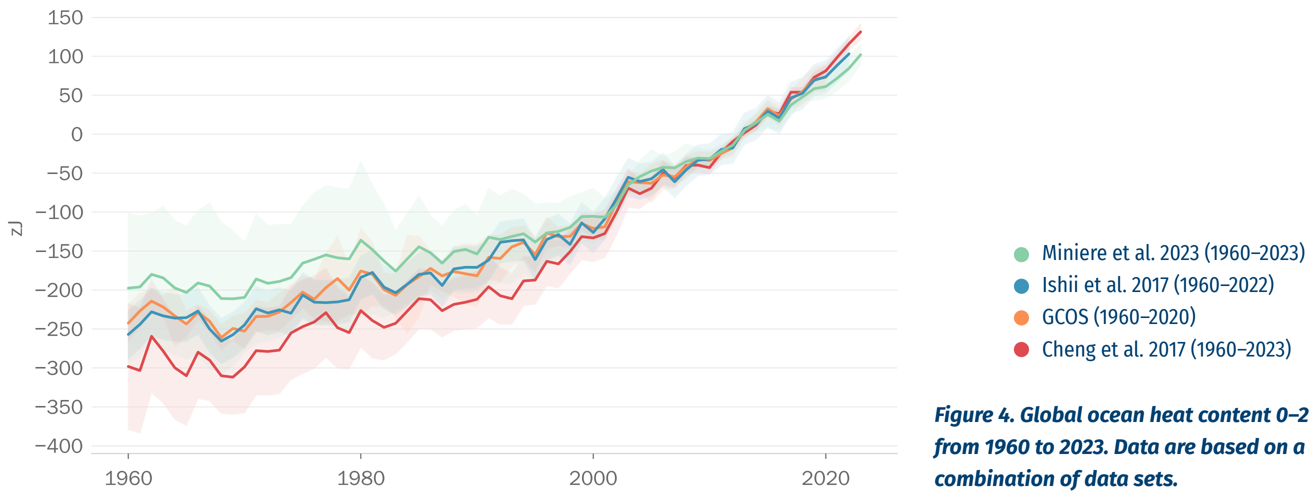


Figure 4. Global ocean heat content 0–2 000 m from 1960 to 2023. Data are based on a combination of data sets.

Cryosphere

Human influence is very likely the main driver of the decrease in Arctic sea-ice area between 1979–1988 and 2010–2019 (IPCC, 2023). Arctic sea-ice cover (both annual and late summer) is currently at its lowest level since at least 1850, and is likely to reach practically ice-free conditions at its summer minimum at least once before 2050. During the period 2019–2023, September Arctic sea-ice extent was on average around 1 million km^2 below the 1991–2020 average (Figure 5). In Antarctica, there was no significant trend in sea-ice extent from 1979 to 2020 due to regionally opposing change and large internal variability (IPCC, 2021). And while Antarctic sea-ice extent increased slowly from the start of the satellite era to a maximum in 2014 (Figure 6), it dropped rapidly between 2015 and 2017 before reaching its lowest annual minimum on record in February 2023. The annual maximum extent in September 2023 was the lowest on record by a very large margin, likely associated with warming of the Southern Ocean (Purich and Doddridge, 2023). In addition to sea-ice extent, preliminary data available for 53 reference glaciers for the glaciological year 2022/2023 indicate an average global mass balance of −1.2 m water equivalent (m w.e.), which is nominally the largest loss of ice on record (WGMS, 2023). Glacier losses were particularly extreme in North America and Europe, with Swiss glaciers losing 10% of their remaining ice in the past two years.

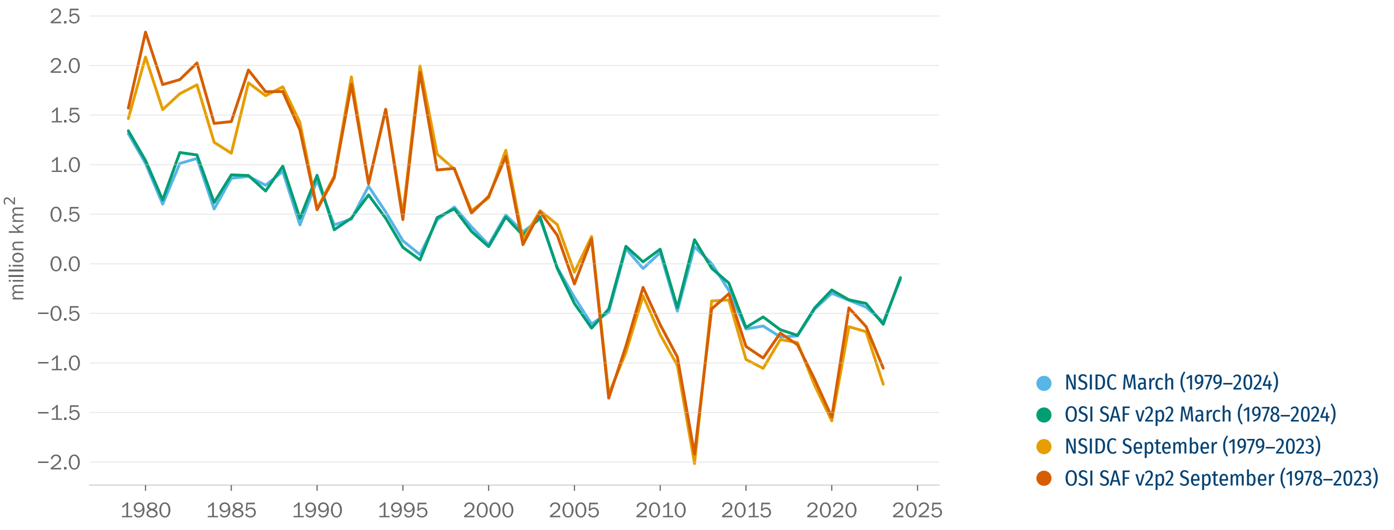


Figure 5. Sea-ice extent differences from the 1991–2020 average in the Arctic for the months with maximum ice cover (March) and minimum ice cover (September) from 1979 to March 2024. Source: **United States National Snow and Ice Data Center (NSIDC) and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF)**

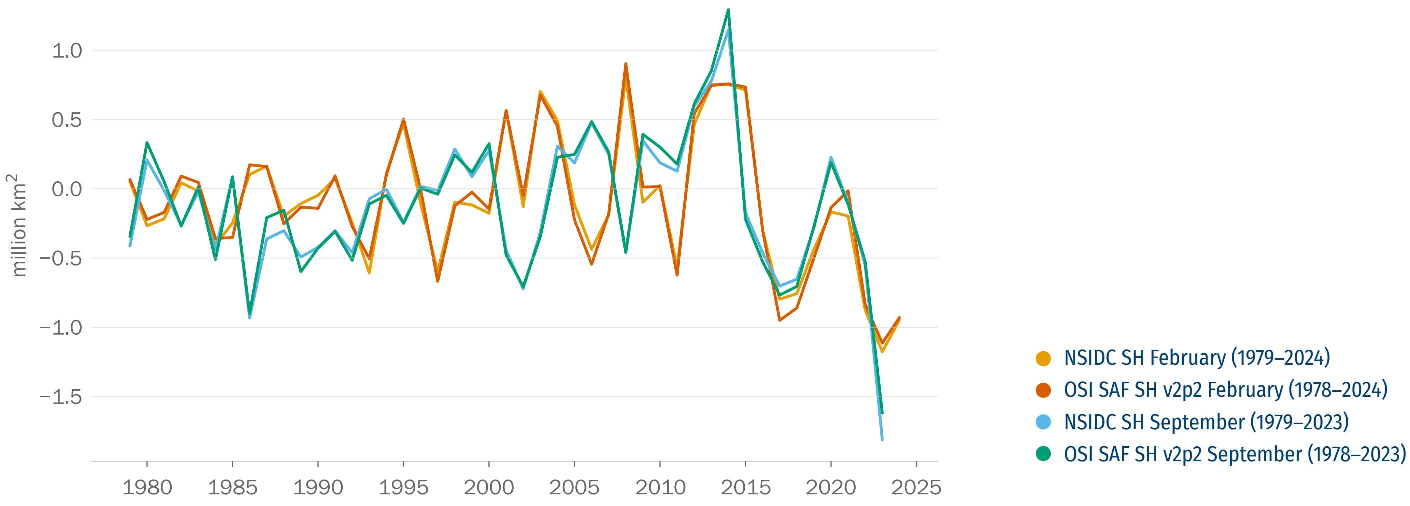


Figure 6. Sea-ice extent differences from the 1991–2020 average in the Antarctic for the months with maximum ice cover (September) and minimum ice cover (February) from 1979 to February 2024. Source: **NSIDC and EUMETSAT OSI SAF**

2024 extreme events

Halfway through the year, the world has already witnessed numerous extreme weather events – from heat waves to floods and tropical cyclones – with devastating impacts to society. Heat waves scorched large parts of Asia in April and May 2024, with a maximum temperature of 47.2 °C recorded in India on 30 April 2024. Schools were closed and the heat was particularly difficult for people living in refugee camps and informal housing, as well as for outdoor workers (WMO, 2024a). In Brazil, the state of Rio Grande do Sul experienced the most severe floods in its recorded history, with over 420 mm of rainfall affecting over 90% of the state and displacing 386 000 people (OCHA, 2024). Hundreds of thousands were left without electricity and water, disproportionately affecting informal settlements and Indigenous villages. A rapid study from World Weather Attribution, based on published, peer-reviewed methods, found that the floods were strongly influenced by the naturally occurring El Niño phenomenon as well as human-induced climate change, which increased the intensity likelihood of the event (Clarke et al., 2024). In Africa, World Weather Attribution also found that El Niño was a key driver of drought in vulnerable Southern African countries in early 2024. Zimbabwe, Zambia, Malawi, Angola, Mozambique and Botswana received less than 20% of the typical rainfall expected for February, with devastating impacts to local communities (Kimutai, 2024). And in the Caribbean, the Atlantic hurricane season began with the unprecedented early-season Category 5 Hurricane *Beryl*, which rapidly intensified and became the strongest June hurricane on record. The storm brought catastrophic winds and storm surge to the southern Windward Islands, setting a foreboding tone for the remainder of the hurricane season, which is predicted to be more active than usual (Thiem, 2024).

Looking ahead: climate predictions for 2024–2028

The year 2023 was record-breaking, becoming the warmest year on record by a huge margin due to a combination of factors, including continued warming from GHG emissions and El Niño (WMO, 2024b). According to the WMO Lead Centre for Annual-to-Decadal Climate Prediction, the trend of increasing global temperatures is expected to continue, with it being likely (86% chance) that at least one year in the next five will exceed the current warmest year on record (2023). It is also highly likely (90% chance) that the mean of the next five years (2024–2028) will exceed that of the previous five years (2019–2023). Annual mean global near-surface temperature for each year in this five-year period is predicted to be between 1.1 °C and 1.9 °C higher than pre-industrial levels, defined as the average over the period 1850 to 1900 (WMO, 2024c).

Additionally, it is likely (80% chance) that the global mean near-surface temperature in at least one of the next five years will exceed 1.5 °C above pre-industrial levels for the first time, and this chance is increasing with time. It is about as likely as not (47% chance) that the five-year mean will exceed this threshold. The Paris Agreement threshold of 1.5 °C refers to long-term warming averaged over 20 years, so temporary exceedances during single months, seasons and years are expected to occur with increasing frequency as long-term global temperatures approach this level (WMO, 2024c).

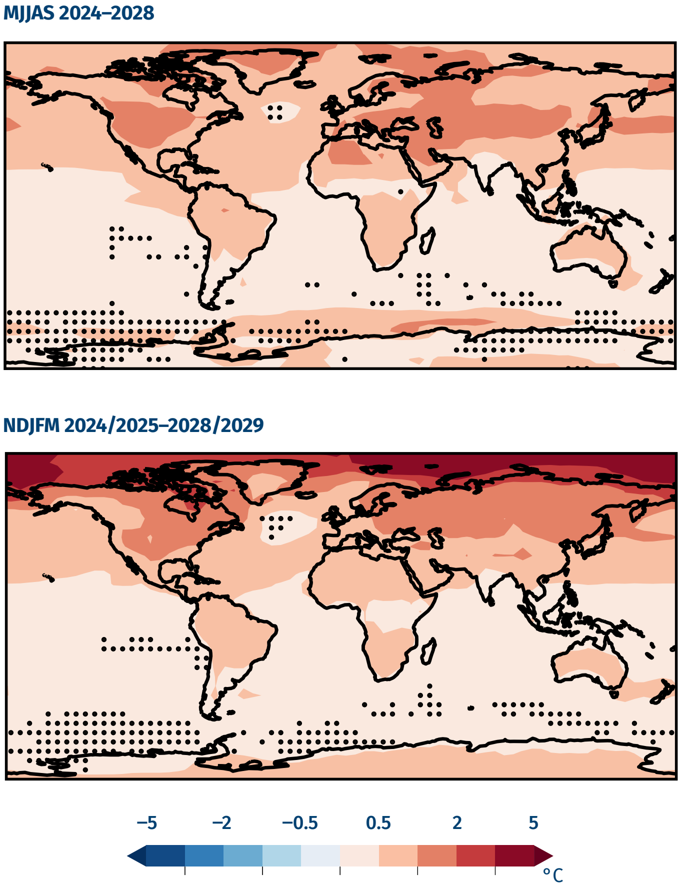


Figure 7. Five-year temperature forecasts. Ensemble mean predictions for near-surface temperature anomalies relative to 1991–2020 for the next five extended seasons of May to September 2024–2028 (left) and November to March 2024/2025–2028/2029 (right). Stippled where more than one third of models disagree on the sign of the anomaly. *Source:* WMO, 2024c

The predicted temperature patterns for two extended seasons, May to September and November to March, for 2024–2028 relative to the 1991–2020 average are presented in Figure 7. For both seasons, temperatures are likely to be above average everywhere, with enhanced warming over land. For November to March, we expect to see increased warming over the northern hemisphere, with the Arctic (north of 60°N) near-surface temperature warming predicted to be three times the global mean warming (WMO, 2024c).

Science for climate action

At the time of the adoption of the Paris Agreement, GHG emissions were projected to increase by 16% by 2030 relative to 2015. Now, that projected increase is 3%, indicating progress in mitigating global GHG emissions. Under the Paris Agreement, countries submit Nationally Determined Contributions (NDCs) every five years that present national efforts to limit global warming to well below 2 °C. By the end of 2023, 149 NDCs had been updated (counting the European Union and its 27 member States as a single Party), and if they are fully implemented, it is estimated that they will reduce global GHG emissions by about 5.0 $GtCO_2e$ (range: 1.8–8.2 $GtCO_2e$) annually by 2030, compared with the initial NDCs (UNEP, 2023a).

Yet, the emissions gap in 2030 remains high. Current unconditional[4] NDCs imply a 14 $GtCO_2e$ gap for keeping warming to 2 °C with a 66% chance, and a 22 $GtCO_2e$ gap for keeping it to 1.5 °C by the end of the century. The additional implementation of the conditional NDCs reduces these estimates by 3 $GtCO_2e$ (Figure 8). It is estimated that the full implementation of unconditional and conditional NDCs would reduce global emissions in 2030 by 2% and 9%, respectively, compared with current policy projections. However, to reach levels consistent with limiting global warming to below 2 °C and 1.5 °C, global GHG emissions in 2030 must be reduced by 28% and 42%, respectively (UNEP, 2023a).

If current policies are continued, it is estimated that global warming will be kept to a maximum of 3 °C (range: 1.9–3.6 °C, 66% chance) throughout the century and further increase after 2100 as CO_2 emissions are not yet projected to reach net-zero levels by 2100. In the most optimistic scenario where all conditional NDCs and net-zero pledges are fully achieved, global warming is projected to be limited to 2 °C (range: 1.8–2.5 °C, 66% chance) over the course of the century. However, net-zero pledges remain highly uncertain, and there is only a 14% chance of limiting global warming to 1.5 °C, with a large possibility of global warming exceeding 2 °C or even 3 °C. As a result, urgent mitigation action is needed to narrow the emissions gap and pave the way for the full fulfillment of all net-zero pledges (UNEP, 2023a).

Ambitious adaptation action is also necessary for reducing the adverse impacts of climate change, minimizing losses and damages and safeguarding sustainable development gains. The complex and escalating nature of climate risks underscores the need for robust adaptation action that is grounded in diverse knowledge and promotes inclusive engagement to effectively reduce vulnerabilities across ecosystems and societies. Adaptation planning and implementation has progressed, but most observed adaptation responses are fragmented, incremental, sector-specific and unequally distributed across

Photo: Frédéric Couzinier

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4. Unconditional NDCs are not contingent on a range of possible conditions, such as the ability of national legislatures to enact the necessary laws, ambitious action from other countries, realization of finance and technical support, or other factors. NDCs that are contingent on various conditions are known as conditional NDCs (UNEP, 2023a).

regions (IPCC, 2023). For example, one out of six countries still lack a national adaptation planning instrument, and a significant finance gap remains, with the flow of international public adaptation finance declining since 2020 (UNEP, 2023b). Additionally, there is increased evidence of maladaptation, which can lock in existing inequalities and vulnerabilities, particularly among marginalized populations. And while there are feasible and effective adaptation options today, many will become less effective as global warming increases and some human and natural systems reach adaptation limits (IPCC, 2023).

The science is clear – rising GHG emissions and atmospheric concentrations are leading to changes in key climate indicators and are affecting extreme events and contributing to devastating impacts globally, particularly among the world's most vulnerable communities. With global temperatures expected to continue rising, urgent and ambitious climate action is needed to mitigate GHG emissions, adapt to the adverse impacts of climate change and minimize losses and damages. Leveraging emerging natural and social science, technology and innovation, climate action can support the achievement of the 2030 Agenda for Sustainable Development and safeguard our future for generations to come.

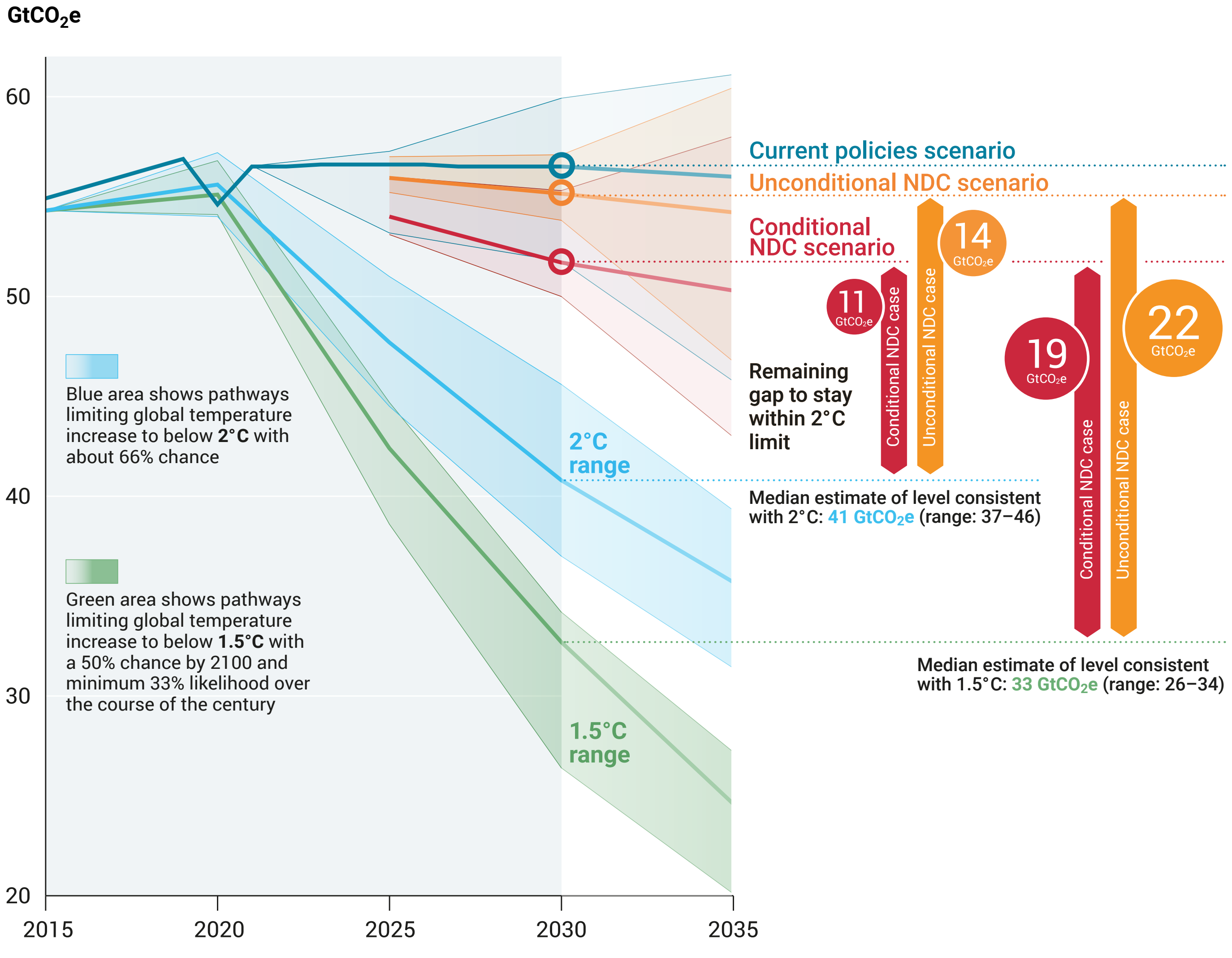

Figure 8. Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and 10th to 90th percentile range). Note: GtCO$_2$-eq – billion tons of carbon dioxide equivalent. *Source:* UNEP, 2023a

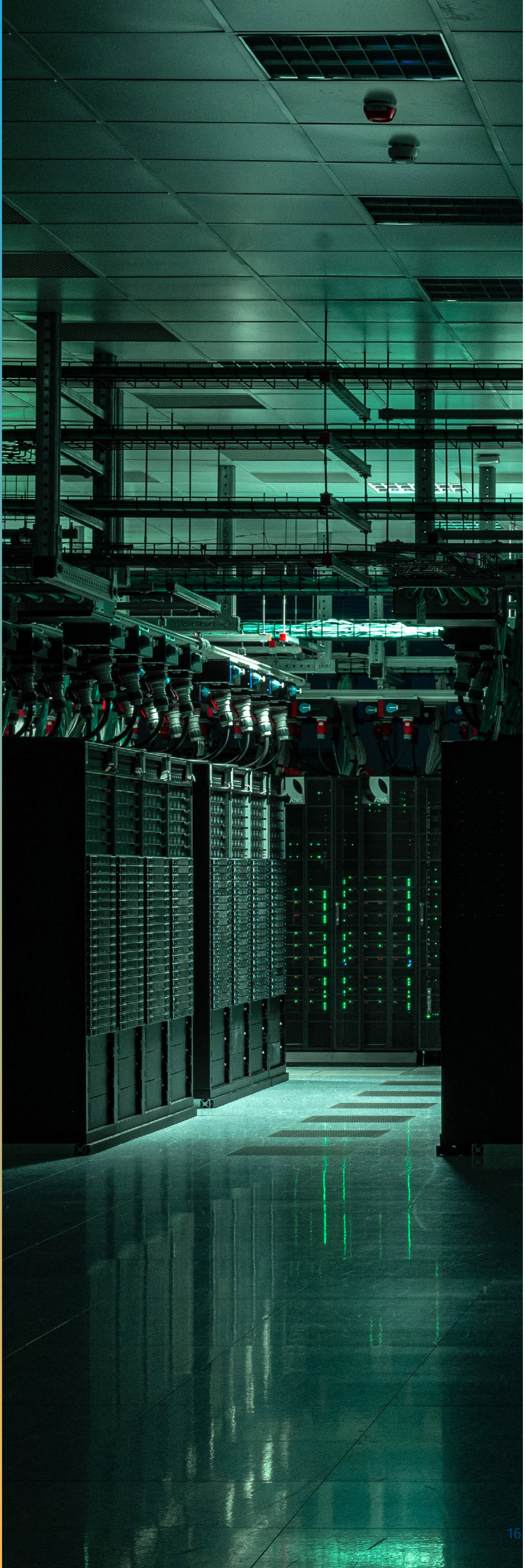

Photo: Stefano Marzoli (ECMWF)

CHAPTER 2

Artificial intelligence and machine learning: revolutionizing weather forecasting

Artificial intelligence and machine learning have emerged as potentially transformative technologies that can revolutionize weather forecasting and could equip society with better tools to drive progress towards climate change adaptation, disaster risk reduction and sustainable development.

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Key messages

- **Artificial intelligence (AI) and machine learning (ML) can make skillful weather modelling faster, cheaper and more accessible, enabling a paradigm shift in predicting extreme and hazardous weather events.**
- **Gaps in data availability, inadequate model resolution and concerns about ethics, such as insufficient transparency and unequal access, are challenges that limit the application of AI/ML for weather forecasting.**
- **Scientific advancements, capacity development and global collaboration can unlock the full potential of AI/ML in supporting climate change adaptation, disaster risk reduction and sustainable development while bridging global technological disparities.**

Introduction

AI and ML are revolutionizing how we confront global issues such as climate change, disaster risk management and sustainable development. AI has been around for decades, but recently the technology's development has been accelerating at an unprecedented pace (United Nations Advisory Body on Artificial Intelligence, 2023). Although closely related, AI and ML serve different functions. AI is a broader concept referring to a wide range of technologies that enable machines to perform tasks typically requiring human intelligence, such as reasoning, learning, and self-correction. ML is a specific subset of AI focused on using algorithms to process data, learn from it, and make decisions or predictions based on these data. This process, known as training, involves teaching computer models to perform tasks like recognizing speech, identifying images or predicting trends by learning from large amounts of data. In meteorology, AI/ML have emerged as potentially transformative technologies that can revolutionize weather forecasting and could equip society with better tools to respond and adapt to climate change.

This chapter highlights how AI/ML can enable a paradigm shift in predicting extreme and hazardous weather events by making weather models cheaper, faster and more accessible to lower-income countries with limited computational capacities. Data-driven AI/ML weather models have shown good performance for many forecasting tasks and AI tools can help contextualize and communicate complex information for decision-making to support climate change adaptation and disaster risk reduction. Yet, there are challenges that limit realization of the full potential of AI/ML for weather forecasting, including gaps in data availability, inadequate model resolution and concerns about ethics, such as a lack of transparency and unequal access. Scientific and technological advances along with strengthened international collaboration can advance AI-driven weather forecasting while promoting equity in support of global goals.

Artificial intelligence and machine learning: revolutionizing weather forecasting

Traditionally, weather forecasting relies on physics-based models to predict the behaviour of the atmosphere through a process known as numerical weather prediction (NWP). These models solve equations that represent physical processes, such as fluid dynamics and thermodynamics, to simulate the state of weather on short time scales. Substantial computational resources are required, however, to solve complex mathematical equations across global and regional scales. As a result, NWP can be costly in terms of computing power and financial and human resources, which is a barrier for many National Meteorological and Hydrological Services (NMHSs).

However, AI/ML are revolutionizing the future of weather forecasting. Instead of relying on costly physics-based numerical models, AI/ML models are trained on reanalysis and observational datasets, making weather forecasting faster and cheaper. And while AI primarily supports weather prediction today, this role may be reversed in the future, with weather prediction becoming primarily driven by AI. In fact, some evaluations have shown that AI/ML models are surpassing physics-based models in predicting some weather variables and extreme or hazardous events, such as tropical cyclones (Figure 1) (see, for example, Keisler, 2022; Pathak et al., 2022; Bi et al., 2023; Lam et al., 2023; Lang et al., 2024). On longer time

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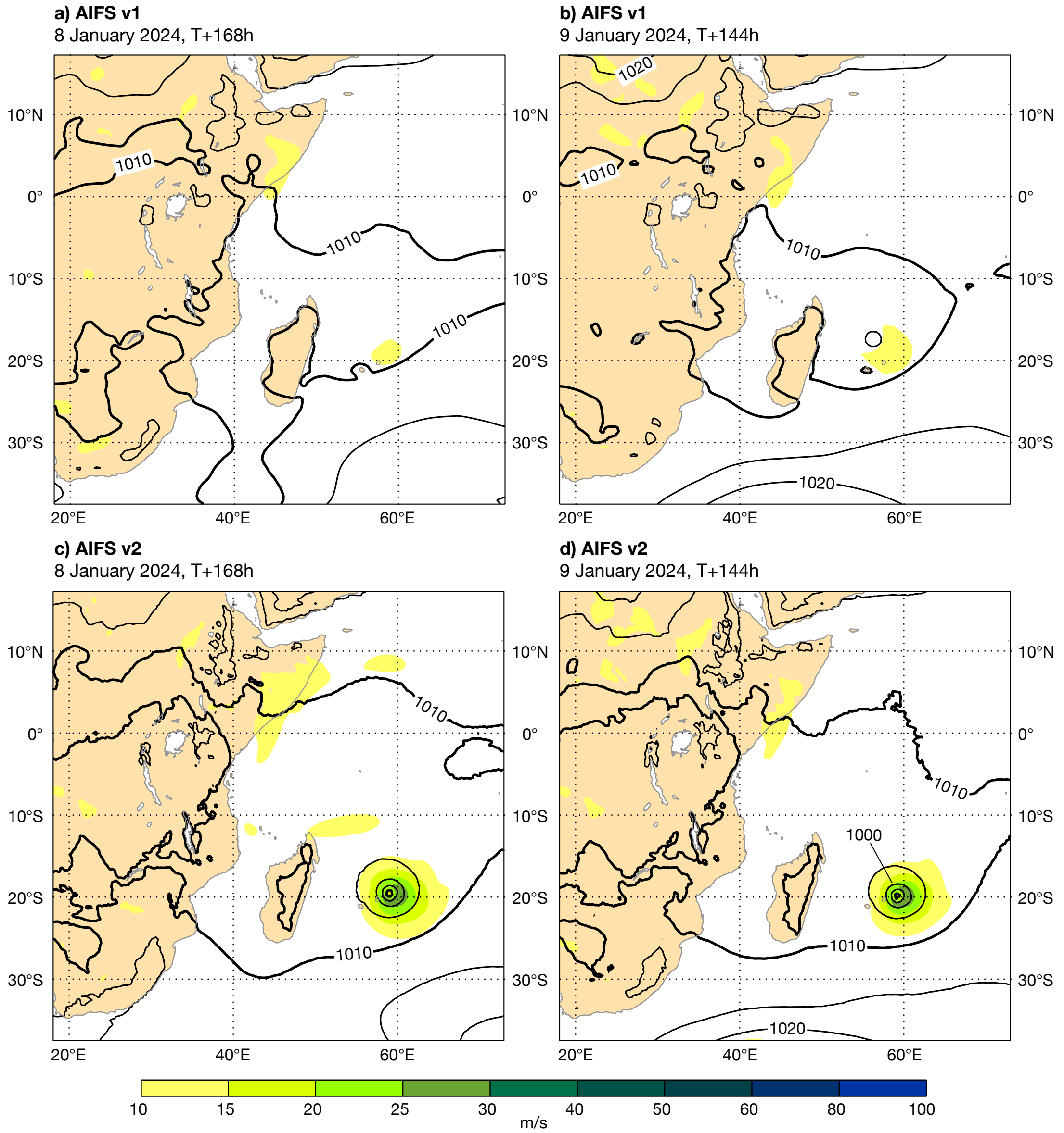

a) AIFS v1
8 January 2024, T+168h

b) AIFS v1
9 January 2024, T+144h

c) AIFS v2
8 January 2024, T+168h

d) AIFS v2
9 January 2024, T+144h

Figure 1. Recent advancements in the Artificial Intelligence/Integrated Forecasting System (AIFS) have improved cyclone detection capabilities by AI/ML models. Tropical Cyclone Belal struck Reunion and Mauritius with intense rains and powerful winds in January 2024 but was detected two days earlier by AIFS version 2 (bottom) compared to version 1 (top) primarily due to a significant increase in horizontal resolution.
The figure shows mean sea level pressure (MSLP) and 850 hPa wind speed on 8 (a) and 9 (b) January 2024, valid at T + 168 h in AIFS version 1, and on 8 (c) and 9 (d) January 2024 for the same valid time in AIFS version 2. *Source:* ECMWF, 2024

scales, studies have shown that AI/ML models can also predict the El Niño Southern Oscillation up to three years ahead (see, for example, Ham et al., 2021; Patil et al., 2023). These developments in AI/ML for weather forecasting have largely been led by big technology companies, such as Google DeepMind, NVIDIA and Huawei, as well as forecasting centres, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and the United States National Oceanic and Atmospheric Administration (NOAA). However, some evaluations of these AI models have found limitations in their performance (Box 1).

Additionally, AI/ML models can reduce the significant computational cost associated with producing the underpinning datasets required to support forecasts. For example, AI/ML methods can enhance weather prediction by checking weather data quality (Sha et al., 2021), fusing different data sources and downscaling weather model outputs (see, for example, Harris et al., 2022). Previously, these capabilities were limited to large global forecasting centres due to the computational burden, but now they can be accessed by NMHSs that previously did not have sufficient resources. As a result, the barrier to entry for running a skillful forecast model for many NMHSs is significantly lowered. Lower costs have also allowed smaller public and private entities to enter the playing field by using AI to mimic weather forecasts of NMHSs.

Through large language models, such as ChatGPT, AI can also help contextualize and communicate complex information for decision-making (see, for example, Koldunov and Jung, 2024). When used appropriately, these tools can enhance disaster preparedness, response and adaptation in support of global initiatives such as Early Warnings for All (EW4All), the Sustainable Development Goals (SDGs), the Paris Agreement and the Sendai Framework for Disaster Risk Reduction. Although the trigger for potential disasters can be hazardous weather events, the decisions on risk, adaptation or mitigation and structural changes in behaviour require information from a wealth of other sources in combination (for example, enhancing global weather and climate information with regional and local information). This can be more readily explored and refined through ML tools, empowering local actors to translate global information to local impacts.

Box 1. **How good are machine learning models?**

The European Centre for Medium-Range Weather Forecasts (ECMWF) has undertaken routine evaluation of AI weather models trained on ERA5, a global climate reanalysis combining observational data with models to provide hourly updates on atmospheric conditions (Figure 2). Predictions of severe weather events like windstorms, extreme temperatures and tropical cyclones were analyzed and the results show that current ML models consistently perform well with some limitations. For example, ML models can accurately forecast the path of tropical storms but may underestimate storm intensity. AI models can also predict intense windstorms several days in advance, but with some underestimations in maximum wind speeds. Additionally, AI forecasts initialized from ECMWF's 9-km resolution forecasts can capture the pattern of summer and winter temperatures, but fall short in capturing extremes accurately, in particular the lowest observed temperatures, which is also a challenge in traditional numerical weather prediction (NWP) forecasts. Comparisons against standard benchmarks showed that AI forecasts initialized from ECMWF's operational 9-km analysis were generally more accurate than any existing global forecasts produced in a traditional way. However, errors in AI forecasts and traditional physics-based model forecasts are often correlated, highlighting common challenges in predicting certain weather situations.

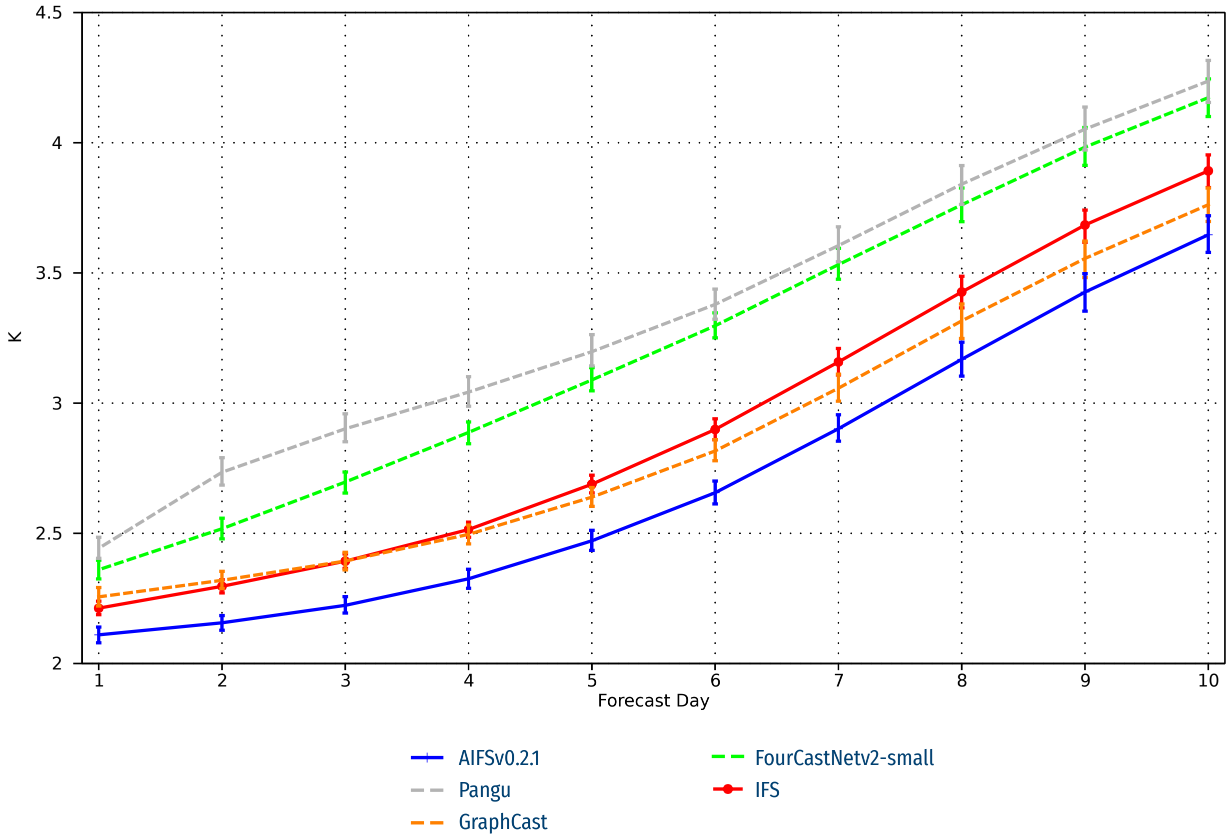

Figure 2. Two-metre temperature error evolution over a 10-day forecast averaged over the southern hemisphere for the year 2022 from different AI modelling systems (Huawei's Pangu-Weather (Bi et al., 2023), NVIDIA's FourCastNet (Pathak et al., 2022), the AIFS (Lang et al., 2024) and Google Deepmind's GraphCast (Lam et al., 2023) with the physical model IFS as a reference (lower error is better). Notably, each of the AI 10-day forecasts takes less than one minute to produce on a single graphics processing unit (GPU). *Source:* ECMWF, 2024

Gaps and challenges

Although tremendous opportunities are arising from advances in AI/ML for weather forecasting, many challenges prevent the full application and realization of the potential of these technologies. In particular, limited data quality and availability remains a principal challenge. Currently, accurate AI/ML models require large, high-quality and consistent data sets (see, for example, ERA5 (Hersbach et al., 2020)), particularly in the training phase. While the global observing system provides a large volume of historical and current data, challenges remain in handling the sheer scale of data required for training, and economic, political and geographical differences between countries can result in uneven data availability. Additionally, gaps in spatial and temporal variability of data, such as the lack of data for small-scale weather phenomena and the absence of high-resolution global reanalysis data, affect training and limit the effectiveness of AI/ML models. As a result, training must rely on model outputs or direct observations, which is more difficult and computationally expensive – a challenge that must be balanced with the need for rapid, accurate and actionable predictions.

Further complicating matters is the absence of harder-to-predict variables, such as ocean, land, cryosphere and carbon-cycle variables, in current AI/ML models. These variables are deeply interconnected, but their absence limits the accuracy of extended-range weather forecasts, seasonal predictions and longer-term climate projections, particularly at local scales (Woolnough et al., 2007; Vellinga et al., 2020). There has been a shift towards targeted enhancements in model resolution (Nippen and Chantry, 2024), where regional specificity is prioritized without the need for comprehensive global resolution upgrades. However, downscaling methods to enhance model resolution require considerable computational resources, which remains a challenge (Mardani et al., 2024).

Additionally, ethical challenges, such as insufficient transparency and unequal access, limit the uptake and effectiveness of AI/ML weather models (McGovern et al., 2022). For example, ML models do not make the physical processes they simulate explicit, potentially eroding public trust and confidence in AI/ML forecasts. Efforts are being made to improve the interpretability of ML models (Ghaffarian et al., 2023), including integrating physics-based constraints (see, for example, Harder et al., 2022) and developing methods to test models' representation of physical processes they have not been trained on (Hakim and Masanam, 2024). However, there is still a need to enhance transparency to ensure trust and confidence, which can lead to greater uptake and acceptance of information that is critical for society. Additionally, AI/ML tools that enable efficient use of the available data are still not accessible to everyone, which risks further exacerbating inequalities, particularly those related to the global digital divide. Limitations in data, computation and user skill sets continue to prevent access to these emerging technologies and must be addressed to ensure everyone can benefit from the many benefits they deliver across society.

Photo: Bruno Fanulin

Photo: UNDP Cambodia

Looking ahead: the future of artificial intelligence and machine learning for weather and climate

Looking ahead, AI/ML will continue to push boundaries across weather and climate. The next frontier will likely involve data assimilation and the development of robust foundation models, which are trained on large, varied datasets without a single specific task in mind, enabling them to be exported and adapted to more specific applications. Additionally, it will be critical to extend existing atmospheric AI/ML models to encompass the full Earth system to enhance not only weather forecasting but also climate prediction capabilities (see, for example, Wang et al., 2024; Watt-Meyer et al., 2023). Broadening the scope of data, including untapped data from commercial satellite providers as well as crowd-sourced data (Internet of Things), holds promising potential to enhance the performance of AI/ML models, which generally improve as the volume and diversity of training data increases. Ensuring these training data are openly available with low-cost federated data storage platforms and computing infrastructure, in combination with standardized tools to utilize data and build ML applications for weather, can help democratize use and exploitation of ML in NWP across the globe.

We are moving towards a future where AI-driven insights support decision-making and empower communities worldwide to mitigate risks associated with climate variability and extreme and hazardous weather. Strong global governance and frameworks are needed to ensure AI/ML are developed with humanity's best interests in mind and are accessible to all. Enhanced transparency in AI/ML weather models, including greater openness and traceability of training data, will be important for building trust and developing standards for the responsible use of these tools. Additionally, ethical AI development must address systemic biases and equal access by ensuring technology considers all communities, particularly those most vulnerable. Training and capacity development are also needed to address the digital divide and ensure the effective, responsible and equitable application of AI/ML tools. The evolution of these technologies underscores the importance of global collaboration to unlock the full potential of AI/ML in enhancing climate action, empowering local actors and bridging technological disparities to support achievement of a more sustainable and resilient future for all.

Photo: NASA

CHAPTER 3

Space-based Earth observations: enhancing weather, climate, water and related environmental applications

Innovations in space-based Earth observations can open new frontiers to advance weather, climate, water and related environmental applications, accelerate progress towards global goals and foster peaceful and sustainable benefits for all.

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Key messages

- **High-resolution and high-frequency observations of the Earth system are crucial for effective weather forecasting, climate prediction and environmental monitoring.**
- **Leveraging public–private partnerships, innovations in space-based Earth observations such as very-high resolution imaging and mega-constellations can open new frontiers and accelerate progress towards global goals.**
- **International collaboration, comprehensive governance frameworks and innovative financing models can support space-based Earth observation for weather, climate, water and related environmental applications.**

Introduction

From pigeons to balloons and satellites, humanity's efforts to observe and measure Earth phenomena have advanced rapidly over the last 100 years. Today, satellites allow us to observe Earth's land, oceans and atmosphere at increasingly higher resolutions and frequencies, providing services that are crucial to society (Emery and Camps, 2017). In the context of weather, climate, water and environmental applications, new satellite technologies can enhance weather data and contribute to the creation of long-term climate data records, which are crucial for climate services, particularly in vulnerable regions. Additionally, satellite technology can be a cost-effective tool in supporting the achievement of global goals, such as the Paris Agreement, Sendai Framework for Disaster Risk Reduction and 2030 Agenda for Sustainable Development (Lemmens, 2011; Hegglin et al., 2022).

This chapter provides a high-level overview of space-based Earth observations for weather, climate, water and related environmental applications and highlights some of the latest advancements in science and technology related to satellite observations. Additionally, this chapter identifies gaps and challenges that limit the realization of the full potential of these advancements and that must be addressed to ensure space-based Earth observations foster sustainable benefits for all.

Space-based Earth observations for weather, climate, water and environmental applications

The world's first weather satellite was launched on 1 April 1960, marking the beginning of a new era (WMO, 2023). Since then, remarkable technological advancements have been achieved. Spectrometers can now measure radiance emitted from the Earth across thousands of wavelength channels, compared to just a few in the past, and advances in scatterometers and altimeters have enhanced ocean monitoring. These advancements have paved the way for improved weather prediction, enhanced understanding of our climate system and more robust environmental monitoring.

The increasing availability of satellite imagery and observation data has improved our ability to predict high-impact weather events across time scales, from hours to days, including in regions with complex terrain or insufficient surface observation data (Du et al., 2021). Technologies such as microwave sounders can "slice" the atmosphere vertically to better understand how key variables in weather forecasting change throughout the atmosphere. Satellite data measuring storm-related variables are essential for nowcasting, or the prediction of rapidly developing atmospheric events, such as thunderstorms, on timescales up to six hours (Box 1).

Additionally, satellite observations improve our ability to monitor the state of our climate and project future changes in climate with reduced uncertainty (Guo et al., 2015). For example, satellite observations and data are essential for monitoring polar ice changes, informing climate models and understanding climate impacts (Hall, 1988). Also, international collaboration enables the use of geostationary satellites to establish long-term records of essential climate variables and headline indicators, which provide a basis for assessing the state of the global climate system (Trewin et al., 2021). This information supports effective decision-making and adaptation, including

Box 1. Space-based Earth observations: building capacity for nowcasting of thunderstorms in Southern Africa

Space-based Earth observations with high temporal and spatial resolution enhance nowcasting capabilities. As a result, weather forecasters can observe thunderstorms as they form, assess how severe they will be and provide early warnings that enable members of the public to take anticipatory action to minimize impacts. In Southern Africa, for example, severe thunderstorms threaten lives and cause significant damage to property and livelihoods, particularly in urban areas. The Weather and Climate Information Services (WISER) Early Warnings for Southern Africa (**EWSA**) project aims to build capacity for nowcasting using real-time satellite images of Africa to predict high-impact hydrometeorological hazards in urban areas (Symonds, 2023). Additionally, the project engages with disaster risk management agencies and non-governmental organizations to co-produce outputs with people living in cities, including disadvantaged groups, such as women and people with disabilities. As a result, the WISER EWSA project aims to not only advance nowcasting technology but also help ensure that everyone receives these early warnings and knows what action to take to reduce the risk of negative impacts.

at local levels, and reduces the risk of maladaptation (***United in Science 2023: Sustainable Development Edition***).

Finally, space-based Earth observations are also pivotal for environmental monitoring. For example, synthetic aperture radar (SAR) imaging, which involves satellites emitting radar signals that are reflected and then recorded by instruments on the same satellite, are particularly useful because they can generate images even when it is dark or cloudy. As a result, SAR imaging offers all-weather, day-and-night Earth observation, which is crucial for many applications, such as tracking deforestation, monitoring sea ice or disaster risk reduction and response. Environmental monitoring utilizing space-based Earth observations can support water and land management by measuring and monitoring soil conditions to detect drought conditions and inform anticipatory action to alleviate food and water insecurity in vulnerable regions across the world (Schollaert Uz et al., 2019; Dube et al., 2022).

Scientific and technological advancements in space-based Earth observations

Science and technology have led to incredible advancements in space-based Earth observations in recent decades, greatly enhancing weather, climate, water and related environmental applications. For example, predicting fast-changing weather events requires information about atmospheric variables, such as temperature, moisture and wind. New hyperspectral technology used in geostationary satellites will soon provide frequent high-resolution temperature and humidity data, and space-based lidar technology is enhancing the measurement of winds. Additionally, the use of a multi-sensor approach that combines data from different types of sensors can improve the tracking and analysis of heavy rainfall and enhance understanding of the hydrological cycle, which is critical for predicting and assessing climate change.

Box 2. **Global Greenhouse Gas Watch (G3W) – informing international climate policy**

Successful implementation of the Paris Agreement will require sustained, near-real time monitoring of GHG fluxes and concentrations to assess the impact and overall effectiveness of mitigation efforts undertaken by the Parties to the Agreement. WMO's Global Greenhouse Gas Watch (G3W) initiative will provide a platform for the international exchange of space-based and surface-based observations and modelling products to estimate the fluxes of CO_2, CH_4 and N_2O, taking into consideration both human and natural influences. Building on WMO's experience in facilitating international collaboration and its longstanding Global Atmosphere Watch programme, G3W will provide quantitative data to help improve our understanding of GHG cycles and better prediction of long-term climate trajectories. As a result, the initiative will provide information to support decision-making regarding mitigation actions and monitor progress towards achieving commitments.

Additionally, the resolution of satellite imaging continues to improve thanks to scientific and technological advances. The latest generation of very high resolution (VHR) Earth observation satellites offers sub-metre resolution imagery imagery up to 30 cm per pixel, enabling more precise monitoring of environmental changes from global to local scales (Neigh et al., 2019). These days, there are numerous commercial VHR data sources that complement existing government-funded Earth observation systems. These initiatives highlight the importance of private-sector investments in space-based Earth observations and a public- and private-sector industry that can advance Earth observation data through collaboration.

Global navigation satellite systems (GNSS), which have provided global positioning, navigation and timing services for decades, are increasingly being used in innovative ways to enhance ocean observations. For example, GNSS reflectometry technology uses reflected signals to infer sea-surface heights and temperatures, wind speeds and significant wave heights, among other variables, which are critical for enhancing understanding of atmospheric and ocean coupling to improve weather and climate prediction (Xing et al., 2022). Additionally, GNSS radio occultation, another remote sensing technique utilizing GNSS, can analyze atmospheric temperature profiles that are critical to enhancing numerical weather prediction skill.

In addition, the capabilities of satellite observations to monitor atmospheric composition are growing rapidly. For example, the Copernicus Anthropogenic Carbon Dioxide Monitoring Constellation will combine high-resolution satellite measurements of CO_2 and CH_4 emissions with ground-based measurements and modelling to distinguish anthropogenic emissions from natural sources (ESA, 2022). Other initiatives, such as NASA's Orbiting Carbon Observatory-3 (**OCO-3**), as well as private-sector space missions will provide complementary high-resolution global GHG monitoring. These advancements are giving rise to new initiatives that can inform international policy (Box 2) and societal applications, particularly in the health sector, which requires air quality information to inform decision-making and adaptation (***2023 State of Climate Services: Health***).

Finally, recent advances, including large constellations of satellites being developed, laser communication and edge computing, could enhance space-based Earth observation data collection, connectivity and data availability. For example, commercial providers are breaking technological barriers with the miniaturization of instrument components, which has reduced the size, weight and cost of satellites. This has led to a new era of small satellites (SmallSats) that are more agile, cheaper to produce and launch, and easier to coordinate. These SmallSats form large constellations that help collect different types of weather and environmental data faster and in more agile ways. They also provide global broadband access and enhance Earth observation data distribution, offering easier near real-time access to remote sensing data received from satellites. However, the growing number of objects in space has also led to an increase in space debris, which can threaten to impair or destroy other spacecraft in orbit (UNOOSA and ESA, 2023). Additionally, research indicates that the use of laser communication can significantly improve the speed of data transfers between satellites and ground-based infrastructure, making access to imagery data faster and easier (Marbel et al., 2022). Edge computing is also increasingly being used to process data directly on the satellite, rather than transmitting raw data to Earth for analysis, which can provide faster insights for decision-making (Leyva-Mayorga et al., 2023).

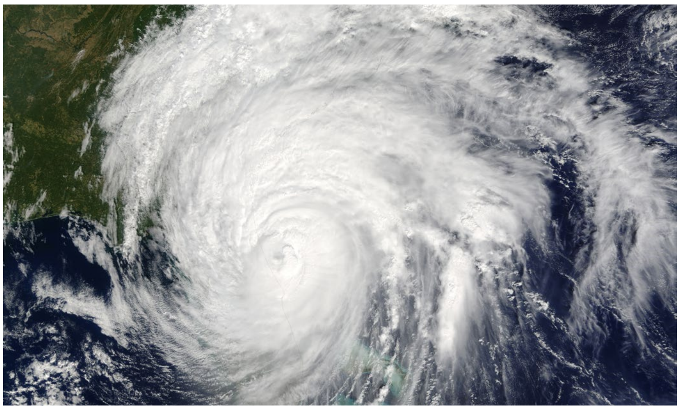

Photo: NASA

Gaps and challenges

Despite scientific advancements and expanding investments in new space technologies, gaps remain in accurately measuring critical ocean, climate, aerosol and hydrological variables and in covering sparsely observed areas such as the cryosphere. Additionally, data accessibility and standardization pose significant challenges, particularly for lower-income countries that lack the infrastructure, resources and expertise to effectively utilize space-based data (Macphail, 2009). Moreover, the differences in data formats and collection methods create interoperability issues, complicating the integration of data from various sources. Additionally, high data quality and ground-truthing are needed to increase the accuracy of satellite data, which require calibration and validation through ground-based observations (Militino, et al., 2018), which are often limited in remote regions and in low-income areas, leading to inconsistencies and uncertainties in satellite-derived information.

Technological and funding limitations are also significant barriers (Andries et al., 2019). Many satellites still rely on traditional data transmission methods because new technological solutions are not fully operational or cost-effective, especially in lower-income countries. These traditional methods can lead to delays in data transmission processing, where timeliness is essential, particularly for nowcasting services supporting early warning systems. They are also increasingly at risk due to the growing demand for radio frequencies by the telecommunications industry. Additionally, launching and maintaining satellites remains prohibitively expensive for many nations and organizations, despite the rise of SmallSat constellations and commercial Earth observation companies. Funding limitations also hinder access to data, despite negotiation efforts by the United Nations to reduce the cost of satellite data.

Finally, challenges remain in establishing and implementing international frameworks for space-based Earth observations. While progress has been made in establishing global data sharing regulations, geopolitical tensions can influence the willingness of nations to share crucial Earth observations and information, hindering international collaboration and data access (Harris and Baumann, 2021). Additionally, in the context of the growing number of objects and actors in space, further collaboration is needed to strengthen governance frameworks to ensure the safe and sustainable use of space in support of global goals.

Looking ahead: the future of space-based Earth observations

Moving forward, a multifaceted approach is needed to enhance the quality, coverage, quantity and accessibility of space-based Earth observations and data, particularly in lower-income countries. Improving the quality of satellite data can be achieved through rigorous calibration and validation with ground-based observations, which will reduce uncertainties and improve the accuracy of climate models and disaster assessments, for example (Yamamoto et al., 2010). Additionally, data accessibility can be enhanced through new technologies and international initiatives. For example, Earth observation data and related services are increasingly moving to “the cloud”, which provides on-demand availability of computing resources from various locations globally. Utilizing the cloud can enhance data storage, processing and accessibility, therefore reducing costs and facilitating rapid data dissemination. However, accessibility barriers still remain in lower-income countries where Internet access is challenging. Innovative financing models, public–private partnership and increased investments can address funding limitations, help reduce costs, scale up the use of tools and enable research into novel observation methods, which can open new frontiers in Earth observations and data (Salcedo-Sanz et al., 2020).

Finally, stronger international collaboration is important to promote open data sharing as well as capacity building, training and technology transfer, which can empower countries to process and analyze satellite data for climate action and disaster risk reduction. Collaboration is also essential to establish clear regulations on issues such as data sharing, security and space debris, for example, and to promote comprehensive governance frameworks, such as the WMO Integrated Global Observing System, which addresses observations needs for weather, climate, water and related environmental services (*Vision for WIGOS in 2040* (WMO-No. 1243)). As a result, advances in space-based Earth observations can be optimized to foster peaceful and sustainable benefits for all.

Photo: Dan Roizer - Unsplash

CHAPTER 4

Bridging virtual and physical realms: leveraging immersive technologies for water and land management

Immersive technologies such as digital twins, virtual reality and the metaverse can revolutionize land and water management by enabling interactive and data-driven solutions that bridge the physical and digital worlds, enhancing decision-making and the engagement of diverse actors.

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Key messages

- **Socioeconomic impacts and climate change are straining water and land resources, threatening food and water security and highlighting the need for integrated water and land management to support sustainable development and climate action.**
- **Immersive technologies such as digital twins, virtual reality and the metaverse can revolutionize land and water management by offering immersive, interactive and data-driven solutions that bridge the physical and digital worlds to enhance decision-making and the engagement of diverse actors.**
- **International cooperation, knowledge sharing and robust multilateral frameworks are crucial for adopting these innovative solutions to better manage land and water resources and ensure a sustainable and equitable future.**

Introduction

Since the beginning of time, land has served as the foundation for human settlements and water has shaped the Earth's surface, playing a major role in the rise and fall of civilizations (Roberts et al., 1998; DGB Group, 2023; Pacific Institute, 2023). Today, population growth, complex socioeconomic impacts and a changing climate have put immense pressure on both water and land resources, leading to widespread degradation that threatens society. For example, flood hazards are increasingly exacerbated by land degradation and poor water management, resulting in heightened vulnerability for communities, especially in rural areas. Additionally, current research suggests a close relationship between areas experiencing significant water and land degradation and areas troubled by high levels of rural poverty and malnutrition, threatening sustainable development. As a result, integrating water and land management is crucial to achieving the 2030 Agenda for Sustainable Development.

Recognizing the growing land and water degradation crisis, this chapter highlights the promise of emerging technologies, including digital twins, the metaverse and virtual reality (VR). These technologies offer immersive, interactive and data-driven solutions, enhancing our understanding and management of complex processes that govern water and land resources. From simulating flood and drought events to predicting water flow and accumulation, as well as land degradation, digital twins and immersive technologies can drive innovation and solutions. However, challenges such as limitations in data availability, quality and interoperability as well as gaps in funding and legal and regulatory frameworks must be overcome for these technologies to reach their full potential. Through international collaboration, engagement with diverse actors and data collection and standardization initiatives, we can advance efforts to incorporate the use of digital twins and immersive technologies to address global challenges.

A growing crisis: the water and food nexus threatened by land and water degradation

Water and land resources management are at the heart of socioeconomic development. The interconnected issues of surface and groundwater depletion and land degradation can impede efforts to achieve the Sustainable Development Goals (SDGs). For example, agriculture accounts for nearly 70% of consumption of freshwater resources, with this percentage increasing to 90% in low-income countries (Fujs and Kashiwase, 2023). In many countries, however, agriculture employs unsustainable water usage practices and remains one of the largest polluters of both groundwater and surface water. Additionally, sectoral interests have dominated water resource allocation for decades without proper consideration of the impacts downstream or the need to sustain water resources. In addition, the use of improper practices can displace soils, leading to erosion, which reduces the depth, nutrient content and water-retaining capacity of soils. Unchecked erosion can transform productive agricultural areas into barren wasteland and cause severe downstream impacts such as polluted drinking water, silt-filled rivers and irrigation canals and degraded coastal ecosystems, and increasing the risk of landslides (Jinendradasa, 2002).

Land degradation and climate change are also deeply intertwined. For example, land degradation reduces the Earth's capacity to sequester carbon, as healthy soils and vegetation can act as carbon sinks. Additionally, when land is degraded through deforestation or erosion, stored carbon is released into the atmosphere, increasing CO_2 levels. The loss of vegetative cover also disrupts the climate system by altering the albedo of land surfaces, or the amount of sunlight they reflect, which has an impact on temperature regulation. Climate extremes exacerbate these problems, and management of both land and water resources globally, including in developed and least-developed countries, is a serious governance challenge. Furthermore, for basins that cross national borders, water management decisions made upstream can have trickle-down impacts that threaten peace and global security.

The promise of emerging technologies: metaverse, digital twins and virtual reality

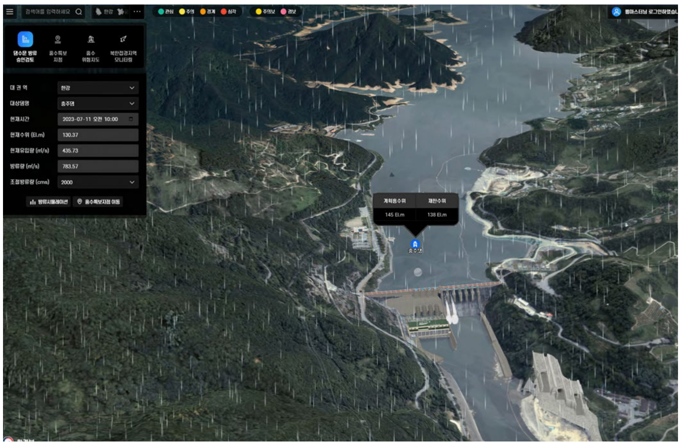
Throughout history, technologies such as water-capturing cisterns, aqueducts and dams, as well as advances in land-use practices, such as conservation tillage and crop rotation, have helped communities access and manage water resources and mitigate land degradation. Today, as the pressure on water resources and land grows, there is an increasing interest in leveraging new technologies to collect and digest observations and to visualize different scenarios. While technologies such as AI, drones and the Internet of Things (IoT) have been gaining popularity, a new set of technologies leveraging digital twins and the metaverse is emerging that creates highly detailed, interactive digital replicas of real-world environments.

Digital twins are defined as a virtual representation designed to accurately reflect a physical object or system (**What Is a Digital Twin?**). The metaverse, on the other hand, is an integrative ecosystem of virtual worlds that provides immersive experiences, creating new value from economic, environmental, social and cultural perspectives (ITU FG-MV, 2023). Digital twins are essentially the building blocks of the metaverse, enabling us to visualize different scenarios and enhancing the immersive experience for users.

Digital twins have been in existence for several decades. The United States National Aeronautics and Space Administration (NASA) was one of the initial pioneers of digital twin technology, creating replicas of spacecraft on Earth for study and simulation by flight crews during the 1960s space exploration missions (Allen, 2021). However, it is only more recently that they have gained traction across the weather, climate, water and related environmental domains, including land and water resources management.

One example is a project spearheaded by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) that will develop methods to predict interactions between land and torrential surface water flows for the Beetaloo sub-basin in Australia (Huth et al., 2023). The goal is to protect surface water and vegetation while mitigating soil erosion and damage. Using high-resolution aerial photography, billions of data points were captured, which allowed for precise geolocation and the creation of an accurate three-dimensional (3D) digital model of the area. Such high-resolution models help landowners and companies to identify areas that are at high risk of erosion and to address this issue before any major damage occurs. Typically, areas with low levels of grass cover as a result of cattle grazing or poor soil health are at a higher risk of erosion. This digital twin enables researchers to use modelling software to visualize where rainfall collects into runoff streams and calculate upstream catchment areas. When these models are overlaid onto high-resolution maps, they provide clear visualizations of water flow and accumulation in the landscape, helping to identify areas that are susceptible to erosion and, thereby, help resolve the issue in advance.

Another example is the development of a comprehensive digital twin of all river basins across the Republic of Korea by 2026 (Figure 1). The Ministry of Environment is leading this project, which leverages high-resolution 3D spatial information and real-time monitoring of dams and basins to create accurate simulations of flood response operations. The digital twin will allow users to visualize flood depths and extents under various scenarios, providing critical information to local residents for timely evacuation and accurate damage assessment for compensation. Furthermore, digital twins have also been created for existing dams. These digital models enable dam operators to digitally assess structural damages or leaks that are not easily visible, significantly enhancing flood prevention and forecasting capabilities. Complementing the digital twin system is an advanced AI system that utilizes data collected from numerous sensors deployed across the river basins to help predict potential flood events, thereby improving overall flood management and response.



대권역: 한강
대상댐명: 충주댐
현재시간: 2023-07-11 오전 10:00
현재수위 (El.m): 130.37
현재유입량 (㎥/s): 435.73
방류량 (㎥/s): 783.57
조절방류량 (cms): 2000

계획홍수위	제한수위
145 El.m	138 El.m

Figure 1. An example of flood forecasting using a digital twin in the Republic of Korea. *Source:* **Han River Flood Control Office, Ministry of Environment, Republic of Korea**

Regarding immersive technologies like the metaverse and VR, the integration of complex and specific hydrological data presents significant technical challenges. As a result, most efforts to date have focused around creating interactive, educational simulations to educate diverse actors in water resources management. For example, Malaysia recently studied flood preparedness among higher education students using a metaverse environment (Sa don et al., 2023). These studies demonstrated that immersive tools help users better understand flood risk concepts, which can be difficult to grasp for those who have not experienced a flood event firsthand. Unlike traditional tabletop exercises, VR can be used to effectively communicate the severity of the situation and raise awareness on flood-related hazards and their impacts. In recent years, VR and simulation technologies have been used more widely to enhance disaster preparedness and response, aligning with the Sendai Framework's objective to support the development of user-friendly systems for sharing information on effective practices (Alizadeh et al., 2023; Hsu and Gourbesville, 2023).

The future, however, likely will not be dominated by a single technology such as digital twins or the metaverse but instead will see the integration of multiple technologies. Combining different technological advancements will be key to driving innovation and addressing complex challenges. For instance, Tampere, a city in Finland, has unveiled a Metaverse Vision 2040 that will leverage several advanced technologies (Figure 2). It explores how a metaverse environment, integrating technologies like AI, digital twins and virtual realities, can enhance urban governance, sustainability, equality and the well-being of its

Figure 2. Schematic of a cognitive city. *Source:* Rantanen, 2023

citizens. The vision illustrates future scenarios where AI and the metaverse facilitate personalized services and participatory governance.

Gaps and challenges

Although these technologies greatly enhance our ability to manage land and water resources, several gaps and challenges remain (Botai et al., 2023). Notably, limitations in data availability and quality, particularly in remote and rural areas, hinder the effectiveness of these technologies. Additionally, inadequate data interoperability when dealing with data formats from different sources and integrating them with existing systems, tools and platforms that are used by diverse actors can pose a significant challenge. It is also necessary to ensure that sufficient digital infrastructure is in place and training and capacity building are provided when transitioning to these technologies.

Access to sustainable funding mechanisms and effective governance frameworks is lacking, while public trust and understanding require improvement. Moreover, existing legal and regulatory frameworks need to be adapted to accommodate the use of these technologies in transboundary contexts, addressing concerns such as data sharing, ownership, decision-making, liability and intellectual property rights. Putting in place strong policies covering data governance, standardization, education and public awareness is crucial while adopting these technologies (Amarnath, 2024).

Looking ahead: the future of digital twins, virtual reality and the metaverse

As we look to the future, it is crucial to understand the added value and limitations of emerging technologies before investing in and relying on them for land and water management. As a result, a multifaceted approach is necessary to ensure the seamless adoption of these technologies. Governments and organizations, including international organizations, academia and the private sector, should invest in comprehensive data collection initiatives to improve the availability of high-quality data. Additionally, standardization efforts can help resolve issues related to data interoperability and integration across platforms and systems (ITU, 2024).

Transparent communication strategies and educational campaigns are also essential to build public trust and understanding around the use of these technologies. As they evolve, fostering international cooperation and knowledge sharing becomes increasingly important, facilitating the adoption of best practices and innovative solutions. In this regard, the United Nations and its specialized agencies, such as WMO and the International Telecommunication Union (ITU), can advance efforts to incorporate the use of digital twins and the metaverse to address the SDGs, which was the focus of the First United Nations Virtual Worlds Day held in June 2024 (ITU, 2024).

The synergy between digital twins, VR and the metaverse has the potential to revolutionize how we interact with both virtual and physical worlds, providing comprehensive solutions for modelling, simulations, visualization and real-time interaction in decision-making for land and water management. By embracing these emerging technologies within a robust multilateral framework, we can better manage land and water resources, ensuring a sustainable and equitable future for generations to come.

Photo: Dipayan Bose

CHAPTER 5

Towards pathways to sustainable futures: the role of transdisciplinary approaches to weather, climate, water and related environmental and social sciences

Addressing complex global challenges such as climate change, disaster risk reduction and sustainable development requires an enhanced rethinking and reimagining of how diverse perspectives, knowledge and experiences can help us co-create knowledge and implement solutions through transdisciplinary approaches.

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Key messages

- **Global challenges such as climate change, disaster risk reduction and sustainable development cannot be addressed by one form of knowledge alone – they require a transdisciplinary approach that unites actors across environmental, social and cultural contexts to co-create and implement solutions.**
- **When used appropriately, transdisciplinary approaches have the potential to boost the impact of perspectives offered by weather, climate, water and related environmental and social sciences by enabling diverse perspectives, knowledge and solutions.**
- **Enhanced philosophies of transdisciplinarity, including education and training, should be embraced and encouraged to prepare the next generation to address the challenges of the future.**

Introduction

Global challenges such as poverty, hunger, inequality and environmental degradation are threatening sustainable development. In many cases, these compounding challenges are exacerbated by extreme weather events and the impacts of climate change, which disproportionately affect the world's most vulnerable communities. Conventional approaches often address challenges by focusing on understanding the dimensions of natural and social sciences, policy and society separately. However, addressing complex global challenges such as climate change, disaster risk reduction and sustainable development requires an enhanced rethinking and reimagining of how diverse perspectives, knowledge and experiences can help us co-create and implement solutions.

This chapter introduces the concept of transdisciplinarity and explores how a transdisciplinary approach can be applied in the context of weather, climate, water and related environmental and social sciences. This approach can help apply these sciences in local contexts and boost their impact to support achievement of global goals, including the Paris Agreement, Sendai Framework and 2030 Agenda for Sustainable Development. While gaps and challenges limit the full use and effectiveness of transdisciplinary approaches, opportunities are identified to enhance understanding, governance, collaboration and education to create enabling environments that foster transdisciplinarity moving forward.

Understanding transdisciplinarity

A transdisciplinary approach brings together diverse actors, such as scientists, policymakers, practitioners and civil society, including local and Indigenous communities, to co-create knowledge and develop solutions that are relevant to local contexts. It differs from a multidisciplinary approach, where experts from different disciplines work on the same issue separately. It also differs from an interdisciplinary approach, where experts from various disciplines share methodologies and findings, resulting in better integration. A transdisciplinary approach goes a step further by requiring an enhanced understanding of the multiple ways of knowing and making sense of reality to collaborate to find solutions outside of their own discipline (Matsuura and Razak, 2019).

A transdisciplinary approach can be applied across the science–policy–society interface, including as a research method (Figure 1) or framework for policy or practice, for example. It involves collectively framing problems, co-creating solution-oriented knowledge, and integrating and applying this knowledge to address complex societal challenges (Klein, 2001; Walter et al., 2007; Lang et al., 2012; Brandt et al., 2013; Bréthaut et al., 2019; Hoffmann et al., 2019; Norström et al., 2020; Bergmann et al., 2021; Kaiser and Gluckman, 2023). Throughout the process, participatory methods of engagement are often utilized to ensure the voices, experiences, views and values of actors are legitimized and included.

Photo: Indonesia Meteorological and Geophysical Agency, BMKG

Collective problem-framing involves engaging with diverse actors to develop a shared contextual understanding of problems through the integration of various perspectives, worldviews and values (Brandt et al., 2013; Norström et al., 2020). Throughout this process, power asymmetries between actors must be addressed to ensure their perspectives, cultural norms and values are included (Bréthaut et al., 2019; Hoffmann et al., 2019; Barth et al., 2023). This shared understanding of the problem lays the foundation for the co-creation of solution-oriented knowledge, which may be achieved through participatory research or methods, such as citizen science. The knowledge produced during this process should be contextualized and grounded in local realities to ensure it can be effectively implemented to address complex challenges (Norström et al., 2020).

A transdisciplinary approach to weather, climate, water and related environmental and social sciences

Weather, climate, water and other environmental systems are deeply interconnected across all aspects of society. Therefore, working together is essential because global challenges such as climate change, disaster risk reduction and sustainable development cannot be solved through one view point, understanding or discipline alone. Transdisciplinary approaches have the potential to amplify the impact of perspectives offered by weather, climate, water and related environmental and social sciences and services by enabling diverse actors to contribute their perspectives, knowledge and solutions in support of climate action. Increasing the diversity of actors makes it possible to accelerate political commitment and global efforts to address climate change (IPCC, 2023).

For instance, engaging diverse actors from the beginning, including scientists, policymakers, practitioners and local and Indigenous communities, among others, contributes to the development of a contextual understanding of climate change impacts on the ground. In this process, it is essential to acknowledge that experience and knowledge outside the realm of weather, climate, water and related environmental and social sciences can contribute meaningful perspectives. These perspectives must be recognized, legitimized and included to develop a deeper and more complete understanding of climate impacts, vulnerabilities and adaptive capacities.

Additionally, in some contexts, the use of participatory methods, such as citizen science, can support the co-production of knowledge for climate action by involving diverse actors in scientific research. In the context of weather, climate water and related environmental and social sciences, these methods have been used to identify and collect local data to enhance weather forecasts and climate predictions as well as to facilitate feedback from users to evaluate and verify these forecasts and predictions (WMO, 2023).

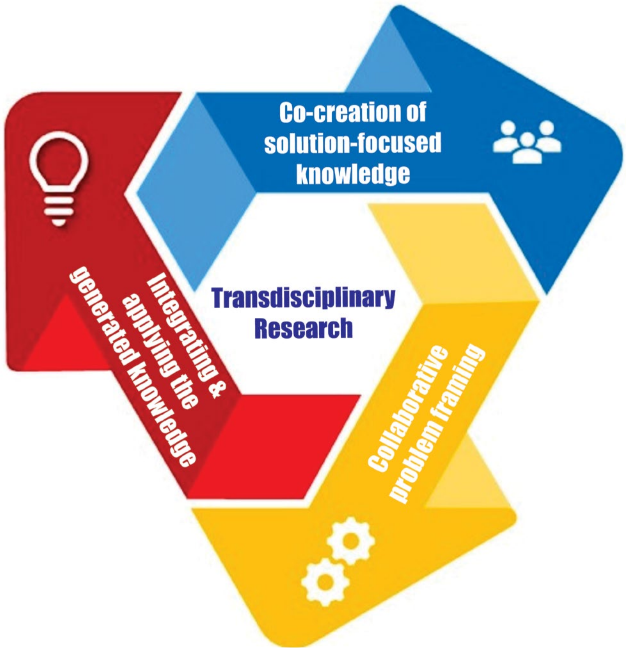


Figure 1. The fundamental stages of a transdisciplinary approach can be applied across the science–policy–society interface, including in the context of research as highlighted in this figure. *Source:* Irasema Alcántara

Community participation not only improves science but also enhances local communities' environmental awareness and resilience, leading to more inclusive and equitable outcomes (Paton and Buergelt, 2019). For example, in a study on climate change adaptation in France, a transdisciplinary approach was used to integrate scientific research with local knowledge through active stakeholder engagement, including policymakers, land managers and community members. This approach fostered a comprehensive understanding of climate challenges, resulting in a dynamic adaptation framework tailored to local needs. The outcome was a robust, adaptable model that addressed immediate environmental issues and provided a scalable solution for other mountain areas facing similar climate challenges (Tschanz et al., 2022). In another example, the Future Resilience for African CiTies And Lands (FRACTAL) project worked in several African countries using a transdisciplinary approach to better understand climate processes and the complex decision-making in governments and local communities through the use of Learning Labs, as highlighted in Box 1.

A transdisciplinary approach can also enhance trust in various actors and institutions and empower the use of weather, climate, water and related environmental and social sciences, and diverse knowledge, data and information to implement solutions for climate action across scales. For example, by embracing a transdisciplinary approach and engaging with diverse actors, NMHSs can build trust as authoritative voices on weather, climate and water. Considering diverse knowledge and perspectives outside of formal science can also strengthen these institutions and enhance their ability to provide crucial scientific information and services that underpin national climate and disaster risk reduction priorities and contribute to global goals, such as the Paris Agreement and Sendai Framework for Disaster Risk Reduction. Additionally, a transdisciplinary approach empowers actors across various contexts to collaborate and implement potential science-based solutions that may be informed by and resonate with local realities. As a result, climate action, sustainable development and disaster risk reduction initiatives are more effective, leading to stronger, more resilient communities in the face of evolving global challenges (Ismail-Zadeh et al., 2017).

Box 1. FRACTAL: a transdisciplinary approach in action

Through engagement with different actors, the Future Resilience for African CiTies And Lands (FRACTAL) project created opportunities for collaboration, revealed cultural and institutional insights and enhanced climate resilience, including in the urban and water sectors (Taylor et al., 2021; McClure et al., 2023). One element of this project was the establishment of Learning Labs, which involved engaging with various knowledge holders to identify and explore critical issues, such as how climate science can be better informed by various actors and shared more easily (Jack et al., 2021). For instance, instead of risk information being data and science heavy, a narrative approach that explains plausible scenarios supported with scientific, local and socioeconomic evidence proved to be more effective. As a result, various actors and decision makers across scales engaged with, questioned and co-produced the climate science information they needed in their context. The FRACTAL City Learning Lab approach emphasizes the co-production of knowledge and has significant benefits, allowing for a detailed examination of critical issues, strengthening actor relationships through a collaborative process and facilitating shared problem-solving (Koele et al., 2019). Additionally, it has demonstrated effectiveness through success stories in Lusaka, Windhoek and Maputo. In the case of the Lusaka, the FRACTAL process and engagements were taken up in the city's strategic planning, while in Maputo, the local municipality began working on a resilience hub, and Windhoek used the approach to assist in planning its Integrated Climate Change Strategy and Action (Vincent et al., 2021).

climate
better understand southern Africa's climate, its drivers and systematic impacts on city-regions

multiple scales
explore connections between climate sensitivities and decision-making at urban, national and regional scales

governance
better understand decision-making in southern African city-regions on water, energy, food and climate issues

learning labs
multi-stakeholder learning processes to co-explore and co-produce knowledge on climate-sensitive 'burning issues'

city regions
fostering context – relevant yet transferable learning within and between 9 city-regions, to varying degrees

city learning
ongoing and iterative learning processes (including learning labs) and dialogues that drive the co-production of relevant climate knowledge

Figure 2. The FRACTAL approach to research is transdisciplinary, leading to useful outcomes that have a measureable impact.
Source: **FRACTAL project**

Figure 2. Numerous challenges limit the full use, effectiveness and potential of transdisciplinarity. *Source:* Irasema Alcántara

Gaps and challenges

Transdisciplinarity is an approach that holds huge potential to boost the impact of science, knowledge and understanding in support of actionable solutions. However, significant gaps and challenges (Figure 2) continue to limit the full use and effectiveness of this approach, particularly in the fields of weather, climate, water and related environmental and social sciences, which have traditionally remained siloed from other forms of knowledge, perspectives and disciplines, such as economic and political sciences. One particular challenge is that transdisciplinary is often misunderstood and confused with terms like interdisciplinary and multidisciplinary. This leads to inconsistent implementation of transdisciplinary approaches in practice across the science–policy–society interface. Additionally, gaps in transdisciplinarity-focused education, training and capacity building limit the understanding and effectiveness of this approach.

Practical implementation of a transdisciplinary approach is also challenging and time consuming. Collaboration and communication with various actors are essential in effectively integrating perspectives, co-creating knowledge and implementing solutions. In the science community, institutional barriers and academic structures around disciplines hinder collaboration and funding that span disciplinary boundaries. Additionally, cultural and social norms pose challenges to effective collaboration and communication across diverse actors, systems of knowledge and disciplines, requiring significant time and resources to build trust and challenge power dynamics among the various actors engaged.

Finally, ensuring the sustainability and legacy of transdisciplinary endeavours remains a persistent challenge, necessitating long-term engagement and comprehensive assessment frameworks to effectively evaluate societal impacts and outcomes (Pohl and Hirsch Hadorn, 2008; Pohl, 2011). Additionally, significant resources are needed to scale up successful initiatives in order to apply them in diverse contexts. Overcoming these multifaceted challenges is crucial for advancing transdisciplinary approaches to address complex societal and environmental issues now and in the future.

Looking ahead: a transdisciplinary path forward

Solving complex global challenges, such as climate change, disaster risk reduction and sustainable development, will require inclusive collaboration across diverse systems of knowledge to co-create sustainable solutions and help communities thrive (Matsumoto et al., 2022). Transdisciplinary approaches, particularly when applied across weather, climate, water and related environmental and social sciences, can enhance the coherence and impact of international agendas focused on disaster risk reduction, climate change and sustainable development (Bendito and Barrios, 2016). However, moving forward, governance, partnerships, education and training must be enhanced to improve the effectiveness of transdisciplinary approaches that embrace diverse ways of knowing and valuing the world.

Strong governance and institutions at all levels are crucial for creating enabling environments that foster transdisciplinarity. Support through funding and policy frameworks can strengthen transdisciplinary research and practice while also building a culture of trust and respect that will foster collaboration across actors and institutions. For example, research funding programmes implemented by the International Science Council, including **Transformations to Sustainability** and **Leading Integrated Research for Agenda 2030 in Africa**, provide important insights and lessons learned on advancing transdisciplinary approaches and creating enabling environments (ISC, 2023; Paulavets et al., 2023; Moser, 2024; Mukute et al., 2024). Additionally, fostering formal partnerships and global networks between governments, universities and civil society organizations, among other interested actors, will drive innovation, foster knowledge exchange, facilitate access to resources and accelerate the dissemination of best practices (Bharwani et al., 2023). Finally, moving forward, it will be crucial to prepare the next generation to address the challenges of the future. Transdisciplinary education and training should be embraced and encouraged along with hands-on learning opportunities and mentorship programmes to provide practical skills to foster a community of transdisciplinary thinkers across the science–policy–society interface.


Photo: Ade Bayu Indra

CHAPTER 6

A future where everyone is protected by life-saving early warning systems

Advancements in natural and social sciences, technological breakthroughs and transdisciplinary approaches, alongside robust partnerships, adequate resources and enhanced capacities, underpin effective multi-hazard early warning systems and support the Early Warnings for All initiative.

Authors: Daniela Cuéllar Vargas (WMO), Salla Himberg (IFRC), Vanessa Gray (ITU), Rosie McDonald (ITU), Amélie Grangeat (ITU)

Key messages

- **Countries with limited to moderate multi-hazard early warning system (MHEWS) coverage have a disaster-related mortality ratio nearly six times higher than those with substantial to comprehensive coverage.**
- **Innovation in science, technology and tools such as artificial intelligence (AI), multi-channel and digital communication platforms, and citizen science enable game-changing advancements to support the Early Warnings for All (EW4All) initiative.**
- **Leveraging innovation across the natural and social sciences, alongside robust partnerships, adequate resources and enhanced capacities can help achieve EW4All and safeguard sustainable development gains.**

Introduction

Multi-hazard early warning systems (MHEWS) are critical for mitigating the adverse effects of hazardous weather events, which are becoming more frequent and severe, in part due to climate change. The Early Warnings for All (EW4All) initiative is a groundbreaking effort launched by the United Nations Secretary-General that aims to ensure everyone on Earth is protected from hazardous weather, water or climate events through life-saving early warning systems by the end of 2027. EW4All supports national efforts on adaptation, minimizing losses and damages, and building resilience. Additionally, as part of the United Nations Secretary-General's Climate Action Acceleration Agenda, the initiative contributes to delivering climate justice to those at the frontlines of climate change and aligns with global goals, including the Paris Agreement, the Sendai Framework for Disaster Risk Reduction and the 2030 Agenda for Sustainable Development.

As highlighted throughout this report, natural and social sciences, technological advances and transdisciplinary approaches underpin effective MHEWS. Advancements in AI, space-based Earth observations and immersive technologies can contribute to this critical initiative by advancing weather forecasting, contextualizing and communicating complex information for decision-making and creating interactive, educational simulations to visualize different hazard scenarios and potential impacts to support anticipatory action. Additionally, transdisciplinary approaches that embrace diverse perspectives, knowledge and experiences, including participatory methods such as citizen science, can enhance the effectiveness of MHEWS through the co-development of knowledge and solutions that are relevant to local contexts.

Hence, EW4All exemplifies how integrating global efforts can transform a collection of disparate parts into a cohesive and comprehensive system while also fostering innovation to protect lives, livelihoods and the environment from the increasing threats posed by natural hazards

The urgent need for global multi-hazard early warning systems

Countries across the world are already feeling the impacts of climate change, underscoring the urgent need to close critical gaps in MHEWS to protect lives, livelihoods and the environment. Evidence shows that countries with limited to moderate MHEWS coverage have a disaster-related mortality ratio nearly six times higher than those with substantial to comprehensive coverage.

Progress has been made in enhancing country capacities and coverage of MHEWS, with more than half of the world's countries now reporting having MHEWS. According to the report on the *Global Status of Multi-Hazard Early Warning Systems* (WMO and UNDRR, 2023), 101 countries, or 52% of all countries globally, have reported the existence of MHEWS – an increase from the 2022 report and a doubling from the 2015 baseline (Figure 1). In particular, Arab States and countries in Asia and the Pacific, Europe and Central Asia have reported a significant increase in MHEWS coverage. However, while there has been progress across many regions, some still face significant gaps in coverage, including in Africa, the Americas and the Caribbean. Additionally, progress in least developed countries (LDCs) and small island developing States (SIDS) remains low, with less than 50% reporting MHEWS coverage.

Game changing science, technology and innovation for Early Warnings for All

End-to-end, people-centred MHEWS are built around four interconnected pillars that create a value cycle as shown in Figure 2. Science, technology and innovation underpin all pillars of an end-to-end MHEWS, from informing disaster risk knowledge to advancing observations, monitoring, analysis and forecasting, and enabling warning dissemination and anticipatory action. For example, satellite imagery and AI can aid in collating and standardizing data, while multi-channel and digital communication platforms provide effective dissemination of warnings. In particular, natural and social sciences and technological breakthroughs can provide game-changing advancements to support the EW4All initiative in several key areas, including strategic risk communication, impact-based forecasting and warning, Common Alerting Protocol (CAP) and anticipatory action, as highlighted in Figure 3.

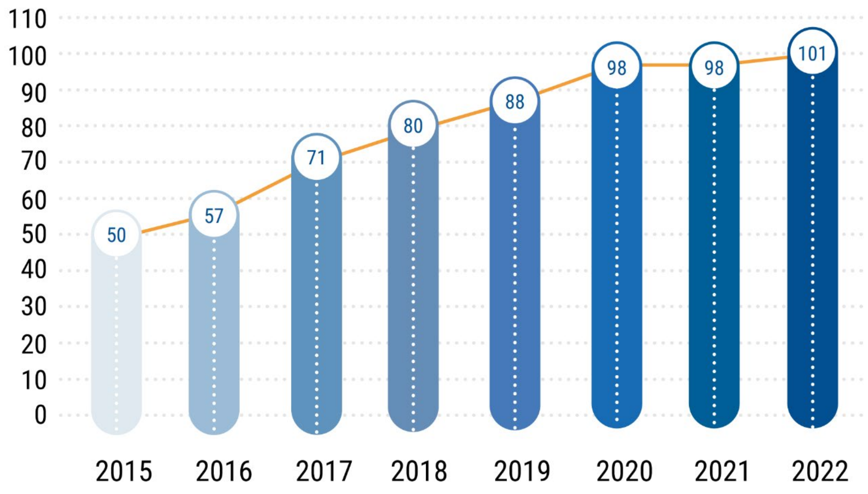


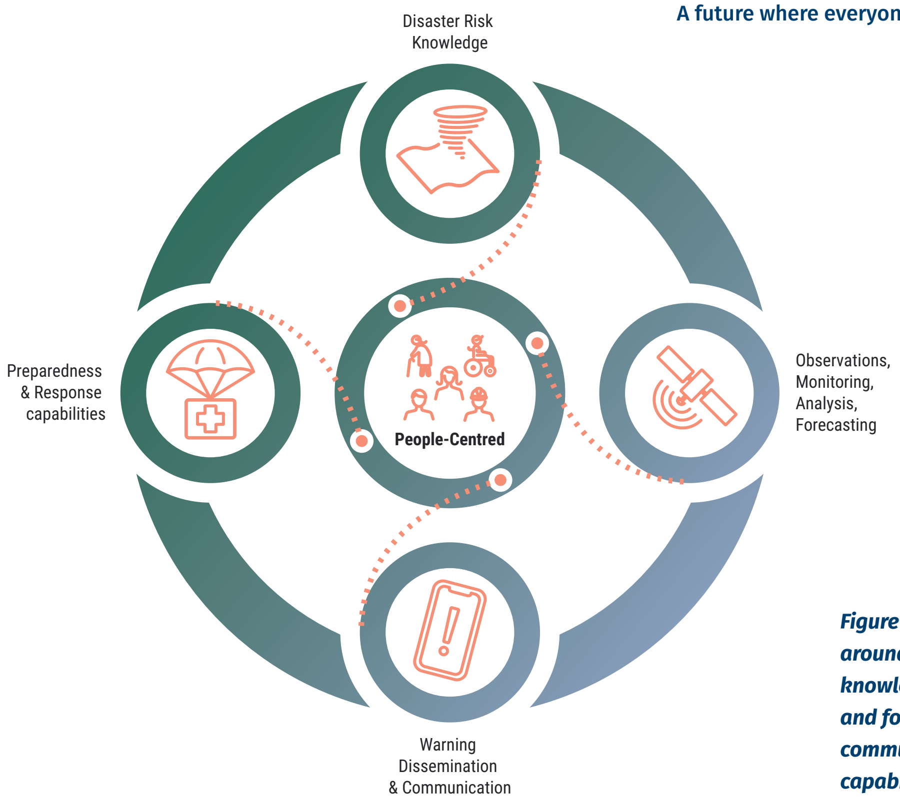
Figure 1. Cumulative number of countries reporting the existence of MHEWS.
Source: WMO and UNDRR, 2023

Strategic risk communication requires collecting, aggregating, processing and distilling information on vulnerability, hazards and exposure. This information must be timely, accurate, understandable and conducive to action. Technological tools such as data aggregation platforms (that is, geographic information systems (GIS)) enable the visualization of data. Additionally, immersive technologies such as virtual reality are enhancing disaster risk knowledge and strategic risk communication by helping actors understand flood risk concepts, which can be difficult to grasp for those who have not experienced a flood event firsthand. Rapid advances in AI and ML can be used to process large volumes of raw satellite imagery to create standardized baseline data on exposure, such as data on built-up areas and population. For example, ML-based mapping was used in Belize to provide updated estimates of the status of the country's major coastal and marine ecosystems. This not only provided key insights for improving risk knowledge, but also informed the National Adaptation Plan of Belize (GEO, 2023).

Impact-based forecasting and warning integrates traditional forecasting of physical hydrometeorological hazards and understanding of societal exposure and vulnerability to those hazards to inform decision-making and enable action to reduce impacts to society and ensure sustainable development (Golding, 2022). Scientific and technological advances, including AI and space-based Earth observations, have revolutionized weather models, improving their resolution, accuracy and relevance. For example, in Indonesia, the meteorological and disaster management agencies jointly developed a system called Signature with various models for weather prediction and analysis to produce and calibrate impact-based forecasts for different hydrometeorological hazards (BMKG, 2024). Additionally, surface-based weather and climate observations are crucial to continuously monitor weather conditions and provide historical and real-time data to inform impact-based forecasting. In Uganda, for example, ground observation data, as well as satellite-based data, were used to analyze historical drought-induced crop failures, which enabled the government to establish a predetermined hazard threshold value to trigger disaster risk finance for anticipatory action (Nakalembe and Kotani, 2022).

CAP was developed to standardize alert communications across diverse platforms and systems to ensure critical information is disseminated in a timely, accurate and consistent format. Technological advances such as multi-channel alert distribution have improved warning dissemination and communication by using multiple channels, such as cell broadcast, location-based SMS, email, social media and sirens. Using multiple channels ensures that alerts reach diverse audiences and cater to their specific needs. Additionally, interoperable communication platforms can facilitate seamless communication between different systems and agencies, such as national hydrometeorological and emergency response agencies. Regardless of the technologies used, it is crucial for alerting systems to be unified and adhere to CAP for standardized communication.

Anticipatory action is defined as a set of actions taken to prevent or mitigate potential disaster impacts before a shock or before acute impacts are felt (IFRC, 2022). These actions are based on risk knowledge, forecast-based triggers and effective warning dissemination and communication in relation to the specific hazard at hand across institutions and individuals. Scenario analysis uses tools, such as GIS or virtual reality, to simulate and visualize different hazard scenarios and their potential impacts, aiding in planning and decision-making for anticipatory action. Another tool that can support anticipatory action is citizen science, which is a transdisciplinary participatory engagement method that involves diverse actors in the co-production of knowledge and implementation of anticipatory solutions in local contexts. An example is the use of mobile apps that allow citizens to report early signs of hazards (such as rising water levels or weather patterns), providing real-time data to authorities. Additionally, data platforms that allow community members to contribute local observations and knowledge can be leveraged to enrich official datasets, which underpin anticipatory action.



A future where everyone is protected by life-saving early warning systems

Figure 2. A people-centred, end-to-end MHEWS is built around four interconnected pillars: (1) disaster risk knowledge, (2) observations, monitoring, analysis and forecasting, (3) warning dissemination and communication, and (4) preparedness and response capabilities.

→ Strategic risk communication

Citizen reporting tools: Develop mobile apps that allow citizens to report early signs of hazards, such as rising water levels and unusual weather patterns, and provide real-time data to authorities.

AI and ML: Employ AI to process large datasets and distill them into actionable insights.

→ Impact-based forecasting and warning

Advanced weather modelling: Implement high-resolution weather models that incorporate hazard, vulnerability and exposure data.

AI predictive analytics: Use AI-driven predictive analytics to improve the accuracy and relevance of forecasts.

Remote sensing: Employ satellite imagery and remote sensing technology to monitor and predict environmental changes and hazards.

Automated weather stations: Deploy automated stations in remote areas to continuously monitor weather conditions and provide data for anticipatory actions.

→ Common Alerting Protocol

Unified alerting systems: Develop systems that adhere to the Common Alerting Protocol (CAP) for standardized communication.

Multi-channel alert distribution: Use multiple channels (cell-broadcast, SMS, email, social media, sirens) to ensure alerts reach diverse actors.

Interoperable communication platforms: Implement platforms that facilitate seamless communication between different agencies and systems.

→ Anticipatory action

Citizen reporting tools: Use mobile apps that allow citizens to report early signs of hazards (for example, rising water levels, unusual weather patterns), providing real-time data to authorities.

Community-based data collection: Leverage platforms where community members can contribute local observations and experiences to enrich official datasets.

Scenario analysis: Use GIS tools to simulate and visualize different hazard scenarios and their potential impacts, aiding in planning and decision-making.

Figure 3. Key areas where natural and social sciences and technological breakthroughs can provide game-changing advancements to support the EW4All initiative.

Box 1. **Leveraging artificial intelligence for disaster connectivity mapping**

The International Telecommunication Union (ITU) is spearheading the development of an AI-powered advanced visualization tool that will improve the assessment of subnational connectivity levels during and after disasters, facilitating more effective communication in high-risk areas. Launched in 2020 with the United Nations Emergency Telecommunications Cluster and the GSM Association (GSMA), the Disaster Connectivity Map has been activated over 50 times in more than 30 countries, aiding first responders, United Nations agencies and governments by providing near real-time information on communication network status (ITU, 2024a). The tool utilizes AI to rapidly analyze satellite imagery and generate high-resolution, time-enabled population density maps. It also processes and visualizes connectivity data, offering both historical baselines and real-time performance maps. The tool plays a key role supporting EW4All by identifying gaps in telecommunication coverage and assessing which messaging channels (fixed broadband, 2G SMS, 3G+, etc.) are available for disseminating early warning notifications. By quantifying the offline population – those unable to receive emergency alerts due to lack of network coverage – the tool helps determine the reach and effectiveness of early warning systems before and after disasters. Initial piloting is underway in Fiji, Tonga and Vanuatu, with plans to expand to additional countries involved in EW4All to enhance disaster response and connectivity resilience globally (ITU, 2024b).

Gaps and challenges

Despite advances in science and technology and the incredible potential of MHEWS to save lives, minimize losses and damages and safeguard sustainable development gains, gaps and challenges hinder the full achievement of comprehensive MHEWS. For example, a significant barrier is insufficient disaster risk information, including information on historical losses and damages and on trends in hazardous events, and predictive capacity for hazards. There is an urgent need to improve risk knowledge across the world, especially in the Arab States and in LDCs to improve the effectiveness of MHEWS. Additionally, significant data gaps remain, resulting in inadequate observation, monitoring and forecasting. Surface and upper air meteorological observation data are an essential input to computer models predicting the future state of the atmosphere, which NMHSs rely on to forecast the location, intensity and likelihood of high-impact weather events. Significant gaps in these essential data persist, however, across much of the African continent and parts of the Pacific (WMO and UNDRR, 2023).

Despite advances in science and technology, especially connectivity technology, some communities and populations remain difficult to reach and support. Limited communication channels can present barriers in effectively reaching remote communities as well as vulnerable populations such as women, children, older persons and persons living with disabilities. Additionally, gaps in technical resources, human capacities and sustainable funding present challenges across all levels – from developing forecasting products to enabling anticipatory action and providing ad hoc funding to ensure community leaders have sufficient credit or data on their mobile phones to receive warnings by SMS or Internet (WMO and UNDRR, 2023).

Looking ahead: leveraging innovation for Early Warnings for All

Addressing the gaps and challenges in MHEWS requires a multifaceted approach that leverages innovation across the natural and social sciences, alongside robust partnerships, adequate resources and enhanced capacities. Enhanced data collection and monitoring through advanced sensor networks, space-based Earth observations and the Internet of Things (IoT) can improve weather forecasting of extreme and hazardous events.

Additionally, risk knowledge is also improved through technology, with increasing opportunities for local actors to collect information from remote locations using drones and smartphone applications and quickly share it over mobile Internet. There are significant opportunities to leverage advances in science, technology and innovation for warning communication and dissemination, especially in terms of mobile networks and Internet connectivity, to reach remote and vulnerable communities. Additionally, fostering public understanding through educational campaigns, strengthening technical resources via capacity-building initiatives and employing cutting-edge technologies such as AI will create a more resilient and responsive system (WMO and UNDRR, 2023).

Achieving these advancements necessitates strong public–private partnerships that bring together diverse actors, including governments, non-governmental organizations, private-sector entities, scientists and local communities. Adequate funding and investment are essential to support the development and maintenance of these systems, while capacity-building efforts are needed to ensure that all regions, particularly those most vulnerable, have the technical skills and infrastructure to implement and sustain MHEWS. The EW4All initiative exemplifies how integrating global efforts can transform disparate parts into a cohesive and comprehensive system and foster innovation to protect lives, livelihoods and the environment from the increasing threats posed by natural hazards.

Appendix

Data sets

Global temperature data sets

Berkeley Earth: Rohde, R. A.; Hausfather, Z. The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data* **2020**, *12*, 3469–3479. https://doi.org/10.5194/essd-12-3469-2020.

ERA5: Hersbach, H.; Bell, B.; Berrisford, P. et al. *ERA5 Monthly Averaged Data on Single Levels from 1940 to Present*; Copernicus Climate Change Service (C3S) Climate Data Store (CDS), **2023**. https://doi.org/10.24381/cds.f17050d7.

GISTEMP: GISTEMP Team, 2022: *GISS Surface Temperature Analysis (GISTEMP), version 4*. NASA Goddard Institute for Space Studies, https://data.giss.nasa.gov/gistemp/. Lenssen, N.; Schmidt, G.; Hansen, J. et al. Improvements in the GISTEMP Uncertainty Model. *Journal of Geophysical Research: Atmospheres* **2019**, *124*, 6307–6326. https://doi.org/10.1029/2018JD029522.

HadCRUT5: Morice, C. P.; Kennedy, J. J.; Rayner, N. A. et al. An Updated Assessment of Near-surface Temperature Change From 1850: The HadCRUT5 Data Set. *Journal of Geophysical Research: Atmospheres* **2021**, *126*, e2019JD032361. https://doi.org/10.1029/2019JD032361. HadCRUT.5.0.1.0 data were obtained from http://www.metoffice.gov.uk/hadobs/hadcrut5 on 1 March 2023 and are © British Crown Copyright, Met Office 2024, provided under an Open Government Licence, http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

JRA-3Q: Kosaka, Y.; Kobayashi, S.; Harada, Y. et al. The JRA-3Q Reanalysis. *Journal of the Meteorological Society of Japan. Ser. II* **2024**, *102* (1), 49–109. https://doi.org/10.2151/jmsj.2024-004.

NOAAGlobalTemp v6.0: Huang, B.; Yin, X.; Menne, M. J. et al. Improvements to the Land Surface Air Temperature Reconstruction in NOAAGlobalTemp: An Artificial Neural Network Approach. *Artificial Intelligence for the Earth Systems* **2022**, 1, e220032. https://doi.org/10.1175/AIES-D-22-0032.1. Huang, B.; Yin, X.; Menne, M. J. et al. *NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 6.0.0* [Global Mean]. NOAA National Centers for Environmental Information. https://doi.org/10.25921/rzxg-p717.

Ocean heat content data sets

Cheng, L.; Trenberth, K. E.; Fasullo, J. et al. Improved Estimates of Ocean Heat Content from 1960 to 2015. *Science Advances* **2017**, *3*, e1601545. https://doi.org/10.1126/sciadv.1601545.

Church, J. A.; White, N. J.; Konikow, L. F. et al. Revisiting the Earth's Sea-level and Energy Budgets from 1961 to 2008. *Geophysical Research Letters* **2011**, *38*. https://doi.org/10.1029/2011GL048794.

Desbruyères, D. G.; Purkey, S. G.; McDonagh, E. L. et al. Deep and Abyssal Ocean Warming from 35 Years of Repeat Hydrography. *Geophysical Research Letters* **2016**, *43*, 310–356. https://doi.org/10.1002/2016GL070413.

Desbruyères, D.; McDonagh, E. L.; King, B. A. et al. Global and Full-Depth Ocean Temperature Trends during the Early Twenty-First Century from Argo and Repeat Hydrography. *Journal of Climate* **2017**, *30*, 1985–1997. https://doi.org/10.1175/JCLI-D-16-0396.1.

Domingues, C. M.; Church, J. A.; White, N. J. et al. Improved Estimates of Upper-ocean Warming and Multi-decadal Sea-level Rise. *Nature* **2008**, *453*, 1090–1093. https://doi.org/10.1038/nature07080.

Gaillard, F.; Reynaud, T.; Thierry, V. et al. In Situ-based Reanalysis of the Global Ocean Temperature and Salinity with ISAS: Variability of the Heat Content and Steric Height. *Journal of Climate* **2016**, *29*, 1305–1323. https://doi.org/10.1175/JCLI-D-15-0028.1.

Good, S. A.; Martin, M. J.; Rayner, N. A. EN4: Quality Controlled Ocean Temperature and Salinity Profiles and Monthly Objective Analyses with Uncertainty Estimates. *Journal of Geophysical Research: Oceans* **2013**, *118*, 6704–6716. https://doi.org/10.1002/2013JC009067.

Hosoda, S.; Ohira, T.; Nakamura, T. A Monthly Mean Dataset of Global Oceanic Temperature and Salinity Derived from Argo Float Observations. *JAMSTEC Report of Research and Development* **2008**, *8*, 47–59. https://www.jstage.jst.go.jp/article/jamstecr/8/0/8_0_47/_article.

Ishii, M.; Fukuda, Y.; Hirahara, S. et al. Accuracy of Global Upper Ocean Heat Content Estimation Expected from Present Observational Data Sets. *SOLA* **2017**, *13*, 163–167. https://doi.org/10.2151/sola.2017-030.

Kuusela M.; Stein, M. L. Locally Stationary Spatio-temporal Interpolation of Argo Profiling Float Data. *Proceedings of the Royal Society A* **2018**, *474*, 20180400. http://dx.doi.org/10.1098/rspa.2018.0400.

Kuusela, M.; Giglio, D. Global Ocean Heat Content Anomalies based on Argo Data (2.0.0). *Zenodo* **2023**. https://doi.org/10.5281/zenodo.7562281.

Levitus, S.; Antonov, J. I.; Boyer, T. P. et al. World Ocean Heat Content and Thermosteric Sea Level Change (0-2 000 m) 1955–2010. *Geophysical Research Letters* **2012**, *39*, L10603. https://doi.org/10.1029/2012GL051106.

Li, H.; Xu, F.; Zhou, W. et al. Development of a Global Gridded Argo Data Set with Barnes Successive Corrections. *Journal of Geophysical Research: Oceans* **2017**, *122*, 866–889. https://doi.org/10.1002/2016JC012285.

Li, Y.; Church, J. A.; McDougall, T. J. et al. Sensitivity of Observationally Based Estimates of Ocean Heat Content and Thermal Expansion to Vertical Interpolation Schemes. *Geophysical Research Letters* **2022**, *49*, e2022G. https://doi.org/10.1029/2022GL101079.

Lyman, J. M.; Johnson, G. C. Estimating Global Ocean Heat Content Changes in the Upper 1800 m since 1950 and the Influence of Climatology Choice. *Journal of Climate* **2014**, *27*, 1945–1957. https://doi.org/10.1175/JCLI-D-12-00752.1.

Minière, A.; von Schuckmann, K.; Sallée, J.-B. et al. Robust Acceleration of Earth System Heating Observed over the Past Six Decades. *Sci Rep* **2023**, *13* (1), 22975. https://doi.org/10.1038/s41598-023-49353-1.

Roemmich, D.; Gilson, J. The 2004–2008 Mean and Annual Cycle of Temperature, Salinity, and Steric Height in the Global Ocean from the Argo Program. *Progress in Oceanography* **2009**, *82*, 81–100. https://doi.org/10.1016/j.pocean.2009.03.004.

Roemmich, D.; Church, J.; Gilson, J. et al. Unabated Planetary Warming and its Ocean Structure Since 2006. *Nature Climate Change* **2015**, *5*, 240. https://doi.org/10.1038/nclimate2513.

von Schuckmann, K.; Le Traon, P.-Y. How Well Can We Derive Global Ocean Indicators from Argo Data? *Ocean Science* **2011**, *7*, 783–791. https://doi.org/10.5194/os-7-783-2011. Data available at: https://marine.copernicus.eu/access-data/ocean-monitoring-indicators.

Wijffels, S.; Roemmich, D.; Monselesan, D., et al. Ocean Temperatures Chronicle the Ongoing Warming of Earth. *Nature Climate Change* **2016**, *6*, 116–118. https://doi.org/10.1038/nclimate2924.

Sea ice data sets

EUMETSAT Ocean and Sea Ice Satellite Application Facility, Sea-ice Index 1979-Onwards (v2.1, 2020), OSI-420, Data Extracted from OSI SAF FTP Server: 1979–2020, Northern and Southern Hemisphere.

Fetterer, F.; Knowles, K.; Meier, W. N. et al., 2017, updated daily. Sea Ice Index, Version 3. Boulder, Colorado, USA. National Snow and Ice Data Center (NSIDC), https://nsidc.org/data/G02135/versions/3.

Lavergne, T. Sørensen, A. M.; Kern, S. et al. Version 2 of the EUMETSAT OSI SAF and ESA CCI Sea Ice Concentration Climate Data Records. *The Cryosphere* **2019**, *13* (1), 49–78. https://doi.org/10.5194/tc-13-49-2019.

REFERENCES

State of climate science: the need for urgent and ambitious climate action

Canadell, J. G.; Poulter, B.; Bastos, A. et al. Chapter 1 – Balancing Greenhouse Gas Sources and Sinks: Inventories, Budgets, and Climate Policy. In *Balancing Greenhouse Gas Budgets*; Poulter, B., Canadell, J. G., Hayes, D. J., Thompson, R. L., Eds.; Elsevier, 2022; 3–28. https://doi.org/10.1016/B978-0-12-814952-2.00024-1.

Cheng, L.; Trenberth, K. E.; Fasullo, J. et al. Improved Estimates of Ocean Heat Content from 1960 to 2015. *Science Advances* **2017**, *3* (3), e1601545. https://doi.org/10.1126/sciadv.1601545.

Clarke, B.; Barnes, C.; Rodrigues, R. et al. *Climate Change, El Niño and Infrastructure Failures behind Massive Floods in Southern Brazil*; 2024. https://doi.org/10.25561/111882.

Ernst, Y.; Archibald, S.; Balzter, H. et al. The African Regional Greenhouse Gases Budget (2010–2019). *Global Biogeochemical Cycles* **2024**, *38* (4), e2023GB008016. https://doi.org/10.1029/2023GB008016.

Friedlingstein, P.; O'Sullivan, M.; Jones, M. W. et al. Global Carbon Budget 2023. *Earth System Science Data* **2023**, *15* (12), 5301–5369. https://doi.org/10.5194/essd-15-5301-2023.

Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O.; Roberts, D. C.; Masson-Delmotte, V. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2019. https://www.ipcc.ch/srocc/.

Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team; Lee, H.; Romero, J., Eds.; IPCC, Geneva, 2023. https://www.ipcc.ch/report/ar6/syr/.

Kimutai, J.; Zachariah, M.; Nhantumbo, B. et al. El Niño Key Driver of Drought in Highly Vulnerable Southern African Countries; Imperial College London, 2024. https://doi.org/10.25561/110770.

Purich, A.; Doddridge, E. W. Record Low Antarctic Sea Ice Coverage Indicates a New Sea Ice State. *Communications Earth and Environment* **2023**, 4 (1), 1–9. https://doi.org/10.1038/s43247-023-00961-9.

Saunois, M.; Martinez, A.; Poulter, B. et al. Global Methane Budget 2000–2020. *Earth System Science Data Discussions* **2024**, 1–147. https://doi.org/10.5194/essd-2024-115.

Thiem, H. *Category 5 Hurricane Beryl Makes Explosive Start to 2024 Atlantic Season*; National Oceanic and Atmospheric Administration (NOAA) Climate.gov, 2024. https://www.climate.gov/news-features/event-tracker/category-5-hurricane-beryl-makes-explosive-start-2024-atlantic-season.

Tian, H.; Pan, N.; Thompson, R. L. et al. Global Nitrous Oxide Budget 1980–2020. *Earth System Science Data* **2024**, *16* (6), 2543–2604. https://doi.org/10.5194/essd-16-2543-2024.

Trewin, B.; Cazenave, A.; Howell, S. et al. Headline Indicators for Global Climate Monitoring. *Bulletin of the American Meteorological Society* **2021**, *101* (1), E20–E37. https://doi.org/10.1175/BAMS-D-19-0196.1.

United Nations Environment Programme (UNEP). *Emissions Gap Report 2023: Broken Record – Temperatures Hit New Highs, Yet World Fails to Cut Emissions (Again)*; UNEP: Nairobi, 2023a. https://www.unep.org/resources/emissions-gap-report-2023.

United Nations Environment Programme (UNEP). *Adaptation Gap Report 2023: Underfinanced. Underprepared. Inadequate Investment and Planning on Climate Adaptation Leaves World Exposed*; UNEP: Nairobi, 2023b. https://www.unep.org/resources/adaptation-gap-report-2023.

United Nations Office for the Coordination of Humanitarian Affairs (OCHA). *Brazil: Floods in Rio Grande do Sul – United Nations Situation Report, as of 12 July 2024*; Reliefweb, 2024. *https://reliefweb.int/report/brazil/brazil-floods-rio-grande-do-sul-united-nations-situation-report-12-july-2024*.

Villalobos, Y.; Canadell, J. G.; Keller, E. D. et al. A Comprehensive Assessment of Anthropogenic and Natural Sources and Sinks of Australasia's Carbon Budget. *Global Biogeochemical Cycles* **2023**, *37* (12), e2023GB007845. https://doi.org/10.1029/2023GB007845.

World Glacier Monitoring Service (WGMS). *Global Glacier Change Bulletin No. 5 (2020–2021)*; Zemp, M.; Gärtner-Roer, I.; Nussbaumer, S. U. et al., Eds. (based on database version: doi:10.5904/wgms-fog-2023-09); WGMS: Zurich, Switzerland, 2023. https://wgms.ch/downloads/WGMS_GGCB_05.pdf.

World Meteorological Organization (WMO). *WMO Greenhouse Gas Bulletin (GHG Bulletin), No. 19: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2022*; WMO: Geneva, 2023.

World Meteorological Organization (WMO). *Global Temperature Record Streak Continues, as Climate Change Makes Heatwaves More Extreme*; WMO: Geneva, 2024a. https://wmo.int/media/news/global-temperature-record-streak-continues-climate-change-makes-heatwaves-more-extreme.

World Meteorological Organization (WMO). *WMO Confirms that 2023 Smashes Global Temperature Record*; WMO: Geneva, 2024b. https://wmo.int/media/news/wmo-confirms-2023-smashes-global-temperature-record.

World Meteorological Organization (WMO). *WMO Global Annual to Decadal Climate Update – Target Years: 2024 and 2024–2028*; WMO: Geneva, 2024c.

REFERENCES

Artificial intelligence and machine learning: revolutionizing weather forecasting

Bi, K.; Xie, L.; Zhang, H. et al. Accurate Medium-Range Global Weather Forecasting with 3D Neural Networks. *Nature* **2023**, *619* (7970), 533–538. https://doi.org/10.1038/s41586-023-06185-3.

European Centre for Medium-Range Weather Forecasts (ECMWF). *Charts*; ECMWF, 2024. https://www.ecmwf.int/en/forecasts/charts.

Ghaffarian, S.; Taghikhah, F. R.; Maier, H. R. Explainable Artificial Intelligence in Disaster Risk Management: Achievements and Prospective Futures. *International Journal of Disaster Risk Reduction* **2023**, *98*, 104123. https://doi.org/10.1016/j.ijdrr.2023.104123.

Hakim, G. J.; Masanam, S. Dynamical Tests of a Deep Learning Weather Prediction Model. *Artificial Intelligence for the Earth Systems* **2024**, *3* (3). https://doi.org/10.1175/AIES-D-23-0090.1.

Ham, Y.-G.; Kim, J.-H.; Kim, E.-S. et al. Unified Deep Learning Model for El Niño/Southern Oscillation Forecasts by Incorporating Seasonality in Climate Data. *Science Bulletin* **2021**, *66* (13), 1358–1366. https://doi.org/10.1016/j.scib.2021.03.009.

Harder, P.; Watson-Parris, D.; Stier, P. et al. Physics-Informed Learning of Aerosol Microphysics. *Environmental Data Science* **2022**, *1*, e20. https://doi.org/10.1017/eds.2022.22.

Harris, L.; McRae, A. T. T.; Chantry, M. et al. A Generative Deep Learning Approach to Stochastic Downscaling of Precipitation Forecasts. *Journal of Advances in Modeling Earth Systems* **2022**, *14* (10), e2022MS003120. https://doi.org/10.1029/2022MS003120.

Hersbach, H.; Bell, B.; Berrisford, P. et al. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society* **2020**, *146* (730), 1999–2049. https://doi.org/10.1002/qj.3803.

Keisler, R. Forecasting Global Weather with Graph Neural Networks. *arXiv* **2022** [preprint]. https://doi.org/10.48550/arXiv.2202.07575.

Koldunov, N.; Jung, T. Local Climate Services for All, Courtesy of Large Language Models. *Communications Earth and Environment* **2024**, *5* (1), 1–4. https://doi.org/10.1038/s43247-023-01199-1.

Lam, R.; Sanchez-Gonzalez, A.; Willson, M. et al. Learning Skillful Medium-Range Global Weather Forecasting. *Science* **2023**, *382* (6677), 1416–1421. https://doi.org/10.1126/science.adi2336.

Lang, S.; Alexe, M.; Chantry, M. et al. AIFS – ECMWF's Data-Driven Forecasting System. *arXiv* **2024**. https://doi.org/10.48550/arXiv.2406.01465.

Mardani, M. ; Brenowitz, N. ; Cohen, Y. et al. Residual Diffusion Modeling for Km-scale Atmospheric Downscaling. *Nature Portfolio* **2024** [preprint]. https://doi.org/10.21203/rs.3.rs-3673869/v1.

McGovern, A.; Ebert-Uphoff, I.; Gagne, D. J. et al. Why We Need to Focus on Developing Ethical, Responsible, and Trustworthy Artificial Intelligence Approaches for Environmental Science. *Environmental Data Science* **2022**, *1* (6). https://doi.org/10.1017/eds.2022.5.

Nippen, T.; Chantry, M. *Data Driven Regional Modelling* (European Center for Medium-Range Weather Forecasts AIFS Blog); European Center for Medium-Range Weather Forecasts, *Artificial Intelligence for the Earth Systems* **2024**. https://www.ecmwf.int/en/about/media-centre/aifs-blog/2024/data-driven-regional-modelling.

Pathak, J.; Subramanian, S.; Harrington, P. et al. Fourcastnet: A Global Data-driven High-resolution Weather Model Using Adaptive Fourier Neural Operators. *arXiv* **2022** [preprint]. https://doi.org/10.48550/arXiv.2202.11214.

Patil, K. R.; Doi, T.; Jayanthi, V. R. et al. Deep Learning for Skillful Long-Lead ENSO Forecasts. *Frontiers in Climate* **2023**, *4*. https://doi.org/10.3389/fclim.2022.1058677.

Sha, Y.; Gagne II, D. J.; West, G. et al. Deep-Learning-Based Precipitation Observation Quality Control. *Journal of Atmospheric and Oceanic Technology* **2021**, *38* (5), 1075–1091. https://doi.org/10.1175/JTECH-D-20-0081.1.

Wang, C.; Pritchard, M.; Brenowitz, N. et al. Coupled Ocean-Atmosphere Dynamics in a Machine Learning Earth System Model. *arxiv* **2024**. https://arxiv.org/html/2406.08632v1.

Watt-Meyer, O.; Dresdner, G.; McGibbon, J. et al. ACE: A Fast, Skillful Learned Global Atmospheric Model for Climate Prediction. *arXiv* **2023** [preprint]. https://doi.org/10.48550/arXiv.2310.02074.

Woolnough, S. J.; Vitart, F.; Balmaseda, M. A. The Role of the Ocean in the Madden–Julian Oscillation: Implications for MJO Prediction. *Quarterly Journal of the Royal Meteorological Society* **2007**, *133* (622), 117–128. https://doi.org/10.1002/qj.4.

United Nations Advisory Body on Artificial Intelligence. *Interim Report: Governing AI for Humanity*. United Nations, **2023**. https://www.un.org/sites/un2.un.org/files/un_ai_advisory_body_governing_ai_for_humanity_interim_report.pdf.

Vellinga, M.; Copsey, D.; Graham, T. et al. Evaluating Benefits of Two-Way Ocean–Atmosphere Coupling for Global NWP Forecasts. *Weather and Forecasting* **2020**, *35* (5), 2127–2144. https://doi.org/10.1175/WAF-D-20-0035.1.

Space-based Earth observations: enhancing weather, climate, water and related environmental applications

Andries, A.; Morse, S.; Murphy, R. et al. Translation of Earth Observation Data into Sustainable Development Indicators: An Analytical Framework. *Sustainable Development* **2019**, *27* (3), 366–376. https://doi.org/10.1002/sd.1908.

Du, J.; Kimball, J. S.; Sheffield, J. et al. Satellite Flood Inundation Assessment and Forecast Using SMAP and Landsat. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **2021**, *14*, 6707–6715. https://doi.org/10.1109/JSTARS.2021.3092340.

Dube, T.; Shekede, M. D.; Massari, C. Remote Sensing for Water Resources and Environmental Management. *Remote Sensing* **2023**, *15* (1), 18. https://doi.org/10.3390/rs15010018.

Emery, W.; Camps, A. The History of Satellite Remote Sensing. In *Introduction to Satellite Remote Sensing*; Emery, W., Camps, A., Eds.; Elsevier, 2017; 1–42. https://doi.org/10.1016/B978-0-12-809254-5.00001-4.

European Space Agency (ESA). *Full Steam Ahead for Carbon Dioxide Monitoring Mission*. ESA, 2022. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Full_steam_ahead_for_carbon_dioxide_monitoring_mission.

Guo, H.-D.; Zhang, L.; Zhu, L.-W. Earth Observation Big Data for Climate Change Research. *Advances in Climate Change Research* **2015**, *6* (2), 108–117. https://doi.org/10.1016/j.accre.2015.09.007.

Hall, D. K. Assessment of Polar Climate Change Using Satellite Technology. *Reviews of Geophysics* **1988**, *26* (1), 26–39. https://doi.org/10.1029/RG026i001p00026.

Harris, R.; Baumann, I. Satellite Earth Observation and National Data Regulation. *Space Policy* **2021**, *56*, 101422. https://doi.org/10.1016/j.spacepol.2021.101422.

Hegglin, M. I.; Bastos, A.; Bovensmann, H. et al. Space-Based Earth Observation in Support of the UNFCCC Paris Agreement. *Frontiers in Environmental Science* **2022**, *10*. https://doi.org/10.3389/fenvs.2022.941490.

Lemmens, M. Earth Observation from Space. In *Geo-information: Technologies, Applications and the Environment*; Lemmens, M., Ed.; Springer Netherlands: Dordrecht, 2011; 171–196. https://doi.org/10.1007/978-94-007-1667-4_9.

Leyva-Mayorga, I.; Martinez-Gost, M.; Moretti, M. et al. Satellite Edge Computing for Real-Time and Very-High Resolution Earth Observation. *IEEE Transactions on Communications* **2023**, *71* (10), 6180–6194. https://doi.org/10.1109/TCOMM.2023.3296584.

MacPhail, D. Increasing the Use of Earth Observations in Developing Countries. *Space Policy* **2009**, *25* (1), 6–8. https://doi.org/10.1016/j.spacepol.2008.12.007.

Marbel, R.; Ben-Moshe, B.; Grinshpoun, T. Pico-Sat to Ground Control: Optimizing Download Link via Laser Communication. *Remote Sensing* **2022**, *14* (15), 3514. https://doi.org/10.3390/rs14153514.

Militino, A. F.; Ugarte, M. D.; Pérez-Goya, U. Improving the Quality of Satellite Imagery Based on Ground-Truth Data from Rain Gauge Stations. *Remote Sensing* **2018**, *10* (3), 398. https://doi.org/10.3390/rs10030398.

Neigh, C. S. R.; Carroll, M. L.; Montesano, P. M. et al. An API for Spaceborne Sub-Meter Resolution Products for Earth Science. In *IGARSS 2019–2019 IEEE International Geoscience and Remote Sensing Symposium*, Yokohama, Japan, 28 July–2 August 2019; Institute of Electrical and Electronics Engineers: 2019; 5397–5400. https://doi.org/10.1109/IGARSS.2019.8898358.

Salcedo-Sanz, S.; Ghamisi, P.; Piles, M. et al. Machine Learning Information Fusion in Earth Observation: A Comprehensive Review of Methods, Applications and Data Sources. *Information Fusion* **2020**, *63*, 256–272. https://doi.org/10.1016/j.inffus.2020.07.004.

Symonds, D. Protection for All: WISER-EWSA Aims to Transform Nowcasting and Early Warning Systems in Southern Africa, Particularly for the Most Vulnerable Communities. *Meteorological Technology International*, April 2023, 10–11. https://www.ukimediaevents.com/publication/8cf6eceb/12.

Schollaert Uz, S.; Ruane, A. C.; Duncan, B. N. et al. Earth Observations and Integrative Models in Support of Food and Water Security. *Remote Sensing in Earth Systems Sciences* **2019**, *2* (1), 18–38. https://doi.org/10.1007/s41976-019-0008-6.

Trewin, B.; Cazenave, A.; Howell, S. et al. Headline Indicators for Global Climate Monitoring. *Bulletin of the American Meteorological Society* **2021**, *101* (1), E20–E37. https://doi.org/10.1175/BAMS-D-19-0196.1.

United Nations Office for Outer Space Affairs (UNOOSA) and European Space Agency. *Updated UNOOSA and ESA Space Debris Infographics and Podcasts*. UNOOSA and ESA, 2023. https://www.unoosa.org/oosa/en/informationfor/media/unoosa-and-esa-release-infographics-and-podcasts-about-space-debris.html.

World Meteorological Organization (WMO). *Vision for WIGOS in 2040* (WMO-No. 1243). Geneva, 2019.

World Meteorological Organization (WMO): *20th Century*. WMO: Geneva, 2023. https://wmo.int/20th-century.

World Meteorological Organization (WMO). *United in Science 2023: Sustainable Development Edition*; WMO: Geneva, 2023.

World Meteorological Organization (WMO). *2023 State of Climate Services: Health* (WMO-No. 1335). Geneva, 2023.

Xing, J.; Yu, B.; Yang, D. et al. A Real-Time GNSS-R System for Monitoring Sea Surface Wind Speed and Significant Wave Height. *Sensors* **2022**, *22* (10), 3795. https://doi.org/10.3390/s22103795.

Yamamoto, H.; Kamei, A.; Nakamura, R. et al. Field Sensor Virtual Organization Integrated with Satellite Data on a Geo Grid. *Data Science Journal* **2010**, *8* (0). https://doi.org/10.2481/dsj.SS_IGY-015.

Bridging virtual and physical realms: leveraging digital twins and immersive technologies for land and water management

Alizadeh, B.; Sakib, M.; Behzadan, A. Immersive Virtual Reality to Measure Flood Risk Perception in Urban Environments. In *Proceedings of the 30th International Conference on Intelligent Computing in Engineering (EG-ICE)*, London, 4–7 July 2023; University College London: 2023, 103–112. https://www.ucl.ac.uk/bartlett/construction/sites/bartlett_construction/files/9014.pdf.

Allen, B. D. Digital Twins and Living Models at NASA. Paper presented at Digital Twin Summit, Online, 3–4 November 2021; National Aeronautics and Space Administration, 2021. https://ntrs.nasa.gov/api/citations/20210023699/downloads/ASME%20Digital%20Twin%20Summit%20Keynote_final.pdf.

Amarnath, G. Mitigating the Global Water Crisis: Digital Twin Earths Offer a Promising Solution. *Frontiers Policy Labs* **2024**. https://doi.org/10.25453/plabs.25981804.v1.

Botai, J. O.; Ghosh, S.; Matheswaran, K. et al. *Options for Digital Twin Application in Developing Country River Basin Management: A Review*; CGIAR Initiative on Digital Innovation. Colombo, Sri Lanka: International Water Management Institute (IWMI), 2023. https://cgspace.cgiar.org/items/f4977d8e-5c31-4e93-9f6b-1e6d45a39fb3.

REFERENCES

DGB Group. *The Decline of the Maya Civilisation: How Environmental Factors Played a Role in their Collapse*. DGB Group, 2023. https://www.green.earth/blog/the-decline-of-the-maya-civilisation-how-environmental-factors-played-a-role-in-their-collapse.

Fujs, T.; Kashiwase, H. *Strains on Freshwater Resources: The Impact of Food Production on Water Consumption*; World Bank Data Blog, World Bank: Washington, DC, 2023. https://blogs.worldbank.org/en/opendata/strains-freshwater-resources-impact-food-production-water-consumption.

Hsu, H. M.; Gourbesville, P. Introduction of Integrated Decision Support System for Flood Disaster Management. *IOP Conference Series: Earth and Environmental Science* **2023**, *1136*, 012019. https://iopscience.iop.org/article/10.1088/1755-1315/1136/1/012019.

Huth, N. I.; Adam, S.; Abbott, B. et al. *Putting Land Management Knowledge into Practice – Final Project Report*; Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2023. https://gisera.csiro.au/wp-content/uploads/2023/10/CSIRO-GISERA-final-report-L10-NT-Putting-land-management-knowledge-into-practice.pdf.

International Telecommunication Union (ITU). *UN Executive Briefing on Unlocking the Potential of Virtual Worlds and the Metaverse for the Sustainable Development Goals*. ITU: Geneva, 2024. https://www.itu.int/net/epub/TSB/2024-UN-Executive-Briefing-on-unlocking-potential/index.html#p=2.

International Telecommunication Union (ITU). *ITU Technical Specification: Definition of Metaverse*; Version 1.0. ITU: Geneva, 2023. https://www.itu.int/en/ITU-T/focusgroups/mv/Documents/List%20of%20FG-MV%20deliverables/FGMV-20.pdf.

International Telecommunication Union (ITU). *New UN Initiative to Reduce Disaster Risk with AI* [Press release]. 20 August 2024. https://www.itu.int/hub/2024/08/new-un-initiative-to-reduce-disaster-risk-with-ai/.

Jinendradasa, S. S. *Implications of Land and Water Degradation on Food Security; Comprehensive Assessment of Water Management in Agriculture*. CGIAR: Colombo, Sri Lanka, 2002. https://cgspace.cgiar.org/items/d49b242e-03da-4fa8-9dc9-a900673b0445.

Pacific Institute. *Water Conflict Chronology*. Pacific Institute: Oakland, USA, 2023. https://www.worldwater.org/water-conflict/.

Rantanen T. Tampere Metaverse: How New Technologies Can Help in Disasters. In *Episode #33: Disaster Risk Reduction in the Digital Transformation Age: Leveraging Emerging Technologies*; ITU Digital Transformation Webinar Series. International Telecommunication Union (ITU): Geneva, 2023. https://www.itu.int/cities/wp-content/uploads/2023/10/5-Teppo-Rantanen.pdf.

Roberts, B.; Atkins, P.; Simmons, I. People, *Land and Time: An Historical Introduction to the Relations Between Landscape, Culture and Environment*, 1st ed.; Routledge: Abingdon, UK, 1998. https://doi.org/10.4324/9780203765777.

Sa don, N. F.; Sa don, H. S.; Alias, R. A. et al. Flood Preparedness Module for Malaysian Higher Education Students via Metaverse Environment. *IOP Conference Series: Earth and Environmental Science* **2023**, *1144* (1), 012011. https://doi.org/10.1088/1755-1315/1144/1/012011.

Towards pathways to sustainable futures: the role of transdisciplinary approaches to weather, climate, water and related environmental and social sciences

Barth, M.; Jiménez-Aceituno, A.; Lam, D. P. et al. Transdisciplinary Learning as a Key Leverage for Sustainability Transformations. *Current Opinion in Environmental Sustainability* **2023**, *64*, 101361. https://doi.org/10.1016/j.cosust.2023.101361.

Bendito, A.; Barrios, E. Convergent Agency: Encouraging Transdisciplinary Approaches for Effective Climate Change Adaptation and Disaster Risk Reduction. *International Journal of Disaster Risk Science* **2016**, *7* (4), 430–435. https://doi.org/10.1007/s13753-016-0102-9.

Bergmann, M.; Hirsch Hadorn, G.; Metag, J., Eds. *Conceptualising Transdisciplinarity – Origins, Approaches and Challenges*. Springer Nature, 2021.

Bharwani, S.; Daron, J.; Siame, G. et al. *Supporting Climate-resilient Urban Planning: 10 Lessons from Cities in Southern Africa*. Future Resilience for African Cities and Lands (FRACTAL) project, 2023. https://www.fractal.org.za/wp-content/uploads/2023/09/supporting-climate-resilient-urban-planning.pdf.

Brandt, P.; Ernst, A.; Gralla, F. et al. A Review of Transdisciplinary Research in Sustainability Science. *Ecological Economics* **2013**, *92*, 1–15. https://doi.org/10.1016/j.ecolecon.2013.04.008.

Bréthaut, C.; Gallagher, L.; Dalton, J. et al. Power Dynamics and Integration in the Water-Energy-Food Nexus: Learning Lessons for Transdisciplinary Research in Cambodia. *Environmental Science & Policy* **2019**, *94*, 153–162. https://doi.org/10.1016/j.envsci.2019.01.010.

Hoffmann, S.; Thompson Klein, J.; Pohl, C. Linking Transdisciplinary Research Projects with Science and Practice at Large: Introducing Insights from Knowledge Utilization. *Environmental Science & Policy* **2019**, *102*, 36–42. https://doi.org/10.1016/j.envsci.2019.08.011.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team; Lee, H.; Romero, J., Eds.; IPCC, Geneva, 2023. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf.

International Science Council. *LIRA 2030 Africa: Learning from Practising Transdisciplinary Research for Sustainable Development in African Cities*; International Science Council: Paris, 2023. https://council.science/wp-content/uploads/2020/06/LIRA-Learning-Study-Report-230321-WEB.pdf%22.

Ismail-Zadeh, A. T.; Cutter, S. L.; Takeuchi, K. et al. Forging a Paradigm Shift in Disaster Science. *Natural Hazards* **2017**, *86* (2), 969–988. https://doi.org/10.1007/s11069-016-2726-x.

Jack, C. D.; Marsham, J.; Rowell, D. P. et al. Climate Information: Towards Transparent Distillation. In *Climate Risk in Africa: Adaptation and Resilience*; Conway, D., Vincent, K., Eds.; Springer International Publishing: Cham, Switzerland, 2021; 17–35. https://doi.org/10.1007/978-3-030-61160-6_2.

Kaiser, M.; Gluckman, P. *Looking at the Future of Transdisciplinary Research*; International Science Council (ISC): Paris, 2023. https://council.science/wp-content/uploads/2024/06/2023-04-26Futureoftransdisciplinaryresearch.pdf.

Klein, J. T. The Discourse of Transdisciplinarity: An Expanding Global Field. In *Transdisciplinarity: Joint Problem Solving among Science, Technology, and Society: An Effective Way for Managing Complexity*; Klein, J. T., Häberli, R., Scholz, R. W., Grossenbacher-Mansuy, W., Bill, A., Welti, M., Eds.; Birkhäuser: Basel, Switzerland, 2001; 35–44. https://doi.org/10.1007/978-3-0348-8419-8_4.

Koele, B.; Daniels, E.; Kavonic, J. et al. FRACTAL City Learning Lab Approach, IMPACT STORY, 1 October 2019, Cross-City **2019**

Lang, D. J; Wiek, A.; Bergmann, M. et al. Transdisciplinary Research in Sustainability Science: Practice, Principles, and Challenges. *Sustainability Science* **2012**, *7* (1), 25–43. https://doi.org/10.1007/s11625-011-0149-x.

Matsumoto, Y.; Kasamatsu, H.; Sakakibara, M. Challenges in Forming Transdisciplinary Communities of Practice for Solving Environmental Problems in Developing Countries. *World Futures* **2022**, *78* (8), 546–565. https://doi.org/10.1080/02604027.2021.2012878.

Matsuura, S.; Razak, K. A. Exploring Transdisciplinary Approaches to Facilitate Disaster Risk Reduction at National and Local Levels through Education, Training and Field Practice. In *Global Assessment Report on Disaster Risk Reduction (GAR 2019)*; United Nations Office for Disaster Risk Reduction (UNDRR): Geneva, 2019. https://www.undrr.org/publication/exploring-transdisciplinary-approaches-facilitate-disaster-risk-reduction-national-and.

McClure, A.; Patel, Z.; Ziervogel, G. et al. Exploring the Role of Transdisciplinary Learning for Navigating Climate Risks in African Cities: The Case of Lusaka, Zambia. *Environmental Science & Policy* **2023**, *149*, 103571. https://doi.org/10.1016/j.envsci.2023.103571.

Moser, S. Social *Transformations to Sustainability through a Critical Lens*; Belmont Forum, International Science Council, NORFACE, 2024. https://council.science/wp-content/uploads/2024/07/ISC-T2SReports-Synthesis.pdf.

Mukute, M.; Colvin, J.; Burt, J. *Programme Design for Transformations to Sustainability Research*; Belmont Forum, International Science Council, NORFACE, 2024. https://council.science/wp-content/uploads/2024/07/ISC-T2SReports-ProgrammeDesign.pdf.

Norström, A. V.; Cvitanovic, C.; Löf, M. F. et al. Principles for Knowledge Co-Production in Sustainability Research. *Nature Sustainability* **2020**, *3* (3), 182–190. https://doi.org/10.1038/s41893-019-0448-2.

Paton, D.; Buergelt, P. Risk, Transformation and Adaptation: Ideas for Reframing Approaches to Disaster Risk Reduction. *International Journal of Environmental Research and Public Health* **2019**, *16* (14), 2594. https://doi.org/10.3390/ijerph16142594.

Paulavets, K.; Moore, S.; Denis, M. Advancing Transdisciplinary Research in the Global South. In *Handbook of Transdisciplinarity: Global Perspectives*; Lawrence, R., Ed.; Edward Elgar, 2023. https://www.elgaronline.com/edcollchap-oa/book/9781802207835/book-part-9781802207835-27.xml.

Pohl, C. What Is Progress in Transdisciplinary Research? *Futures* **2011**, *43* (6), 618–626. https://doi.org/10.1016/j.futures.2011.03.001.

Pohl, C.; Hadorn, G. H. Methodological Challenges of Transdisciplinary Research. *Natures Sciences Sociétés* **2008**, *16* (2), 111–121. https://doi.org/10.1051/nss:2008035.

Taylor, A.; Siame, G.; Mwalukanga, B. Integrating Climate Risks into Strategic Urban Planning in Lusaka, Zambia. In *Climate Risk in Africa: Adaptation and Resilience*; Conway, D., Vincent, K., Eds.; Springer International Publishing: Cham, Switzerland, 2021; 115–129. https://doi.org/10.1007/978-3-030-61160-6_7.

Tschanz, L.; Arlot, M. P.; Philippe, F. et al. A Transdisciplinary Method, Knowledge Model and Management Framework for Climate Change Adaptation in Mountain Areas Applied in the Vercors, France. *Regional Environmental Change* **2022**, *22* (1), 15. https://doi.org/10.1007/s10113-021-01862-3.

Vincent, K.; Steynor, A.; McClure, A. et al. Co-Production: Learning from Contexts. In *Climate Risk in Africa: Adaptation and Resilience*; Conway, D., Vincent, K., Eds.; Springer International Publishing: Cham, Switzerland, 2021; 37–56. https://doi.org/10.1007/978-3-030-61160-6_3.

Walter, A. I.; Helgenberger, S.; Wiek, A. et al. Measuring Societal Effects of Transdisciplinary Research Projects: Design and Application of an Evaluation Method. *Evaluation and Program Planning* **2007**, *30* (4), 325–338. https://doi.org/10.1016/j.evalprogplan.2007.08.002.

World Meteorological Organization (WMO). *United in Science 2023: Sustainable Development Edition*; WMO: Geneva, 2023.

A future where everyone is protected by life-saving early warning systems

Golding, B., Ed. *Towards the "Perfect" Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication*; Springer International Publishing: Cham, Switzerland, **2022**. https://doi.org/10.1007/978-3-030-98989-7.

Group on Earth Observations (GEO). *GEO Highlights 2023*. GEO: Geneva, 2023. https://earthobservations.org/storage/app/media/documents/Events/GEO-Week-2023/GEO%202023%20Highlights%20Report.pdf.

Indonesia Meteorological, Climatological and Geophysical Agency (BMKG). *Signature – System for Multi Generation Weather Model Analysis and Impact Forecast*; BMKG, 2024. https://signature.bmkg.go.id/.

International Telecommunications Union (ITU). *Disaster Connectivity Map*. ITU: Geneva, 2024a. https://www.itu.int/en/ITU-D/Emergency-Telecommunications/Pages/Disaster-Connectivity-Map.aspx.

International Telecommunications Union (ITU). *AI Sub-Group of Early Warnings for All Initiative*. ITU: Geneva, 2024b. https://www.itu.int/en/ITU-D/Emergency-Telecommunications/Pages/AI-Sub-Group-EW4All-.aspx.

International Federation of Red Cross and Red Crescent Societies (IFRC). *Operational Framework for Anticipatory Action 2021–2025*. IFRC: Geneva, **2022**. https://www.ifrc.org/document/operational-framework-anticipatory-action-2021-2025.

Nakalembe, C. L.; Kotani, R. *Ugandan Crop Monitoring System Enables Early Drought Response*. Earth Observations Risk Toolkit, **2022**. https://earth-observation-risk-toolkit-undrr.hub.arcgis.com/pages/drought-early-warning-in-uganda#fn1.

World Meteorological Organization (WMO) and United Nations Office for Disaster Risk Reduction (UNDRR). *Global Status of Multi-Hazard Early Warning Systems 2023*. Geneva, 2023. https://www.undrr.org/reports/global-status-MHEWS-2023#download.

For more information please visit:
public.wmo.int/en/resources/united_in_science

WORLD METEOROLOGICAL ORGANIZATION
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