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2025 – Celebrating 75 years of WMO Science for Action

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2025 - Celebrating 75 Years of WMO Science for Action

WMO – its 193 Members and its Secretariat – will be celebrating the Organization's 75th anniversary in 2025. The WMO Convention was enacted on 23 March 1950, creating the World Meteorological Organization which would be officially recognized as a specialized agency of the United Nations exactly a year from that date. Since then, the scientific work of WMO, through its network of National Meteorological and Hydrological Services and research institutions, has provided high-quality weather data and forecasts and climate assessments and projections for policy and sustainable socioeconomic development and related weather, water, climate and environmental warnings to better protect populations. The work of WMO has highlighted the need for global action to the threat of climate change.

Through perseverance and dedication, WMO Members have created, maintained and extended the Earth system observation network and shared the collected data, have continuously improved and refined forecasting and services, have improved capacity through knowledge sharing and have invested in further research and development. So much has been achieved that listing them all would fill this entire *Bulletin*.

Let's just recall the World Climate Conferences:

- The First World Climate Conference, convened by WMO in 1979, led to alerts about climate change and resulted in the creation of the World Climate Programme (WCP), the World Climate Research Programme (WCRP) and the International Panel for Climate Change (IPCC) in 1988 by WMO and United Nations Environmental Programme (UNEP).

- The Second World Climate Conference in 1990 led to the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, and to the creation of the Global Climate Observing System (GCOS).

- The Third World Climate Conference in 2009 defined the areas where climate science could contribute to the achievement of the United Nations Millenium Development Goals and the goals of the Hyogo Framework for Action on Disaster Risk Reduction, and led to the establishment of the Global Framework for Climate Services.

Today many challenges lay ahead. Climate change is impacting our lives, early warnings are a priority to save lives and mitigate disaster risk, and more science and research is needed to further improve the quality of forecasts and to guide policy and decision-making. It is important, therefore, that WMO Members and Secretariat take the time in 2025 to pay tribute to the technicians, meteorologists, hydrologists, climatologists and researchers in various fields who have made a difference in our lives over the last 75 years and who face these challenges full on.

Prof. Celeste Saulo
WMO Secretary-General

The Triple Dividends of Early Warning Systems and Climate Services

By Emma (Bing) Liu, Daniel Kull, Moyenda Chaponda – WMO Secretariat

The life-saving power of Early Warning Systems

Cyclone Freddy's landfall in Mozambique in 2023 is a powerful testament to the life-saving benefits of early warning systems. It demonstrated that preparedness and the right tools for action can mitigate the devastating impacts of extreme climate-related natural hazards, safeguarding lives and the future of communities.

Just four years earlier, in March 2019, *Cyclone Idai* had unleashed its fury on central Mozambique, tearing through the region with winds reaching up to 195 kilometres per hour (km/h). The Cyclone's wrath led to catastrophic flooding and widespread devastation, leaving a trail of destruction in its wake. Over 600 lives were lost, and the economic toll was staggering, with damages estimated at US$ 3 billion[1]. Schools, roads, bridges, energy assets and water treatment facilities were decimated, bringing the nation to its knees and underscoring the devastating impact of natural hazards.

Cyclone Idai was a stark wake-up call, highlighting Mozambique's urgent need for a strong Early Warning System (EWS). Supported by the United Nations and the World Bank's US$ 265 million Disaster Risk Management and Resilience Program, Mozambique had embarked before the year was out on a mission to develop a comprehensive EWS to empower communities through action, using cutting-edge technology, resilient infrastructure and a coordinated emergency preparedness and response framework. In a short time, the Government of Mozambique began producing meteorological warnings, based on forecasts that use satellite imagery and data from the surface observational network, and disseminating them through community radio stations and trained brigades, guiding at risk communities to safety ahead of extreme weather. Early warnings help to protect lives and preserve hard-earned development gains by enabling timely interventions that minimize the impact on both people and property.

Fast forward to 2023, when *Cyclone Freddy* – a behemoth of a storm and one of the strongest, longest-lasting tropical cyclones on record – battered central Mozambique not once, but twice, with terrifying wind speeds reaching 230 km/h. This time, the story was different. Thanks to the newly enhanced EWS, the devastation was by large averted. Communities were prepared and had been relocated ahead of the event to safe areas with sufficient supplies of food and water. The death toll from *Cyclone Freddy* was much lower: 198 lives were lost compared to the 603 during *Cyclone Idai*. Economic damages were also significantly lower: estimated at US$ 500 million[2], an astonishing 83% reduction compared to the previous event. This substantial decrease in both human and economic losses highlight the extraordinary effectiveness of the EWS.

The benefits were felt across Mozambique. Regina Mutoro, a member of the local disaster committee in Chinde District, shared her experience: "With *Cyclone Freddy*, we knew what would happen and felt more in control. We were able to prepare and ensure our families were safe."

This is just one vivid example of the immense benefits of early warnings: they save lives and protect property from natural hazards. These immediate benefits are impressive, but they only scratch the surface of the long-term advantages that EWS and climate services can provide.

Triple Dividend of Resilience

To fully appreciate and understand the broader benefits from investments in EWS – beyond the

1 2018-2019 Mozambique Humanitarian Response Plan Revised following *Cyclones Idai* and *Kenneth*, May 2019 (November 2018 - June 2019)

2 https://www.arc.int/news/arc-group-announces-insurance-payout-republic-madagascar-aid-recovery-tropical-cyclone-freddy

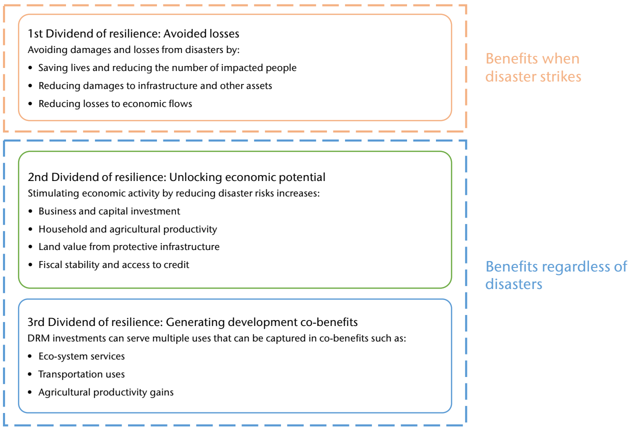

Figure 1. Triple dividend framework

Source: Adapted from Tanner et al., 2015

protection of lives and assets – the Triple Dividend of Resilience (TDR)[3] framework offers a systematic approach for evaluating the benefits of climate resilience investments. Specifically, TDR reveals that resilience investments yield three types of benefits or "dividends":

- Avoiding economic losses when hazard strike
- Stimulating economic activity thanks to reduced disaster risk even when no hazard occurs
- Generating development co-benefits (Figure 1).

While the first dividend is the most common motivation for investing in resilience, the second and third dividends are equally important. Both accrue regardless of whether the anticipated climate risk materializes, resulting in high adaptation benefit-cost ratios (BCRs), even when the value of potentially avoided losses is not factored in[4]. Better awareness of and evidence for the full range of benefits demonstrate higher climate resilience investment returns and generate more information useful in decision-making across sectors. There are immediate and significant economic benefits to households, the private sector and, more broadly, at the macroeconomic level, which makes the economic case for supporting adaptation through EWS and other climate services stronger.

The First Dividend of Resilience: Avoided damages and losses

Investment in EWS is usually driven by a desire to reduce the human cost of disasters. It is estimated that countries with limited to moderate Multi-Hazard Early Warning System (MHEWS) coverage have a nearly six-times-higher disaster-related mortality ratio compared with that in countries with substantial to comprehensive coverage – a mortality rate of 4.05 per 100 000 population, compared with 0.71. Similarly, countries with limited to moderate MHEWS coverage have nearly five times more disaster-affected people than countries with substantial to comprehensive coverage – 3 132 compared with 688[5].

The Global Commission on Adaptation (GCA) underscores the economic value of enhancing EWS, revealing a cost-benefit ratio of 1:9 – higher than any other adaptation measure, including investments in resilient infrastructure or improved dryland agriculture (Figure 2). This means that for every US$ 1 invested in EWS, an average of US$ 9 in net economic benefits can be realized. The GCA also reports that providing just 24 hours' notice of an impending storm or heatwave can reduce potential damage by 30%, and a US$ 800 million investment in such systems in developing countries could prevent annual losses of US$ 3 billion–US$ 16 billion[6].

Policy makers, analysts and others generally measure the socioeconomic impacts of natural hazard using the value of the damage inflicted on buildings, infrastructure, equipment and agricultural production during the event. But US$ 1 in losses does not mean the same thing to a wealthy person as it does to a low-income person, the relative severity of a loss depends on who experiences it. A World Bank study[7] demonstrated that losses in

3 ODI and GFDRR 2015 first introduced the concept of "Triple dividend of resilience" in their paper The Triple Dividend of Resilience. Building on this foundation, the World Resource Institute (WRI) 2022 further developed the approach, with a particular focus on the economic, social and environmental benefits of adaptation investment. The study is available at: The Triple Dividend of Building Climate Resilience: Taking Stock, Moving Forward. In this paper, the theory presented is a synthesis of the earlier work, combing elements from both.

4 The Triple Dividend of Building Climate Resilience: Taking Stock, Moving Forward

5 lobal status of multi-hazard early warning systems 2023

6 Adapt now: a global call for leadership on climate resilience

7 Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters

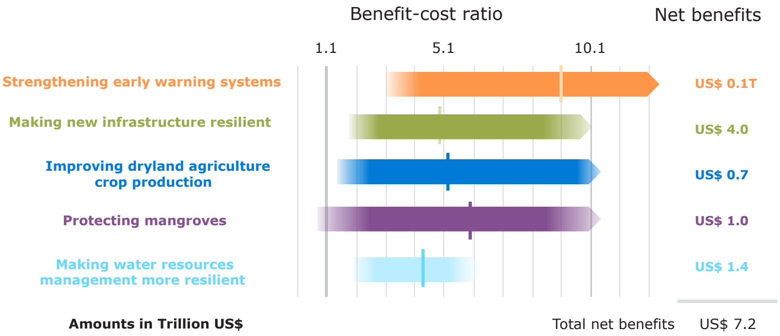

Figure 2. Benefits and costs of illustrative investments in adaptation (Original source: WRI, 2022)

well-being[8] can be as much as 60% higher than asset losses when considering the vulnerability of the impoverished person.

In addition to reducing loss of life and assets, losses in well-being can also be mitigated. The same study highlighted the importance of EWS, revealing that if all countries adopted the recommended "resilience package" policies, global well-being losses from natural hazards could be reduced by US$ 78 billion annually. Further, universal access to EWS could increase these well-being benefits to US$ 100 billion per year. Ongoing World Bank research estimates that between 1978 and 2018, EWS have averted US$ 360 billion–US$ 500 billion in asset losses and US$ 600 billion–US$ 825 billion in welfare losses.[9] Figure 3 highlights the top 15 countries that would benefit the most from EWS as measured by the potential reduction in losses to both assets and well-being, which are of similar magnitude.

The research assessed the global benefits of providing universal access to EWS, assuming that advanced warnings could reduce asset losses from storms, floods and tsunamis by up to an average of 20%. The findings suggest that such warnings could prevent approximately US$ 13 billion in asset losses annually, with well-being gains equivalent to a US$ 22 billion increase in income. These benefits could be weighed against the cost of providing such a service globally. Although no precise estimate exists, a rough calculation suggests an annual cost of around US$1 billion. This indicates that investing in EWS produces significant socioeconomic returns, even without considering their primary benefit: the lives that can be saved.

The study also indicates that socioeconomic and well-being resilience generally increases with income. This is primarily attributed to better disaster risk management infrastructure and systems, higher-quality buildings, more comprehensive public services (for example for health and social protection) and the widespread availability of EWS in wealthier countries.

The second Dividend of Resilience: unlocking economic potential

The second dividend refers to the wider benefits of interventions in reducing "background risk" and unlocking development benefits.

In disaster-prone places, risks of extreme weather events and disasters create an ever-present background risk. Consequently, risk-averse households and firms avoid long-term investments in productive assets, entrepreneurship can be hampered, and planning horizons are shortened, meaning development opportunities are lost. By offering better detection and forecasting of natural hazards and the risks they present, EWS and other climate services can contribute to development gains by encouraging people to take positive risks (for example, larger investments in productive assets, entrepreneurship and innovation)10. Higher confidence that systems are in place to reduce risk also increases a country's attractiveness for foreign direct investment.

For instance, reducing flood risks in urban areas lowers financial costs, increases security and encourages investments. For example, the GCA reports that, "London's Canary Wharf and other developments in East London would have been impossible without flood protection from the Thames Barrier". Since 2014, the Thames Barrier operations have had forecasts of dangerous conditions up to 36 hours in advance. These forecasts – numerical weather predictions – are based on data from weather satellites, oil rigs, weather ships and coastal stations. A range of numerical weather predictions models provide forecasts on expected

8 Here "well-being" refers to meeting various human needs, some of which are essential (for example, being in good health), as well as the ability to pursue one's goals, to thrive and feel satisfied with their life.

9 An ongoing World Bank study: Avoided losses due to improved early warning

10 The 'triple dividend' of early warning systems

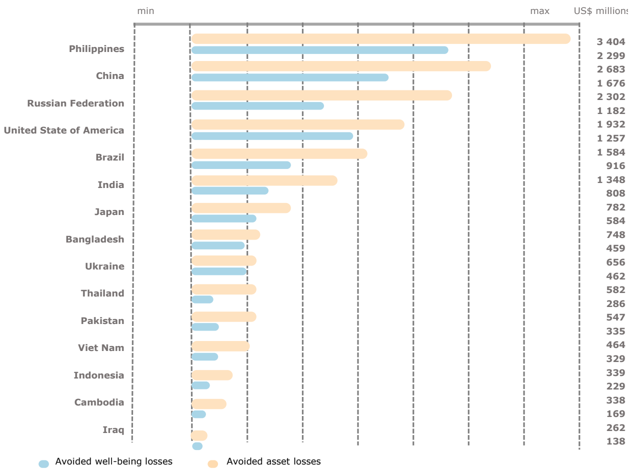

Figure 3. Top 15 countries that benefit most from the EWS by avoiding in assets and well-being losses

(Source: World Bank estimate from the Resilience Indicator Toolbox*)*
Note: Figure shows the avoided asset losses and gains in well-being from assuming universal access to EWS in absolute terms in panel on the left (millions of US$ per year, purchasing power parity adjusted)

sea and river levels, supplemented by data from the Met Office and real-time information from the United Kingdom National Tide Gauge Network[11]. The holistic EWS that informs the Thames Barriers operations is designed to integrate seamlessly with daily life, ensuring the safe development of high-value real estate and commercial areas, thereby safeguarding billions in revenue generation. In 2021, the gross value added per job in London was on average £ 81 400, 40% higher than the national average. This is a substantial contribution to national economic productivity and growth[12].

By reducing the uncertainty associated with climate-related risks and providing accurate weather forecasts, early warnings and other climate services enable critical economic sectors to make well-informed decisions. In the agribusiness sector, such decisions may include adjusting planting dates or modifying supply chains, which helps sustain productivity, minimize economic disruptions, and mitigate losses due to adverse weather, ultimately enhancing overall productivity and yield.

In China weather forecasting services are crucial for the overall national development. According to World Bank statistics, agriculture, forestry and fishing contributed 7.1% to China's Gross Domestic Product (GDP) in 202313. A 2022 study by the China Meteorological Administration14 revealed that from 2008 to 2019, each 1% improvement in weather forecast accuracy resulted in a 0.34% increase in total crop yield, translating to an additional 2.32 million tons of grain. Furthermore, a 1% improvement in forecast accuracy contributed to a 0.5% rise in the added value of the agricultural sector, generating approximately US$ 7.67 billion in revenue in 2021. A national survey also estimated that the overall economic benefits of weather forecasts and meteorological services ranged between US$ 14.4 billion–US$ 1.7 billion. These findings are consistent with ongoing World Bank research in Ethiopia15, which indicates that more accurate forecasts (lower Root Mean Square Error (RMSE)) are associated with reduced crop losses reported by farmers.

The third Dividend of Resilience: co-benefits of resilience investments

The third dividend encompasses the economic, social and environmental co-benefits associated with a specific intervention. These co-benefits, though diverse, offer immediate advantages even in the absence of disasters, thereby reinforcing the overall value of the investment and enhancing the attractiveness of investing in disaster risk mitigation.

On a direct level, strengthening EWS requires consistent and inclusive community engagement, which enhances the involvement of women and marginalized groups. This process fosters trust, builds positive relationships and, ultimately, promotes social cohesion. In addition, the demonstrated benefits of EWS and other climate services in informing investment decisions in the last section stretch across to disaster risk mitigation investment planning and the optimization of infrastructure investments. For instance, early warnings can signal the need for timely maintenance or upgrades, reducing the likelihood of costly failures during extreme weather events. Additionally, the data and guidance from EWS and other climate services can inform actions and investments to protect and manage the environment, including

11 Guidance-The Thames Barrier

12 The London Climate Resilience Review (July 2024)

13 China - Agriculture, Value Added (% Of GDP)

14 The Agricultural Economic Value of Weather Forecasting in China (2022)

15 Ongoing World Bank study on Weather observations, agriculture outcomes, and welfare benefits- Case of Ethiopia

valuing and optimizing ecosystem services. These processes deliver the third dividend while also contributing to the realization of the first two dividends.

The Triple Dividend of EWS: United Republic of Tanzania's Coastal Areas[16]

In early 2016, the Tanzania Meteorological Authority (TMA) and the Met Office launched MHEWS project under the Weather and Climate Information Services for Africa (WISER) program. This initiative aimed to strengthen disaster preparedness by enhancing TMA's capacity to deliver an impact-based five-day weather forecast services for extreme events such as heavy rain, flooding, landslides, strong winds, high waves and extreme temperatures. Initially focused on the coastal regions, the service was later expanded nationwide through further Disaster Risk Management (DRM) investments in Tanzania.

A WISER study in 2020 explored the full spectrum of benefits derived from investments in EWS. The study focused on Tanzania's coastal fishing communities, which provide Tanzania with export revenue and accounts for 35% of rural employment but has faced increasing threats from coastal flooding since 2007. It found that EWS have permitted fishermen and seaweed farmers to become better equipped to plan their economic activities and that

Thames Barrier protecting London Canary Wharf from high tides, storm surge and river flooding (Photo ID 271742917 © Eric Flamant | Dreamstime.com)

some are experiencing a rise in income. However, lower levels of risk from better preparedness do not appear to have encouraged higher levels of saving and investment because of other limiting factors – fishermen are poor with little capacity to save and have no access to microfinancing. The benefits of the EWS investment were categorized into the triple dividend framework:

First Dividend of Resilience:

- People are taking precautions based on the weather information received
- There is a perception that the human casualties and deaths due to extreme weather have decreased along the coast.

Second Dividend of Resilience:

- Lower levels of disaster risk have encouraged small increases in investment, though not yet widespread.

Third Dividend of Resilience:

- Increased community engagement and improved local governance
- Use of forecasts for household economic planning.

Investment in EWS and Climate Services need to be sustainable

Since the launch of the United Nations Early Warning for All initiative in 2022, the major international financing institutions have approved capital investments in EWS of US$ 1.3 billion–US$ 1.5 billion, leveraging and informing over US$ 5 billion in sectoral climate resilience investments17, thereby contributing to the achievement of all of the Sustainable Development Goals and a climate resilient economy. While the costs of operating and maintaining EWS also need to be factored into assessments of economic efficiency, the total investment needs are still minor compared to the total potential benefits. Most of these new investments in EWS are subcomponents of larger projects supporting the resilience of different sectors such as DRM, agriculture, water resources management, urban development and transport, thereby helping to ensure delivery of all three dividends.

16 The 'triple dividend' of early warning systems

17 Source: *Early Warning System Investment Observatory*

EWS programming in Peru and Nepal leads to improved resilience

An impact study by Practical Action that reviewed their programmatic work on early warning systems (EWS) in Peru and Nepal found that their people-centred approach had led to multiple indirect resilience-building benefits. There was improved public disaster risk knowledge and understanding, particularly around the causes, effects and risks of climate-related weather hazards, which also improved the overall psychosocial welfare of community members. Communities also reported greater trust in government sources of forecast information. The EWS project work has strengthened community networks, which are being used for much more than the dissemination of early warnings, including reporting robberies, health campaigns and COVID-19 response. Community participation networks have also created opportunities for women's leadership. (Impact and Lessons from Nepal and Peru, August 2023)

People-centred EWS skills training (left) (Photo from Towards Effective Early Warning Systems - *Impact and Lessons from Nepal and Peru (2023), Practical Action)*
Community members discussing flood EWS in Nepal (right) (Photo Gender Transformative Early Warning Systems - *experiences from Nepal and Peru (2021), Practical Action)*

Without long-term resources and capacity development for the operations and maintenance of EWS and other climate services, these benefits will not be delivered, resulting in wasted investment. The global development community is exploring ways to ensure the sustainability of EWS and other climate services. The Systematic Observations Financing Facility (SOFF) provides an innovative example of how recognition of the "public good" nature of such systems, modern technology and peer support can provide much-needed long-term operational support.

Early Warnings for All: Empowering All to Climate Action

By Muhibuddin Usamah, WMO Secretariat

The climate crisis grows in intensity day by day, and with it the urgency for early warning systems (EWS) to mitigate impacts. These systems are about saving lives, protecting livelihoods and empowering communities to take decisive action. The global Early Warnings for All initiative aims to ensure that everyone, everywhere is equipped with the information they need to protect themselves from high-impact weather, water and climate threats from the most remote villages to the busiest cities.

While the power of EWS are clear, implementing such systems is challenging and the 2027 goal set for providing Early Warnings for All looms.

The power of early warnings

On 14 May 2023, *Tropical Cyclone Mocha* struck the Bay of Bengal, bringing sustained winds of 180 km/h to 190 km/h, violent gusts, heavy rainfall and flooding. The Cyclone's landfall brought compounding impacts that exacerbated local vulnerabilities. Storm surges extended far beyond the immediate impact zones, particularly affecting the low-lying regions of Sittwe, Myanmar, and of Cox's Bazar, Bangladesh. Both Myanmar and Bangladesh are Least Developed Countries (LDCs) on the Bay of Bengal with geographic vulnerabilities. The Cyclone, one of the strongest ever recorded in the Bay of Bengal, swept across densely populated coastal areas, with severe implications for the world's largest refugee camp in Cox's Bazar where nearly one million people reside in precarious, makeshift shelters. Evacuations were conducted ahead of the Cyclone, thanks to the warnings provided by the Bangladesh Meteorological Department and the Regional Specialized Meteorological Centre for Tropical Cyclones over the North Indian Ocean, hosted by Indian Meteorological Department. State media and local officials reported 145 deaths across the country. In 2008, 15 years earlier, *Cyclone Nargis*, a storm of similar magnitude on the same coastline, had resulted in over 138 000 fatalities. Despite the vulnerabilities, *Cyclone Mocha's* impacts had markedly different results from those of previous storms – the power of early warnings.

Another compelling example of the transformative power of EWS comes from Mozambique, a country frequently hit by tropical cyclones. In 2019, *Cyclone Idai* struck Mozambique with devastating force, causing widespread destruction and loss of life. The disaster highlighted the urgent need for better early warning and preparedness systems. In response, the Mozambican Government, with support from international partners, invested in improving its early warning infrastructure. This included upgrading weather forecasting technology, training local communities on how to interpret and respond to warnings, and ensuring that information reaches the most remote areas. Four years later, in 2023, when *Cyclone Freddy* struck Mozambique – at 36 days, it was one of the longest-lasting and most intense tropical storms on record[1] – its impacts were mitigated due to robust EWS. Communities were better prepared, and timely evacuations were conducted, significantly reducing the loss of life compared to previous cyclones. While *Cyclone Freddy* caused substantial damage, effective EWS – early warnings, enhanced preparedness and swift responses – demonstrated life-saving potential.

Japan and the Philippines have also benefited from advanced early warnings during the typhoon seasons, leading to the evacuation of vulnerable communities and minimizing casualties. Moreover, in the United States of America (US), early warnings from the National Weather Service ahead of hurricanes and tornadoes have repeatedly proven essential in safeguarding communities.

The importance of EWS provided by National Meteorological Hydrological Services (NMHSs) has been globally recognized, as these systems have demonstrably reduced the loss of life during extreme events. The global evidence underscores that investing in EWS is not only a measure of preparedness but a critical life-saving tool in the

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face of increasingly frequent and severe natural hazards.

Why EWS are essential

Stories of the tropical cyclones are not unique. Around the globe, communities are facing more intense and frequent extreme events due to climate change. The impacts are everywhere, from rising sea levels to prolonged droughts, from devastating floods to intense heatwaves.The number of medium- or large-scale disaster events is projected to reach 560 a year – or 1.5 each day – by 2030.[2] These events do not just disrupt daily life; they destroy livelihoods, displace families and claim lives.

Inclusive and multi-hazard EWS are one of the most effective ways to save lives and livelihoods in advance of a climate or non-climate hazard. Countries with limited early warning coverage have disaster mortality rates that are eight times higher than countries with substantial to comprehensive coverage.[3] Key benefits of EWS include:

1. **Saving lives:** Early warnings give people the time they need to evacuate or take shelter, reducing the risk of injury or death

2. **Protecting livelihoods:** By allowing communities to prepare, early warnings help safeguard homes, businesses and agricultural production

3. **Reducing economic losses:**Timely warnings can minimize the damage to infrastructure, reducing the economic impacts of natural hazards

4. **Empowering communities:** Knowledge is power. When communities have access to accurate and timely information, they can take control of their own safety and make informed decisions.

The Early Warning for All initiative

The **United Nations Secretary-General called for** Early Warnings for All by **2027** at the 27th Conference of Parties (COP27) to the United Nations Framework Convention on Climate Change (UNFCCC) in Sharm El-Sheikh, Egypt.The initiative aims to ensure universal protection from hazardous hydrometeorological, climatological and other related environmental events through life-saving Multi-Hazard Early Warning Systems (MHEWS), anticipatory action and resilience efforts by the end of 2027.

EWS have already helped decrease the number of deaths and reduced losses and damages resulting from hazardous weather, water and climate events. But major gaps still exist, especially in Small-Island Developing States (SIDS) and LDCs:[4]

- 50% of countries worldwide report having adequate multi-hazard early warning systems. As of recent reports, only about 46% of LDCs and 39% of SIDS have reported the existence of some form of national MHEWS5

- Climate, weather and water-related extremes have led to 15 times more deadly hazards in Africa, South Asia, South and Central America, and SIDS

- Over the past 50 years, 70% of all fatalities from climate-related disasters – including extreme weather events such as cyclones, floods, droughts, and heatwaves – have occurred in 46 LDCs.

Findings from some 24 national Early Warnings for All workshops, conducted by WMO in 2023/2024, revealed major barriers and challenges in implementing MHEWS:

- Infrastructure and technical capacity- In many parts of the world, particularly in low-income countries, the infrastructure for EWS is lacking or inadequate.There is also insufficient technical capacity and high-quality data for downscaled climate modelling and impact-based forecasting.

- Funding and resources – Establishing and maintaining EWS requires significant financial resources, which is a barrier for some countries.

- Institutional and regulatory frameworks-There is insufficient institutional, legislative, and regulatory frameworks and coordination for effective delivery of climate services and MHEWS. Effective early warning services require coordination across multiple sectors and levels of government, which can be difficult to achieve.

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- Cultural and social barriers – In some communities, traditional beliefs and practices may conflict with modern early warning methods, making it challenging to convince people to take action. There is also limited awareness, knowledge and understanding of climate change science and potential impacts.

- Communication and user engagement –There is a lack of targeted communication on climate risk information or early warnings tailored to specific user needs.There are limited capacities at the national, regional and community levels to use climate services and EWS to reduce disaster risks.

To address these challenges, the Early Warning for All initiatives requires coordinated efforts with stakeholders across various sectors. Success hinges on strong national leadership and collaborative engagement throughout the MHEWS value cycle (Figure). In support of these objectives, the Early Warnings For All initiative has developed an interpillar programming guide to clarify and guide actions within and across MHEWS pillars:

1. Impact and risk-based forecasts and warnings – Weather forecasts that warn about pending weather events and their potential impacts on people, housing, services and the environment to help those at risk to better prepare for and respond to weather events

2. Common Alerting Protocol (CAP) and strategic risk communication – Strong communication frameworks and systems are required to share timely, accurate and clear information with everyone before, during and after hazardous events to facilitate informed decision-making to stay safe

3. Early and anticipatory action planning – Work with at risk populations to develop preparedness and early action plans that are integrated into national and local disaster risk management plans to ensure that everyone is prepared and knows what to do in emergencies

4. Comprehensive simulations of MHEWS value cycle – Regular practice and test of EWS through different scenario simulations to improve response strategies and ensures that the systems work well in real-life situations

5. Monitoring and reporting on MHEWS coverage and effectiveness – MHEWS require monitoring and evaluation, the results of which should be shared with national and global stakeholders to continuously improve approaches

6. MHEWS Governance – Clear and effective national management structures are required for EWS, including clear policies, legal frameworks and coordination across different sectors and levels of government, ensuring accountability and proper resource allocation.

In addition, the initiative also looks at three transversal issues for consideration: financing, technology development and transfer, and capacity building.

The role of National Hydrological and Meteorological Services (NMHSs)

NHMSs are at the core of the Early Warning for All initiative.These agencies are the backbone of effective EWS, providing the critical weather and climate information needed to protect lives and livelihoods. As the official providers and the sole authoritative sources of meteorological and hydrological data in their respective countries, NHMSs are uniquely positioned to drive the success of this global initiative.

NHMSs are responsible for monitoring and predicting weather patterns, issuing forecasts and providing early warnings when extreme

Figure. Key interpillar areas of Early Warnings for All weather events threaten the population. Their mandate aligns perfectly with the goals of the Early Warning for All initiative, placing them at the heart of initiative's success.

NHMSs possess the technical expertise and sophisticated technology required to monitor weather conditions accurately and in real-time. Their ability to provide timely and reliable forecasts is crucial for issuing early warnings that can save lives. Every NHMS has a thorough understand of the unique climatic conditions and weather patterns in their countries, better than any external organization. This local knowledge allows them to tailor early warnings to the specific needs of their communities, ensuring that the information is relevant and actionable. As the official source of weather information, NHMS are relied upon by governments, emergency services and the public. This credibility is essential when issuing warnings that require immediate action, as people are more likely to follow guidance from an authoritative source. NHMS are already integrated into national disaster management frameworks, enabling them to coordinate effectively across government and local agencies such as emergency services and health departments. This integration ensures that early warnings lead to swift and coordinated responses.

Strengthening NHMS for effective EWS

To fully realize the potential of NHMSs, it's essential to support and strengthen them. The focus areas highlighted below were identified during the aforementioned national Early Warnings for All workshops and are reflected in the corresponding national roadmaps developed as part of this global effort.

1. Investment in technology – NHMSs need access to the latest weather forecasting and monitoring technology, including advanced radar systems, satellites and data analytics tools. Investments in these technologies will enhance their ability to predict extreme weather events with greater accuracy and lead times.

2. Capacity building – Continuous training and development of NHMS personnel are crucial. Building capacity at all levels – from meteorologists to communication specialists – will ensure that NHMSs can maintain high standards of service and adapt to the evolving challenges posed by climate change.

3. Public engagement – NHMS should engage with the public to raise awareness about the importance of EWS and how to respond to them. This includes running educational campaigns, collaborating with local media, and using social media platforms to reach a broader audience.

4. Collaboration and Partnerships – NHMSs should work closely with other national and international organizations, including nongovernmental organizations (NGOs), private sector companies and research institutions, to enhance their capabilities and ensure that early warnings are part of a broader, coordinated disaster management strategy.

As the climate crisis accelerates, the role of NHMSs is heightened. They must be equipped and empowered to co-lead the Early Warning for All initiative in their respective countries. Governments, international organizations and communities need to recognize the central role of NHMSs and provide the necessary support to ensure their success.

Empowering NHMS as we move forward is not just about enhancing weather forecasting, it is about empowering entire communities to take climate action and building a safer, more resilient future for all.

The Cryosphere – the canary in the coal mine of the climate system

By Rodica Nitu, Michael Sparrow and Stefan Uhlenbrook from WMO Secretariat, and Jeffrey Key (formerly National Oceanic and Atmospheric Administration (NOAA))

Coal mines once used canaries as early indicators of potential danger: their sensitivity to poisonous gases caused their early demise during gas leaks, sounding a danger alarm for miners. Today, "canary in the coal mine" is commonly used to express alert for environmental dangers: "The cryosphere, the white landscapes, is the canary in the coal mine of climate and biodiversity crises due to human pressures including greenhouse gas emissions," said Antje Boetius, Director of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, at the conclusion of the One Planet – Polar Summit in Paris, November 2023. What are the signs and what do we urgently need to do not to miss them?

The changing Cryosphere

Earth's climate is changing. With the rising temperatures, the cryosphere is declining around much of the world. Due to modified ocean-sea-ice-atmosphere interactions, the sea-ice regime is changing. First-year ice is becoming prevalent in areas of the Arctic previously known for second or multi-year ice. In 2023, the sea ice around Antarctica was reported to have reached its lowest extent since satellite monitoring started in 1979. For the June-August 2024 period, the region south of 60°S was 2.1 °C above average (relative to 1979–2020).[1] An anomaly of 2.1 °C is the record highest value for that period since satellite data started to be widely assimilated over Antarctica (1979 onwards). Much of this seasonal anomaly occurred in the 0 ° to 60 °East region of Antarctica. This sector was exceptionally warm around the end of July and into early August according to Thomas Caton Harrison from the British Antarctic Survey.

Intergovernmental Panel on Climate Change (IPCC) reports have estimated the amount of carbon stored in permafrost at about twice the amount in the atmosphere today. Permafrost plays a key role in regulating the global climate system by acting as a carbon sink or source, which alters atmospheric greenhouse gas emissions. The IPCC reports present evidence of that permafrost is undergoing rapid changes. This is creating challenges for planners, decision-makers and engineers as the structural stability and functional capacities of infrastructure are no longer secure as designed.

Rising temperatures in the atmosphere and ocean around Antarctica are melting the ice sheet. Evidence cited in IPCC reports suggests that if global temperature rise exceeds 2 °C in the long-term, both the Greenland and Antarctic ice sheets may reach tipping points[2] beyond which their melting would become unstoppable even with deep cuts in greenhouse gas emissions. In addition to sea-level rise, even a partial melting of ice sheets has large downstream impacts on, for example, ocean circulation and food as well as energy security, exacerbating climate change effects on human societies and the natural world. There are already signs that some large glaciers in Antarctica have entered a state of irreversible retreat and data from Greenland has shown an increase in surface melt and increases in iceberg calving over the last 30 years. The Global Tipping Points Report 2023 noted that "Large-scale tipping points exist for the Greenland and Antarctic ice sheets. Crossing these tipping points would lead to multimetre sea-level rise over hundreds to thousands of years."

Snow, glaciers, frozen ground, freshwater and sea ice extend well beyond polar and high mountain areas, being present in more than 100 countries and covering the entire continent of Antarctica[3]. On seasonal to decadal timescales, changes in

1 This value is based on the air temperature at 2-metre height from the early release (provisional) of the ERA5T climate reanalysis datasets produced by ECMWF.

2 Environmental stresses could become so severe that large parts of the natural world are unable to maintain their current state, leading to abrupt and/or irreversible changes. These moments are called Earth system "tipping points". Global Tipping Points – Summary Report 2023; T. M. Lenton, et al, University of Exeter, Exeter, UK.

3 Marshall, S.J. (2011). *The Cryosphere*. Primers in Climate Science, Princeton University Press.

Figure 1. The diminishing of the Tschierva Glacier beneath Piz Bernina, Switzerland - the highest peak of the Eastern Alps, between 1935 and 2024. This is the site of one of the biggest high-alpine landslide events in recent time (at Piz Scerscen, 16 April 2024). 8-9 million cubic metres of rock and ice have detached and run down into the valley, eroding the glacier. Luckily no damage happened.

Source: Leo Hösli, Matthias Huss (VAW-GL, ETH Zürich, Switzerland) and swisstopo.

snow cover, freshwater and sea ice, glaciers, ice sheets and permafrost impact water resources and ecosystems, including near-coastal and marine ecology. The accelerated changes are felt by people, society, and economies around the globe.

Impacts far and wide

In many places snowfall has been replaced by rain, and the amount and seasonality of runoff have changed. These have local to regional impacts on water resources and on the frequency, magnitude and location of related natural hazards, especially landslides and floods. Human settlements and livelihoods in high mountain areas and the Arctic are exposed to new risks.

On 16 August 2024, a devastating flood struck Thame, a village in the Khumbu region of Nepal. Nepalese scientists confirmed that it was caused by a Glacial Lake Outburst Flood (GLOF) from the Thyanbo Glacial Lake. Thame Village, a prominent village located inside the World Heritage Sagarmatha National Park site, is home to renowned mountaineers. While there was no loss of life, the floods destroyed a large area around the village (Figure 2). It is not an isolated event. According to Professor Rijan Kayastha, Kathmandu University, Nepal, over the last 30 years more than 20 GLOFs have occurred in the Hindu Kush-Himalayan region alone. The risk is great. There are over 25 000 glacial lakes in the Hindu Kush Himalaya region, 47 of them potentially dangerous within the Koshi, Gandaki and Karnali river basins of India, Nepal and the Tibet Autonomous Region of China. The Pakistan Meteorological Department's 2013 inventory of glacier lakes in Northern Pakistan, conducted as part of an internationally funded project through United Nations Development Programme (UNDP), identified 3 044 glacier lakes, of which 36 were assessed as potentially dangerous. Since then, several GLOF events have occurred on the Shishper Glacier Dammed Lake (2019, 2020, 2021 and 2022), causing repeated and significant damage to housing, highways, bridges, agriculture lands, and other infrastructure.

The increasing ice loss from the Greenland and Antarctic ice sheets and of the glaciers around the world contribute to about a half of the sea-level rise observed globally in recent decades (IPCC SROCC, SMP, A3). Coastal environments and small islands are already impacted by the combination of sea-level rise, other climate-related ocean changes and diverse adverse effects from human activities. Even tropical coastal regions feel the effect of melting ice sheets and glaciers through their contribution to sea-level rise.

Dr Garvin Cummings, the Permanent Representative of Guyana to the WMO, recently highlighted that his country, like all coastal states and SIDS, is "not isolated nor insulated from the impacts of melting of ice sheets and glaciers. We may be far away from poles and glaciers but the potential consequences from the escalating threat of sea-level rise are dire and imminent. Sea-level rise is leading to more powerful storm surges, saltwater intrusion and a loss of coastal fertile land. Understanding these

Figure 2. Thame village in the Khumbu region of Nepal following a devastating GLOF

changes is at least as important for countries like Guyana as it is for countries in close proximity to the poles and glaciers."

People with highest exposure and vulnerability to cryosphere hazards are often the ones living in countries that have the least adaptive capacity. The changing of the cryosphere in the changing global climate is exposing vulnerable populations to new hazards, including more frequent GLOFs, landslides and slope detachment/rockfall caused by degrading permafrost, retreating glaciers, and extreme weather events. Improved monitoring – with the backbone of in situ observations – and modelling are paramount to providing policy and decision-makers with the information and climate services they need for mitigation and adaptation to cryospheric changes and their downstream cascading impacts.

Collaboration – The key to understanding the changing cryosphere

Projections of changes in the cryosphere, with a high degree of confidence under different climate scenarios, are needed to augment the capacity of the global community to better prepare, manage and adapt to the many emerging risks and to guide policy and decision-making. Improvements in projections require advances in understanding and representing cryospheric processes via an Earth system approach, supported by systematic observations and engagements across disciplines and organizations.

Collaborative engagements across multiple scientific domains and involving research and operational organizations are essential. Four International Polar Years (IPY) have demonstrated this by propelling science forward through cooperation. The 5th IPY, being planned for 2032/2033, provides WMO with the opportunity to play a leadership role in supporting the international community to address specific scientific and long-term adaptation questions, and to leave a legacy of improved monitoring and modelling capacities to better inform the global community.

The current WMO unified Earth system approach to monitoring and prediction is the response to addressing critical information gaps for mountain and polar regions and those affected by changes in the cryosphere. This includes assessments of climate trends and projections (for example, for climate services), reporting extreme events, producing early warnings for mountain regions, and supporting drought or flood forecasting (for agriculture, and early warnings).

Observations – The challenges

Advances in climate science, climate services and early warning systems require (1) systematic, sustainable observing networks with timely, effective data exchange and access, and (2) modelling systems across Earth system components. Much work is still needed to achieve both, especially for the cryosphere and the surrounding environments. In most countries, the responsibility for observations on the cryosphere continues to be distributed along multiple institutions, ministries and stakeholders, as monitoring of cryospheric regions has developed relatively recently, mostly as scientifically driven bottom-up initiatives. This fragmentation has limited the ability to fully understand and document the current observing system gaps.

A survey conducted by WMO on the Andean countries in 2020, following-up on the conclusions of the 2019 High Mountain Summit, highlighted the complexity of coordinating engagements in the cryosphere domain, especially in mountain environments. In Colombia and Peru, the National Meteorological and Hydrological Services (NMHSs) share responsibsility of observing snow and glaciers with other organizations, while in Argentina, Plurinational State of Bolivia and Chile these observations are under the remit of other national or regional institutions. This is representative of the situation in many other countries around the world.

Even though there have been significant improvements in recent years, globally, many mountain regions have remained insufficiently monitored due to high costs, difficult access, extreme operating conditions, insufficient local technical and operational capacity, and the absence of, or weak, institutional mandates (IPCC SROCC, 2019). Even meteorological stations are sparse at high elevations. This provides an altitudinal bias in precipitation and other observations. Where existing, the resolution of monitoring networks in high-mountains and polar regions is usually insufficient to adequately resolve complex terrain and related hydroclimatic processes.

The Third Pole Regional Climate Centre (link) is a network aimed at developing climate services for the vast high mountain region around the Tibetan Plateau. Figure 3 illustrates that most operational

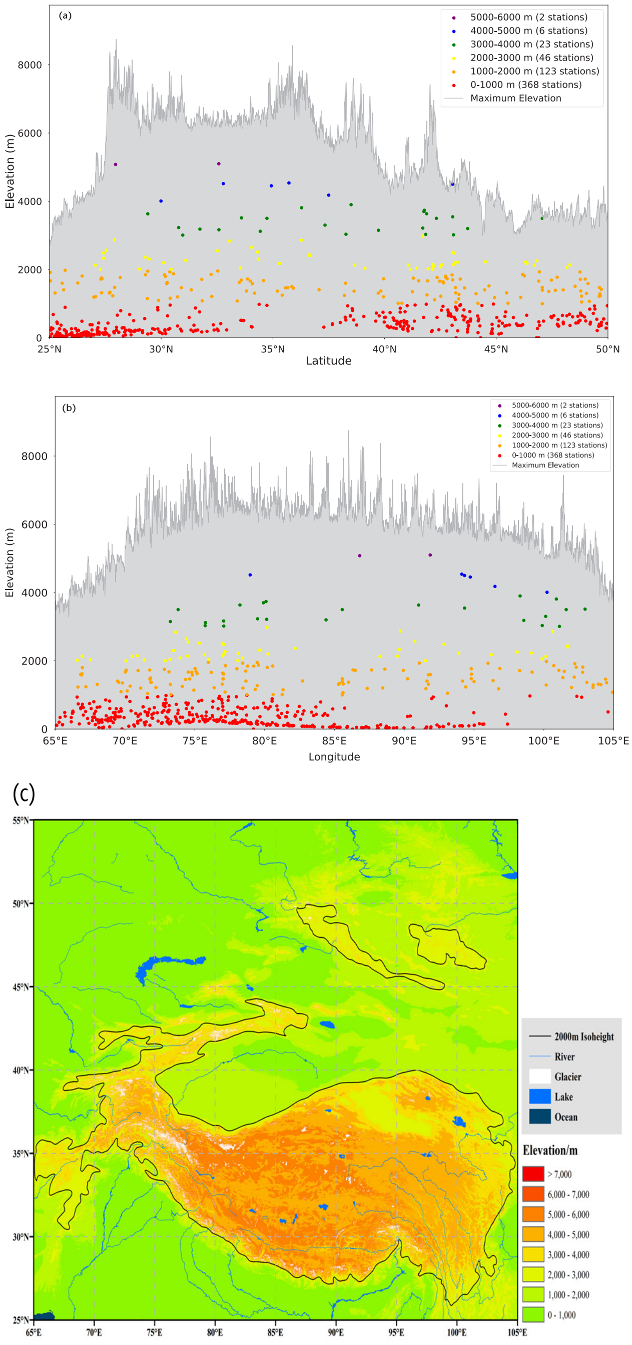

Figure 3. Meteorological stations registered in the WMO Observing Systems Capability Analysis and Review Tool – OSCAR/Surface in the geographical area covered by the Third Pole Regional Climate Centre Network. (a) stations by elevation in the East-West transect of the region 65 °E to 100 °E (elevations from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM); (b) stations by elevation in the North-South transect of the region 25 °N to 50 °N (elevations from SRTM DEM); (c) the geographical area covered by the Third Pole Regional Climate Centre Network (rccra2.org)

Source: Ran Shang (WMO), Pengling Wang (China Meteorological Administration)

meteorological observations[1] are predominantly located at elevations below 1000 m. The limited number of systematic observations, including of air temperature and precipitation, at higher elevations makes it difficult to generate reliable forecasts and predictive products and to monitor extreme events over the vast extent of these mountain regions, which are known to provide water resources for ecosystems and the livelihoods of well over 1.5 billion people.

Globally, observations of snow, glaciers, permafrost and critical tropical highland ecosystems have remained sparse, being operated primarily within time-bound research projects. There are limited engagements with operational entities and these data are seldom used in the production of climate services.

Progress has been made on addressing polar and space-based high mountain cryosphere observing needs by combining optical and radar imaging, altimetry and gravimetry, and Digital Elevation Models (DEM). However, for numerical weather prediction and climate reanalysis there remains the challenge of availability and sustainability of relevant operational satellites. Additionally, to fully harness the wealth of satellites, there remain challenges in accessing, processing and interpreting results from large datasets (S Gascoin, et al., 2023).

WMO has undertaken a consolidated approach to documenting requirements for monitoring of the high mountain cryosphere, which is critical to inform strategic goals of space agencies. The existing observations are not fulfilling the spatiotemporal resolution required by users – for example, for snow extent, melt, surging glaciers, GLOFs or avalanche monitoring – and the combination of satellite and in situ data and models is fundamental to bridge existing sampling issues.

There is still a lack of operational satellite products for accurately measuring solid precipitation, snow depth or the water equivalent of snow cover (SWE), which are needed to respond to hydrological expectations concerning snow water monitoring in high mountain regions. SWE is a crucial parameter for warning on snowmelt conditions and proper runoff modelling. These are of high importance for

1 Registered in the WMO database for Surface Observing System Capability Analysis and Review Tools (OSCAR/Surface), which provides data in real-time for Global Numerical Weather Prediction

water resource management, hydropower energy production, other sectors.

Engagement and active collaboration, especially between research and operational entities, are necessary steps to overcome the current cryosphere information gaps, and to improve the monitoring and assessment of risks due to climate change and melting ice. Installing and sustaining automatic weather stations at high altitudes – over 4 000 m – that transmit data in real time via the WMO Information System (WIS2) is essential for improved monitor and prediction of hazards for effective early warnings systems for GLOFs and other risks further downstream. This is one of the recommendations discussed by the Nepalese experts in the aftermath of the Thyanbo Glacier Lake disaster.

Challenges – Enhancing Earth system Predictions

Cryosphere information needs differ by application, depending on their timescales. For instance, numerical weather prediction (NWP) efforts can generally neglect changes in the polar ice sheets or permafrost over timescales of hours to days. On the other end of the spectrum, climate projections for the end of the century do not require detailed initialization of the current state of seasonal snow and ice cover.

Reliable and long-term climate records on and about the cryosphere are essential for understanding changes, representing processes in models (for example, ice sheet-ocean-atmosphere interaction), projecting future scenarios, and for risk assessments. Near real-time information is essential for monitoring the cryosphere and detecting extreme events for adequate early warning systems.

An increased understanding and model representation of the complex interactions between ocean, land, water, sea ice and atmosphere at scales representative of processes – the inhomogeneous mountain terrain (Rotach et al., 2022[2]) – is required to improve capabilities of Earth system models in polar and high mountain regions.

Land-surface hydrology is an integral part of Earth system modelling. Many applications would benefit from the integration of hydrological models with Earth system models to capture feedback to the atmosphere, for example, soil moisture; open water vs. ice conditions for fluxes of energy, momentum and moisture; the thermal state and albedo of snow and ice surfaces. For other applications, hydrological models run effectively in a "stand-alone" mode, forced by the outputs of weather and climate models, downscaled to the required resolution. This line of modelling enables the generation of ensembles of hydrological predictions (that is, spanning the uncertainties of parameter settings and model forcings) to provide probabilistic information for key applications such as flood forecasts or seasonal water resource scenarios.

Addressing the challenges

There are several domains where WMO is best positioned to advocate and support enhancing capacity to respond to the increasing demand for information in polar and high mountain regions, specifically on the cryosphere.

A priority continues to be the establishment of automatic weather stations for continuously monitoring meteorological and environmental conditions in proximity to glaciers, permafrost and on ice sheets. Real-time access to these observations – in particular air temperature, precipitation and snow – are essential to support monitoring and predicting snow and ice retreat and their associated risks. These are key to establishing early warning systems for these regions. The framework of an expanded WMO coordinated Global Basic Observing Network, with appropriate technical solutions for real-time transmission via satellite, and funding through Systematic Observations Financing Facility (SOFF) are the only way to address current gaps in the framework of the Early Warnings for All initiative launched by the United Nations Secretary-General.

Furthermore, the development of hydrometeorological alerts specific to mountain and polar regions, and modelling and forecast programmes designed for their specific conditions, would benefit from routine access to high spatial resolution satellite images of high mountain areas, including covering the equatorial glaciers.

The Early Warnings for All strategy should evolve a focus in the climate domain for risks related to the

2 Rotach, M. W., et al (2022). A Collaborative Effort to Better Understand, Measure, and Model Atmospheric Exchange Processes over Mountains, *Bulletin of the American Meteorological Society*, 103(5), E1282-E1295. Retrieved 5 September 2022, from https://journals.ametsoc.org/view/journals/bams/103/5/BAMS-D-21–0232.1.xml.

cryosphere, with a time horizon from short term to decade-century scales. These should include the link between the melting of the cryosphere under different climate scenarios, its contribution to sea-level rise and the impacts on coastal areas, low-lying countries and small islands, and the thawing of permafrost and the release of carbon in the atmosphere.

Investment in people remains paramount. Training of technicians and specialists in mountain meteorology, hydrology and cryospheric observations and data management, engaging experts from research and operational organizations in the Member States and Territories directly affected by changes in the cryosphere would build the sustainable solutions to address future challenges.

Over the last decade, WMO, through the Global Cryosphere Watch, has taken concrete steps to building collaborative engagements at regional and global scales with existing programmes and research networks in the cryosphere domain, by building on its proven experience in the meteorological domain. This has fostered an increased understanding of existing observing and data capabilities and collaborative efforts towards addressing systematic observing gaps. An example of these contributions is the publication of the Volume II, Measurement of Cryospheric Variables in the *Guide to Instruments and Methods of Observations* (WMO-No. 8), in collaboration with the International Association of Cryospheric Sciences, the Global Terrestrial Network for Permafrost, the Global Climate Observing System (GCOS), and other scientific networks. A continuation of these engagements is critical for WMO to remain effective in the cryosphere domain in initiatives such as the Mountain Research Initiative, the Third Pole Environment (TPE), the Sustaining Arctic Observing Networks (SAON) and others.

The advocacy and contribution to the strategic actions supported by WMO has been coordinated through the Panel of the Executive Council on Polar and High Mountain Observations, Research and Services (PHORS). PHORS spearheaded the development of WMO Cryosphere High-Level Ambitions endorsed by the 78th session of the WMO Executive Council in June 2024. These are principles for engagement and advocacy in support of the actions on the cryosphere endorsed by the 19th World Meteorological Congress in 2023.

Reference

IPCC, Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), Summary for Policymakers (SMP), A3.

S. Gascoin, 2023: A call for an accurate presentation of glaciers as water resources, WIREs Water, https://doi.org/10.1002/wat2.1705.

WMO Cryosphere High-Level Ambitions

Addressing the gaps and challenges identified in this article and fostering global actions for cooperation across different scales and planning horizons rely increasingly on the ability to communicate to responsible policy makers and implementers, and to increase public awareness.

1. **The urgency:** Everyone on the planet is prepared for, and resilient to, the impacts from changes in the cryosphere-The changing cryosphere affects the global community, whether through the sea-level rise, water and food scarcity, geotechnical risks, leading to threats to economies, livelihoods, energy sources, trade, and geopolitical stability

2. **Global collaboration:** The global community works collaboratively to limit and reduce cryosphere loss and its impacts –The cryosphere transcends international borders and geopolitics and only coordinated action can enable changes towards limiting cryospheric loss and its catastrophic impacts

3. **Accessible data and knowledge:** Data as well as scientific and indigenous knowledge are accessible and provide a sound basis for policies and decisions relating to the cryosphere - Improved observation coverage, good data management, integration of indigenous knowledge and improved global data sharing are needed to enable analysis and prediction services that support decisions

4. **Action:** The importance of the cryosphere and the consequences of its changes are known, universally understood and inspire action - Global, urgent and effective actions need to be mobilized through increased understanding and cooperation to address the root causes of climate change and of the cryosphere loss.

The observance of the International Year of Glaciers' Preservation, supported by WMO, is an example of global engagements to increase awareness at multiple levels about complex changes that affect everyone on the planet.

International Year of Glaciers' Preservation (IYGP 2025)

In December 2022, the United Nations General Assembly adopted resolution A/RES/77/158 to declare 2025 as the International Year of Glaciers' Preservation (IYGP 2025), accompanied by the proclamation that 21 March of each year will be the "World Day for Glaciers", starting in 2025. WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) were invited to facilitate the implementation of the International Year and observance of the World Day. This initiative, through coordinated momentum to address the urgency of the matter, is aimed at raising awareness, pursuing policy advocacy, and facilitating actionable and sustainable measures for preservation of glaciers.

The coordination mechanism of IYGP 2025 is composed of four Task Forces (TF):

- TF-1: Global Campaign for International Year of Glaciers' Preservation 2025 (Lead: FAO Mountain Partnership Secretariat)
- TF-2: International Conference on Glaciers' Preservation, Regional Workshops and Capacity Building (Lead: ICIMOD-International Center for Integrated Mountain Development)
- TF-3: Research and Monitoring Initiatives (Lead: University of Chile in Santiago)
- TF-4: Policy Advocacy, Partnerships and Resource Mobilization (Lead: ICCI- International Cryosphere Climate Initiative)

WMO encourages its Members to actively engage in the initiatives related to the IYGP 2025. Examples of foreseen/ongoing activities range from communication and awareness raising (TF-1 and TF-3) to capacity development and IYGP 2025 launch (TF-2) as well as policy advice, networking, lobbying and advocacy (TF-4) in addition to research and monitoring (TF-3).

The International Polar Year 2032/2033

The planning for a 5th International Polar Year (IPY) for 2032/2033 is taking shape under the early leadership of International Arctic Science Committee (IASC) and Science Committee on Antarctic Research (SCAR) and with the support of WMO. The 5th IPY will foster vital cooperation among countries, disciplines, programmes, and knowledge systems to produce urgently needed actionable information to support evidence-based challenges. It will build directly on the legacy of the 4th IPY (2007/2008), which drew together evidence from thousands of polar scientists and others emphasizing that what happens at the poles has global impacts. It also generated an impetus in polar science communication, education, and public engagement.

The collaborative global efforts will allow researchers and knowledge holders to capitalize on the outcomes of previous IPYs by expanding integrated and coordinated observations of accelerating changes, and long-term monitoring to enhance the understand of current conditions and inform predictions of future states. It will build on the methodological, technological and epistemological advancements of the 4th IPY, including major shifts toward working across knowledge systems.

- It will provide a comprehensive assessment of the operation and evolution of polar ecosystems enabling a more holistic understanding of the Earth's interconnected systems and climate change trajectory, as well as supporting practical global and local adaptation solutions
- An important goal of the 5th IPY is to achieve a step change in transdisciplinary polar research through meaningful integration of natural sciences, social sciences, humanities research, and Indigenous knowledge systems.

For further details see: https://iasc.info/cooperations/international-polar-year-2032-33.

A Science and Technology Vision for WMO

(A list of contributors is provided at the end of the article.)

Recent decades have recorded increasing negative impacts from extreme weather and climate events due to human-induced climate change and population shifts. These regional and local impacts have global consequences. Weather, climate, water- and environmental-related services (herein referred to together as environmental services) provided by WMO Members help governments enhance environmental security, mitigate impacts and support economic growth. But as the climate emergency intensifies, policy makers are requiring environmental service providers to adapt their science and services to better address regional, national and local adaptation and mitigation needs. Thus, WMO already anticipates increased demand for accurate and actionable environmental services, for greater focus on impact attribution, and for better integration between disciplines. Now is the time for the Organization to focus further on translating global scientific advances into locally impactful environmental services, especially for middle- to low-income countries, while engaging users and stakeholders, providing training and support, and fostering international cooperation.

Environmental services are reliant on global infrastructure, numerical models, Earth system observations and skilled personnel. Weather-climate prediction systems have significantly improved over the past 50 years due to enhanced observations, data assimilation, understanding of physical processes and model sophistication. However, climate and weather models still struggle with finer-scale processes like cloud formation and cumulus convection, and the microphysics affecting precipitation representations. A leap in computing power would help to better resolve complex systems and provide robust information on high-impact events, tipping points, and potential irreversible changes.

WMO is ideally placed to coordinate the research and development (R&D) and knowledge sharing revolution that is needed to deliver these urgently needed environmental services. Towards that goal, the Organization needs to assess future demands and disruptors of environmental services and existing or emerging capabilities to tackle the challenges ahead. The 2023 World Meteorological Congress approved the WMO Scientific Advisory Panel 's Recommendations (Resolution 35 (Cg-19), see box entitled Eight Recommendations of the WMO Scientific Advisory Panel) to initiate the required R&D and knowledge sharing revolution that will deliver and support climate mitigation and adaptation. The R&D components of the recommendations are already being delivered in many aspects by the WMO sponsored and co-sponsored research programmes:

- Global Atmosphere Watch (GAW)
- World Weather Research Programme (WWRP)
- World Climate Research Programme[1] (WCRP).

The WMO Research Board is providing guidance to the effort through multiple working groups and initiatives and contributions from the WMO Commission for Observation, Infrastructure and Information Systems (INFCOM) and WMO Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (SERCOM).

A priority for R&D is the improvement of Numerical Earth system Weather-to-Climate Prediction (NEWP) systems and kilometre-scale (km-scale) global information and insights. The digital revolution, a surge in data availability, the expansion of the private sector and the transition to a net-zero carbon economy are set to propel the development of environmental services. The adoption of supercomputing, machine learning and artificial intelligence (AI) will play a crucial role in strengthening environmental services value chains, leading to more accurate predictions, enhanced data analysis, and improved decision-making. These advancements will enable a more integrated and effective approach to environmental services, unlocking new opportunities for innovation

1 The World Climate Research Programme is co-sponsored by WMO, the International Science Council (ISC) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO

and sustainability. Higher spatial and temporal resolution observations, improved understanding, and modelling of the Earth system across weather and climate timescales, and high capability supercomputing are needed for improved NEWP systems. R&D of affordable, non-conventional observations and data assimilation systems should be pursued.

National Meteorological and Hydrological Services (NMHSs) involved in this innovation cycle will need to make strategic decisions in the coming years. As technologies continue to evolve and merge, and new business practices emerge rapidly, some NMHSs may find it challenging to keep pace (see Figure 1).

The innovation cycle involves a collaborative effort between the public, private and academic sectors, as highlighted by Brunet et al. (2021). The operations component focuses on creating forecasts and other products, while the service component is dedicated to delivering these products to stakeholders and customers. It is important to note that each sector can contribute to various aspects of this cycle, including R&D, operations and service.

Within the above context, this paper shall explore the scientific and technical challenges of the future by considering the following two questions in the subsequent sections:

- What do we see as the future demands and disruptors for environmental services?
- What are the existing and emerging capabilities that can help meet these future demands equitably?

Figure 1. Innovation Cycle

Eight Recommendations of the WMO Scientific Advisory Panel

Recommendation 1: Major international climate R&D effort in the exploitation of global kilometre-scale (km-scale) computing and Earth System observations

Recommendation 2: Bridge the gap between developing global science and delivering local impact

Recommendation 3: Develop a digital strategy

Recommendation 4: Accelerate the development of attribution science and techniques

Recommendation 5: Further development of quality assurance strategy for weather, climate and water-related services

Recommendation 6: Work across agencies to enable closer integration of geophysical and social sciences to support better understanding of the impact of weather, climate and water events

Recommendation 7: Develop education and training strategies to broaden expertise beyond traditional disciplines

Recommendation 8: WMO, together with National Meteorological and Hydrological Services (NMHSs), to provide leadership in the move towards to net-zero.

Future demands and disruptors

(1) Demand for greater exactitude and local detail on the impacts of weather, climate, water, and environmental-related events in the context of a changing climate

Users demand improved accuracy and relevance from environmental services. They no longer wish to simply listen to a weather forecast or climate scenario, they are interested in the possible impacts of that event on their physical, social and economic well-being and the environment. Their requirement for increased accuracy, in terms of increased spatial resolution and reduced uncertainty, and for better understanding of impacts has several important drivers on scientific endeavours in the area of meteorology and climatology.

First, it is essential to improve NEWP system accuracy and quantifying uncertainty together with the knowledge of local vulnerabilities to understand weather and climate impacts. Current climate predictions struggle with convective scale processes that cause storms, floods and, indirectly, droughts and heatwaves because of a deficient water cycle representation. Significant numerical and physics modelling limitations persist when representing precipitation patterns, climate variability modes, and extreme event statistics. Uncertainty in knowledge of Earth system interactions is partly due to insufficient comprehensive observations. This observational and modelling uncertainty limits our understanding of high-impact, low-likelihood events, and climate tipping points. Persistent numerical modelling biases in tropical convection, extra-tropical storm-tracks and rainfall have global consequences, affecting atmospheric circulations and midlatitude weather patterns.

NEWP systems are increasingly using ensembles, but further research is needed for optimization and effective utilization. Challenges include providing skillful probabilistic forecasts and addressing uncertainties. Effective communication and visualization are essential for supporting decision-making. Major international efforts are required to develop high-resolution NEWP systems and their associated services, with focus on Recommendations 1, 2 and 6, ensuring value for all communities.

Secondly, understanding the impacts of weather, climate, water-related and other environmental events requires integrating geophysical and social sciences. Future users and policymakers may prefer holistic environmental services that capture event impacts instead of separate services from weather, climate, water and environment agencies. This integration necessitates collaboration between natural and social scientific disciplines, driving the principle behind Recommendation 6.

Finally, attribution of extreme events to anthropogenic climate change is crucial for the future climate services demanded by policy and decision-makers. As the science advances, WMO needs to provide leadership and guidance as requested by Recommendation 4. Detection and attribution require fine spatial scale. WMO should foster research and promote observational and modelling capabilities globally, particularly in vulnerable regions. Continued development in this area will increase the availability of knowledge and techniques in all countries.

(2) Digital revolution and big data

The dramatic increase in personal device usage has transformed how people receive information, with users expecting customized weather data. For example, in the United Kingdom (UK), the use of digital devices for weather information increased from 37% in 2012 to 76% in 2020. This opens opportunities for service providers and government agencies to deliver official warnings directly to the public. The demand emphasizes the need for quality NEWP output, especially in digital services without human intervention. NMHSs must develop agile strategies, possibly through regional collaboration, to maintain authority amidst a fast-changing market with multiple information providers, including the private sector.

Our science, technology and services communities must manage significantly larger quantities of data due to advances in modelling and observations, driven by demand for localized, comprehensive, accurate and timely information. Unprecedented environmental insight, improved predictions, and bespoke services can be achieved by integrating various data sources like remote sensing, ground-based observations, sensor networks, citizen science and online sources. However, this necessitates major investment in big data systems, data analytics, machine learning, and AI, which could be challenging for middle- to low-income countries. Regional scale collaboration and cloud computing could help facilitate pooling of resources and become crucial enablers.

The rapidly expanding data volumes, in part driven by the implementation of new WMO policies and Global Basic Observing Network (GBON) standards, will significantly challenge NMHS's abilities to manage data. Geographic Information System (GIS) platforms and Application Programming Interfaces (APIs) can enable users to access data and create their own services, integrating demographic, economic and vulnerability data from other agencies. Novel approaches, skill development and infrastructure investments are required to remove the barriers that hinder the use of global scientific outputs by all NMHS for local benefits. The challenges of big data and digital revolution in service delivery are addressed in Recommendation 3.

(3) Global science for local impact

Maximizing the use of weather forecasts, climate predictions and environmental factors (such as pollution) requires new methods to ensure that all countries, particularly middle- to low-income countries, can downscale products for local risk reduction and resilience applications. Equitable global participation in environmental sciences, infrastructure development and service delivery is crucial. Middle- to low-income countries should be active participants, driving the future science agenda and making research and innovation a priority. This challenge is addressed in Recommendation 2.

(4) Private sector as an active player and quality assurance of services

The relationship between WMO, the private sector and academia will have to reinforced to resolve weather, climate and air-quality forecasting challenges. WMO should take the lead in quality assurance for data, products and services, and in establishing globally accepted standards. By partnering with the private sector and academia, WMO can develop methodologies for validation and guidance on data use and management for all time scales. WMO should assist in educating users to identify high-quality products that may benefit national and international climate change adaptation policies. Recommendation 5 aims to address this driver.

(5) Move towards a zero-carbon global world

The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) aims to hold global warming below 2 °C and to pursue efforts to limit it to below 1.5 °C, although there is ever more evidence pointing to the latter becoming an unlikely target. Either target requires immediate and sustained reductions of greenhouse gas emissions to reach net-zero carbon emissions by the middle of the 21st century.

The Paris Agreement and net-zero strategies have implications for NMHSs as they are at the forefront of weather and climate science and services. Increasing energy demand for supercomputing may compete with the need for improved NEWP systems, and a more sustainable approach to consumable observational infrastructure, like radiosondes, may be necessary. The WMO Strategic Plan 2024–2027 includes an objective around environmental sustainability, committing to a sustainable, net-zero, resilient world. Recommendation 8 expands on this by addressing computing infrastructure. New collaborations could positively impact diversity and inclusion in WMO operations, and both WMO and NMHSs can become strong voices within the United Nations family and national governments in the transition towards net-zero.

The push for net-zero will create new markets for environmental services. As energy production shifts towards renewables, information on weather, climate, water and the environment will become more valuable for locating and operating wind, solar and hydro power generation sites.

Emerging and existing capabilities to help meet future needs

Exascale computing – The next generation computational technology is crucial for NEWP's advancement. Current investments in supercomputing for weather, climate and air-quality predictions have not fully unlocked NEWP's potential. NEWP R&D must balance investments in resolution, complexity, ensemble size and timeliness for optimal results. A coordinated global effort is needed for Earth system modelling and data analysis at the exascale, motivating Recommendation 1.

Machine learning (ML), artificial intelligence (AI) and cloud computing – ML and AI have numerous potential applications in the environmental services value chain, most notably in improving weather forecasts by removing model biases. The European Centre for Medium-Range Weather Forecasts (ECMWF) has already made revolutionary advances in this area. They are running real-time ML and AI weather predictions and sharing the results. These techniques, which require reforecasting and observational datasets for algorithm training, are already used in operational post-processing systems.

Cloud computing can democratize access to high-powered computing, potentially allowing all countries, including middle- to low-income countries, to utilize top-quality weather and climate information. By managing large datasets in the cloud, data handling issues can be avoided. NEWP model providers and supercomputing vendors could collaborate to integrate multimodels in clusters, making them available as a cloud service. Countries could then affordably access NEWP systems or postprocess global model output for their specific regions without the burden of managing heterogeneous supercomputing and data. This approach is captured in Recommendation 3 and could be the technical implementation for Recommendation 2.

Exascale Computing and Other Opportunities*

A substantial enhancement of Earth System model spatial resolution would reduce the use of approximations for known physical processes. Higher resolution models would deliver more and better information on the water cycle. When combined with better data assimilation – thanks to improved data requirements and standards – and the use of ensembles for improving uncertainty estimation, it would revolutionize environmental services. Capacity today is limited by the availability and affordability of extreme-scale computing and data handling infrastructures and their operation in ecologically sustainable environments. Computing and data handling challenges are nearly identical for weather and climate prediction as well as for the value chain for environmental services applications. A generic solution could therefore benefit all areas simultaneously.

An investment in modern software infrastructures for complex simulation and observation handling workflows is required to improve predictive skill, science-to-service quality and user interaction in the production of environmental services. This would allow exploitation of diverse digital technologies across the entire range of data generation and information extraction, including smart sensors and networks but also data from the Internet of Things, edge and cloud computing, extreme-scale computing and big data handling. Machine learning and new algorithmic frameworks would support faster computing and more effective extraction of user specific information from vast amounts of data. The novel notion of digital twins for the Earth system comprises all these aspects, leading to much enhanced levels of data quality and user interaction.

Novel technologies and related research programmes are increasingly being implemented in individual countries (for example, Destination Earth in Europe and international Earth Virtual Engines (EVE) initiative) and, in selected cases, by commercial enterprises (for example, NVIDIA Earth-2), but these will not suffice. There is a need for global, multinational coordination to maximize the return on investment, to ensure that developments benefit the entire community across high-income and low-income countries, and to produce a step change for our predictive capabilities across all space and timescales. A close science-technology co-design of systems and new levels of digital technology expertise is required.

* Acknowledgements to Peter Bauer, ECMWF.

Research Board Concept Note on use of AI and Data Exploitation in Environmental Modelling*

Summary key points, and related recommendations, raised in the concept note:

• Rapidly evolving research creates an imperative for WMO Members to develop strategies and plans for the adoption of AI methods in operational and production systems. WMO can support this by facilitating discussion between Members.

• Data handling challenges are placing conventional workflows under increasing strain, creating an imperative for changes in approach. WMO can support this by facilitating discussion between Members.

• The use of AI methods combined with the expansion of the range of available datasets creates an opportunity for WMO Members to provide new services, but considerable practical barriers remain. WMO can assist centres by facilitating efforts to elicit requirements and by supporting the development of a coordinated road map to meet these requirements.

• The adoption of common standards and practice is essential to enable effective and efficient sharing of data and methods. WMO should facilitate the development of guidance and standards and identify a suitable body to take ownership of these.

• There is potential for public-private partnerships to deliver benefits through enhanced access to a combination of data, platforms and methods. WMO's Public-Private Partnerships could support this effort which would improve product delivery for middle- to low-income countries.

* Acknowledgements to Adrian Hines, Science and Technology Facilities Council, UK.

Observation technologies and techniques

High-quality, well-managed ground and space-based observations are crucial for weather, climate, water and environment enterprises. However, the number of such systems has decreased worldwide over the past 20 years due to financial constraints. Vulnerable areas, particularly in middle- to low-income countries, need well-equipped stations for early warning systems and as reference points for complementary systems, private partnerships, climate simulations and weather forecasts. Precipitation is challenging to measure, and reliable observations, with the required spatial density and high spatial-temporal resolution essential for validating models against observations, are lacking.

As km-scale modelling progresses, observation density must increase, particularly with respect to data on the water cycle. While GBON provides the basic surface-based observing network for global NEWP modelling and climate analysis, it lacks the coverage needed for future applications. Complementary systems, including technological advances in low-cost communications and sensors, can help fill these gaps, utilizing the "Internet of Things" and mass-market sensors for environmental monitoring. In addition, under-utilized weather stations can contribute to the overall system if sharing arrangements are agreed upon. In addition, the Systematic Observations Financing Facility (SOFF) supports countries to close the basic observational data gap for environmental services. SOFF assistance prioritizes Least Developed Countries and Small-Island Developing States to accelerate the sustained collection and international exchange of the most essential surface-based weather and climate observations in compliance with GBON.

Collating, storing and quality controlling data from various sources, especially "citizen scientists", requires developing and sharing tools and expertise. WMO must consider its approach to data quality and metadata standards as complementary data sources become more common. "Non-conventional" observations, like estimating rainfall from attenuation of signals between cell phone towers, and continued research in new technologies may be essential for achieving comprehensive and affordable data coverage. Facilitating the availability and sharing of these observations should occur under the WMO Unified Data Policy.

Complementary observations can enhance spatial and temporal resolution, but the optimal balance of satellite, surface-based and other observations for specific use cases remains a challenge. Forecast sensitivity studies help target investment for maximum benefits. NEWP's data assimilation systems must accommodate novel observation sources, integrating comprehensive observations with multiscale models. Coupled prediction systems need co-located observations across system interfaces for model development, evaluation and forecast initialization. Global, comprehensive in situ observations, like GAW, with open data access, metadata, quality monitoring and high-resolution are essential for environmental services. These observations are crucial for understanding the Earth system and addressing research, societal and policy-relevant questions. Observations' importance is explicitly captured within Recommendation 1.

Evolving international frameworks

International cooperation is a strength of WMO. Global science collaboration is needed to exploit exascale supercomputing and observation opportunities, but such efforts must be accompanied by mechanisms for countries to utilize these advances in their environmental services as stated by Recommendation 2. WMO Regional Associations, NMHSs and local sector-based user institutions should work together to co-design and deliver multidisciplinary research products and to develop local and regional capacity to seamlessly integrated modelling data and downscale information to regional and local needs.

WMO regional centres can collaborate with the Global Framework for Climate Services (GFCS) to ensure that global science translates into local impacts. Investment in infrastructure and skilled personnel is crucial for regional and national institutions, and working across international organizations and structures is essential for delivering all recommendations.

Including all people

Advancing skills in a gender equal, diverse and inclusive way is a must within the NMHS community and academia, especially in middle- to low-income countries. Impact-based services demand a new approach to education, involving various disciplines like finance, risk management and communication.

Training in whole systems thinking and co-designed science is crucial to connect with affected sectors without neglecting traditional disciplines.

Educating practitioners, researchers and teachers is critical, as is enhancing the understanding of policymakers and decision-makers regarding the value of national services and their benefits and limitations. As NEWP advances lead to more sophisticated data sources, expert interpretation will be necessary for decision and policymakers. Recommendation 7 addresses people development issues.

Conclusion

We have identified drivers, disruptors and enablers impacting environmental services over the next two decades, highlighting scientific, technical and social imperatives. The first three SAP Recommendations are potential game-changers for environmental services in the coming decades. The remaining five complement and enhance the benefits derived from the first three. WMO technical commissions and the Research Board, along the sponsored and co-sponsored research programmes, are actively engaged in investigating related topics identified in the Recommendations. This includes liaising with the Panel on Socioeconomic Benefits to advance the societal impact of WMO science, updating concept notes on exascale computing and data to include an explicit digital strategy, continuing to advance weather and climate simulation and attribution research, and forming a rapid response task team on AI for weather.

These recommendations are critical steps for WMO, its Members, and the international community to address future demands for environmental services in a climate-impacted world. The goal is to provide timely, reliable and relevant information on future climate risks, especially for vulnerable nations. Achieving this requires international collaboration, including the development of km-scale global climate models and dedicated high capability supercomputing and data facilities powered by renewable energy.

It is essential to integrate advances in observing networks, modelling systems and data sharing and to develop seamless data platforms for weather, climate, hydrological and environmental observations. Transforming operational climate data services through cloud-based platforms, data management techniques and close collaboration with the IT private sector is crucial.

To translate climate data into actionable information, interdisciplinary science for impacts and solutions must be developed, integrating geophysical and social sciences. Increased international collaboration should engage and support all nations, building capability and expertise. WMO should develop training strategies to broaden expertise beyond traditional disciplines and foster a new generation of cross-disciplinary researchers and practitioners. The success of these recommendations depends on immediate action to enhance international collaboration and cooperation among entities such as WMO, under WWRP and WCRP, and initiatives led by various NMHSs, including Destination Earth, ECMWF and the MOMENTUM Partnership.

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IMO Prize Lecture 2024

Tim Palmer presenting the IMO Prize lecture at the Seventy-eighth session of the WMO Executive Cuncil (June 2024)

Ensemble Weather and Climate Prediction – From Origins to AI

By Tim Palmer, Department of Physics, University of Oxford

Ensemble prediction is a vital part of modern operational weather and climate prediction, allowing users to estimate quantitatively the degree of confidence they can have in a particular forecast outcome. This, of course, is vital in helping such users make decisions about different weather-dependent scenarios. The development of such ensemble systems for both weather and climate prediction has played a large part in my own research career. Below is a personal perspective on these matters. I conclude with some thoughts about directions we should be taking going forward, especially in the light of the AI revolution. I am grateful and humbled to have been awarded the WMO IMO medal for this work- many of my greatest heroes are IMO medallists.

The birth of operational numerical weather prediction (NWP) began shortly before 1950 when John von Neumann assembled a team of meteorologists, led by Jule Charney (1971 IMO medallist), to encode the barotropic vorticity equation on the ENIAC digital computer. These early models were not global and could only make useful forecasts for a day or two ahead.

Soon meteorologists began asking how far ahead reliable weather forecasts could in principle be made, given global multilayer models which encoded the primitive equations. Studies by Chuck Leith, Yale Mintz and Joe Smagorinsky (1974 IMO medallist) provided estimates of around two weeks, based on the time it took initial perturbations with amplitudes consistent with initial condition error to become as large as randomly chosen states of the atmosphere. The two-week timescale became known as the "limit of deterministic predictability". As I will discuss below, it became a misunderstood concept.

I joined the Met Office (UK) in 1977 after a PhD working on Einstein's general theory of relativity – a childhood ambition of mine. My change in subject was in part driven by a desire to do something more useful for the rest of my research career, and in part due to a chance meeting with Raymond Hide, an inspirational and internationally renowned geophysicist then working at the Met Office. My early work at the Met Office was on stratospheric dynamics. With my colleague Michael McIntyre from the University of Cambridge, we discovered the world's largest breaking waves, and in so doing kick-started the use of Rossby-Ertel potential vorticity as an insightful diagnostic of planetary-scale atmospheric circulation. The general absence of such breaking Rossby waves in the Southern Hemisphere is critically important in explaining why the ozone hole was first discovered in the Southern Hemisphere and not in the Northern Hemisphere, as had been expected.

In this way, I had become an expert in stratospheric dynamics and was promoted to become a Principal Scientific Officer and hence group leader at the Met Office. By a quirk of the UK scientific civil service, this meant I had to move field since there were no vacancies for group leader in the stratospheric group. Indeed, the only research-leader vacancy was in the long-range forecasting branch. And so there I was posted, not knowing anything about long-range forecasting.

In those days, long-range forecasting – on month-to-seasonal timescales – was performed with what were called statistical empirical models. Now, we would call them data-driven models. My job was to introduce physics-based models into the operational long-range forecast system. Early work by J. Shukla (2007 IMO medallist) and Kiku Miyakoda indicated that such models – if they are driven with observed sea-surface temperatures – are in principle able to forecast the planetary-scale flow on these long timescales.

The statistical empirical model output was probabilistic in nature. They would, for example, provide probabilistic forecasts of the occurrence of predefined circulation regimes over the UK (known as Lamb weather types). Hence if physics-based models were to be integrated into the long-range forecast system, the forecast output also had to be probabilistic in nature. My colleague James Murphy and I developed a relatively crude ensemble forecast system based on the Met Office global climate model, using consecutive analyses to form the initial conditions, from which such probabilities could be estimated. This, I believe, was the world's first real-time ensemble forecast system. It began producing probabilistic ensemble forecasts in late 1985.

Early in 1986 I had what might be called a light-bulb moment: Why aren't we using the ensemble forecast system on all timescales, including the medium-range and (even) the short range? I joined the European Centre for Medium-Range Weather Forecasts (ECMWF) in 1986 to try to develop and implement such a system, but I met with some pushback from colleagues. Their argument was that whilst it was fine to use probabilistic ensemble methods to forecast on timescales longer than the limit of deterministic predictability, that is to say on month-to-seasonal timescales, the forecast problem on timescales within this limit was essentially deterministic in character. We should therefore use new computer resources, when they became available (this was the era of Moore's Law), to improve the deterministic forecast system – notably by increasing model resolution – rather that make multiple runs of an existing model.

I felt that this argument was based on a misunderstanding of this notion of "limit of deterministic predictability". My view was that it should be thought of as characterizing the predictability of weather on average, meaning over many instances. There will be instances when such predictability is shorter than the 2-week average, and instances where the predictability of weather is longer than the 2-week average. The key purpose of an ensemble forecast system is to help determine, ahead of time, whether the weather is in a more or less predictable state. I argued that if media forecasters make forecasts with more confidence than the predictability of the flow deserves, the public will lose confidence in meteorologists when things go wrong. (In truth, there were so many instances where the deterministic TV forecasts had gone wrong that the public treated weather forecasting as a rather dark art, to be taken with a large grain of salt.)

Ed Lorenz (2000 IMO medallist) developed his iconic model of chaos to show that the atmosphere did not evolve periodically. However, as shown in Figure 1, his model also illustrates well the concept that the growth of small initial uncertainties, and hence predictability, is state dependent, even in the early stages of a forecast. There can be occasions when small uncertainties grow explosively. Lorenz's model makes it clear that the notion of a limit of predictability is indeed a statistical one, obtained by averaging over many initial conditions.

Whilst some of my colleagues may have thought Lorenz's model was too idealized to be useful, nature spoke decisively in the second half of 1987. The famous October 1987 storm, which ravaged large parts of southern England, had not been forecast the day before. The media called for the resignation of then Met Office Director General, John Houghton. The UK public had indeed lost confidence in the nation's weather forecast service.

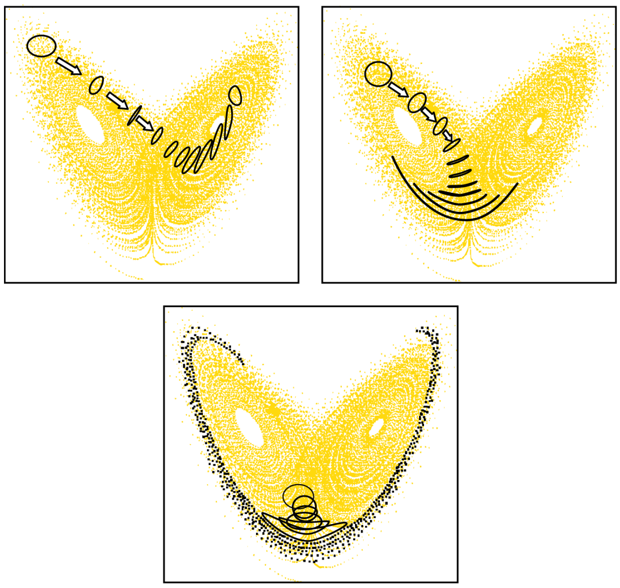

Figure 1. The initial ring of points represents the uncertainty in our knowledge of the initial state (for the famous Lorenz equations). How the ring evolves depends on its position on the attractor. Some initial states are much more unpredictable than others.

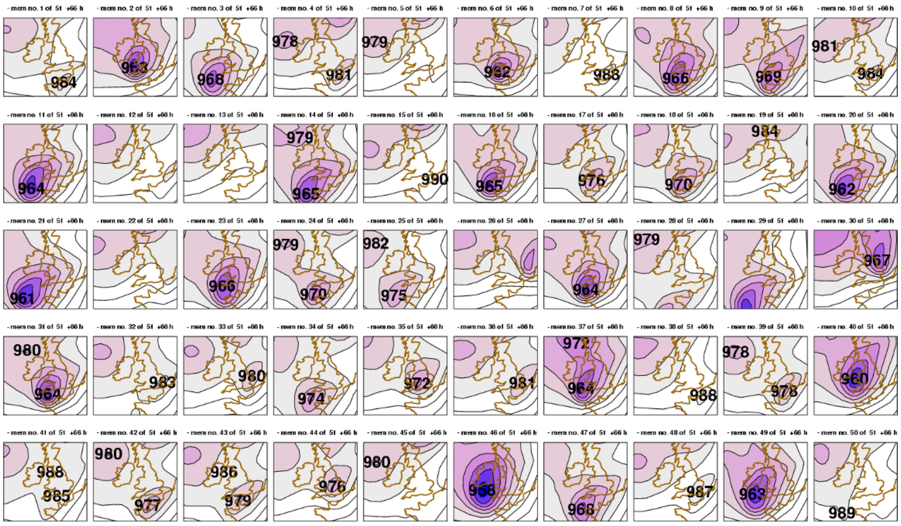

Figure 2. So-called stamp maps for a 2.5-day ensemble forecast for the morning of 16th October 1987. The ensemble shows that the weather is exceptionally unpredictable – much like the most unstable of the Lorenz integrations shown in Figure 1.

My ECMWF colleagues and I retrospectively ran our nascent medium-range ensemble forecast system on this case, and to our relief it showed an extraordinarily unstable and unpredictable flow over the North Atlantic. An ensemble of 50 forecasts at 2.5 days lead time showed ensemble members whose weather over southern England ranged from a ridge of settled weather to hurricane force wind gusts. The individual ensemble members are shown in Figure 2.

But how to communicate such an ensemble to the public? Some colleagues felt – and some still do – that one should average over the individual ensemble solutions and communicate the ensemble-mean. Whilst the root-mean-square error of such an ensemble-mean forecast would be relatively small, an ensemble average would necessarily damp out the extreme weather solutions. Unless the extreme weather is exceptionally predictable, which it rarely is, an ensemble-mean forecast is useless in warning of extreme weather.

I argued that the forecast probability of (say) hurricane force wind gusts should be communicated directly to the public. At the time, many forecasters argued that the public would never understand the notion of probability. My own feeling was that the public understood well the odds on a horse winning a horse race. Why should weather be any different? The probability of hurricane force winds from the ensemble in Figure 2 is shown in Figure 3. Given that "in Hertford, Hereford and Hampshire, hurricanes hardly ever happen", a probability of around 30% is very significant indeed and would have alerted the public to the risk of an exceptional weather event.

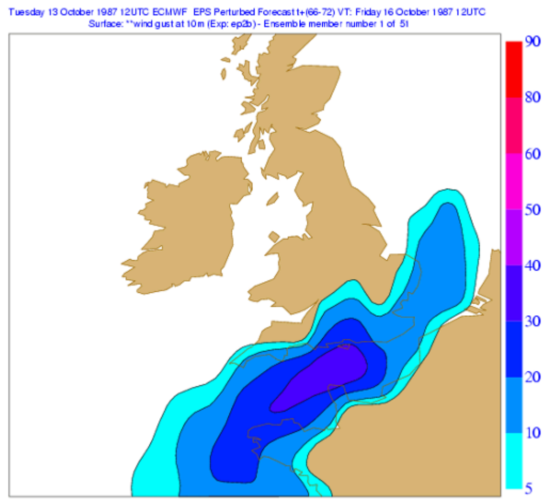

Figure 3. A map showing the probability of hurricane strength winds for the morning of 16th October. Probabilities over southern England are enormously larger than the climatological likelihood of hurricane strength winds in this part of the world.

The success of the ensemble forecast system in retrospectively forecasting the risk of extreme weather in October 1987 was important in convincing colleagues that a centre like ECMWF should take probabilistic ensemble prediction seriously – even though its main task was to make forecasts within the limit of deterministic predictability. The ECMWF Ensemble Prediction System was implemented operationally in 1992: it was the work of many individuals whom I acknowledge in my book The Primacy of Doubt. Colleagues from the National Centers for Environmental Prediction (NCEP) implemented their medium-range ensemble forecast system at the same time. (The NCEP team was then led by a sadly departed colleague Eugenia Kalnay, 2009 IMO medallist, with whom I had many friendly scientific discussions on the most appropriate method to generate initial ensemble perturbations.)

Today, ensemble prediction has become an integral part of weather and climate forecasting on all timescales, from the very short range to climate change timescales and beyond. To some extent, seeing the way in which ensemble forecasting has spread around the world reminds me of Max Planck's adage: you rarely convince your opponents, rather a new generation comes along for whom the idea is obvious.

As part of this transition to ensembles, forecasts of rainfall on Weather Apps are given as probabilities. Whilst the public may not know that these probabilities are formed from ensemble forecasts, they do understand that they provide estimates of forecast uncertainty. Obviously, a forecast of 100% chance of rain is more certain than a forecast of 20% chance of rain. The public understand these forecasts, which help them in making decisions. This could be for something as trivial as whether to pack waterproofs for a hike in the hills. If the probability of rain is 20%, then it is 80% likely you won't need the waterproofs – which you would otherwise have to pack in your backpack, making it a little heavier than it would otherwise be. But if it did rain and you hadn't brought your waterproofs, the rest of the walk would be very uncomfortable. Of course it is up to the user, and not the forecaster, to decide whether to pack the waterproofs. In this case the user must weigh up the risk of getting soaked (probability of rain times inconvenience of wet clothes) against the inconvenience of a heavier backpack. If the likelihood of rain was 5% then perhaps it wouldn't be worth packing rainproofs. If it was 80% then perhaps it would be worth it. Where exactly the dividing line is between packing and not packing is a matter of choice. Forecasts with estimates of uncertainty help the user make better decisions.

One of the most important applications of medium-range ensemble forecasting is for disaster relief. Until recently, humanitarian agencies sent in food, water, medicine, shelter and other types of aid, after an extreme weather event had hit a region. The deterministic forecasts were simply too unreliable for these agencies to take anticipatory action. However, because of ensemble forecasts, matters have changed. Like the dividing line between packing waterproofs or not, ahead of time an agency can estimate objectively a probability threshold for an extreme event, above which anticipatory action can be taken, and below which it should not be taken. If the forecast probability for a specific event exceeds this threshold, then it makes objective sense for anticipatory action to be taken.

We are in the midst of a revolution

Towards the end of 2023, a revolution happened. A group at the company Huawei showed that it was possible to forecast the weather using artificial intelligence (AI). Not only that, ECMWF's deterministic headline scores were matched by the AI system. In some sense, this was a return to the days of statistical empirical models – given lots of data, develop code which would uncover correlations in the data which can be used to make predictions. No knowledge of the laws of physics needed!

Since then, AI has been used to create ensemble forecast systems, again with comparable levels of skill of the ECMWF ensemble (though I haven't yet seen whether they could have forecast the probability of hurricane force winds in 1987 as shown in Figure 2). In the words of the Met Office's Chief AI Officer: "We are in the midst of a revolution in AI where the world's fastest growing deep technologies have the potential to rewrite the rules of entire industries, changing the way we live."

Indeed, will we need numerical weather prediction at all in the future? Will weather prediction become dominated by the commercial sector with their cheap-to-run AI models? Time will tell. However, I believe that in the future, weather forecasting will be a mixture of data-driven AI and physics-based numerical weather prediction. In a sense, we will return to the days when I began developing ensembles for the month-to-seasonal timescale, and the operational forecasts blended the statistical empirical models and the physics-based models.

In Oxford, we have been working on such a mixture. Currently, national weather services run limited-area models to downscale global forecasts to their region. With global ensemble forecasts, this becomes computationally expensive. Indeed, no National Weather Service can afford to create 50 regional downscaled forecasts over the 2-week range of the global forecast system. As a result, valuable information is lost when the downscaling is performed. As an alternative, we have developed a Generative Adversarial Network to perform the downscaling coupled to the ECMWF global ensemble. With this piece of AI, a probabilistic downscaled regional forecast over the whole 2-week forecast period becomes possible at very modest computational cost. We have tested the combined NWP-AI system over the UK using radar data for proxies of precipitation. It appears to work well and the downscaled forecast is more skillful than the raw global ensemble. We are now currently testing the NWP-AI system in East Africa. If it works there, then it should work anywhere in the world. This method has the potential to change the way in which operational weather forecasts are made, worldwide.

Of course, there is a theoretical reason why it is best to try to combine physics-based and AI-based models. With climate change, individual weather events are now occurring with such intensity that they lie outside an AI's training data. It is almost a truism that extrapolation is more unreliable than interpolation in statistics. To maintain trustworthiness in our forecasting systems, it is vital to continue to include the physics-based models.

Indeed, when it comes to the climate timescale, I would argue that there is no alternative than to continue to use physics-based models for regional or global projections of climate change.

Whether it is estimating the likelihood of passing a tipping point, or of some acceleration in climate change due to positive cloud feedback, we cannot rely on AI estimates based on training data which have not seen tipping points or changing global cloud feedback.

I would argue that the climate change problem is itself reason enough to keep physics-based models for weather forecasting too. I am a great believer in what is called seamless prediction. By testing whether an NWP model can accurately forecast tomorrow's maximum temperature, we are implicitly testing the cloud schemes and land surface scheme in this model. A systematic bias in a short-range forecast of maximum temperature is indicative of something wrong in the model's parametrized physics – such as in the cloud schemes or land-surface scheme. And, of course, if there are biases in such schemes, we cannot trust that model's prediction of climate change on the century timescale.

So, how should NWP systems develop to take maximum advantage of this NWP-AI synergy? Personally, I think the most important development now needed in NWP is the development of km-scale global model. As well as being critically important for NWP, it will be important for regional climate prediction too.

A key point about km-scale models is that three important physical processes, deep convection, orographic gravity-wave drag and ocean mixing, will be at least partially resolved. Hopefully this will allow some of the systematic errors that arise when these processes are parametrized to reduce. Of course, there will continue to be uncertainties in the computational representation of the equations of motion. But these uncertainties can be represented using stochastic techniques.

No doubt km-scale modelling will happen if we wait long enough. However, if we extrapolate the resolution of Climate Model Intercomparison Project (CMIP) models, we will not reach km-scale at least until the mid 2050s (Andreas Prein personal communication). This is not good enough in my opinion. If we are going to reach irreversible tipping points or changing cloud feedback in our climate system we need to know about them now, not when it's too late.

My own view is that we need some kind of "CERN [*Conseil Européen pour la Recherche Nucléaire*] for Climate Change" where modelling centres around the world can pool human, computer and financial resources to develop a new generation of seamless km-scale global weather/climate model. Those who argue that we need multiple models in order to represent model diversity and hence uncertainty, I would say that we can represent such diversity better with stochastic representations of unresolved processes. Why better? Because each member of a multimodel ensemble erroneously assumes that the parametrization process is deterministic, which it is not. This is a class error that can be alleviated in a stochastic model.

Some say that if we put computing resources into a km-scale global model, we will not have computing resources to run large ensembles. However, my view is that this is an area where a hybrid AI, physics-based model system could be transformative. The idea would be for the AI system, trained on output from the km-scale model, to generate synthetic high-resolution ensemble members. In this way, based on a skeleton ensemble of maybe 20 members, we could generate ensemble sizes of thousands using AI.

Of course, we will continue to need a hierarchy of climate models. These km-scale models will lie at one end of the hierarchy, which will include both CMIP models and highly idealized models like Lorenz's model of chaos.

I would like to conclude by thanking WMO, not only for this award, but for helping my career develop. The workshops and conferences organized under WMO auspices helped me to meet scientists from different parts of the world, and, importantly, from different areas of weather and climate science, that I would otherwise not have met. These workshops were critical in providing the seeds of ideas that I have discussed in this essay.

Acknowledgement

The work I have described above could not have happened without the help, inspiration and guidance of many colleagues, a number of whom are listed in my book *The Primacy of Doubt*.

Tim Palmer receives the IMO Prize from WMO Secretary-General Celeste Saulo and WMO President Abdulla Al Mandous

Further Reading

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CERN for Climate Change

– An interview with the IMO Prize Lecturer

By Sylvie Castonguay, WMO Secretariat

The IMO Prize lecture delivered byTim Palmer, Royal Society Research Professor in Climate Physics and a Senior Fellow at the Oxford Martin Institute, in June focused on ensemble forecasting for weather and climate, an area he helped to pioneer. Looking forward, Prof Palmer also advocated for "some kind of CERN [*Conseil Européen pour la Recherche Nucléaire*] for climate change where modelling centres around the world can pool human, computer and financial resources to develop a new generation of seamless kilometre-scale global weather/climate model." It is a grand idea with a sense of urgency. The Bulletin interviewed Professor to learn why this idea has caught on with many climate scientists.

Bulletin: *What more than existing climate models could a "Km-scale Climate-CERN" provide?*

Professor Palmer: Scientists, and specifically climate scientists, have done a very good job warning society about the risk of climate change and global warming thanks to the global climate models that we have. But we urgently need to know much more than the existing models can provide: Countries require more information to guide infrastructure investments to adapt to climate change. Some countries are thinking about targeted or local geoengineering: injecting aerosols into clouds to make them brighter to reflect sunlight back into space, which could have a regional cooling effect. But what is the global implication of that? Would weakening a heat wave in one part of the world exacerbate a heat wave in a different region? Then there is the losses and damages discussion, which will be an important part of the upcoming Conference Of Parties (COP) of the United Nations Convention on Climate Change (UNFCCC) in Azerbaijan. A stronger scientific basis is required to attribute extreme events to climate change in a quantitative way. There is a lot of discussion in the media about tipping points – that we might do something irreversible to the ice sheets, ocean circulation or rainforests. Finally, tipping points have implications for mitigation policies: cuttings emissions after a tipping point has been reached will be completely ineffective. For these reasons and many, many more reasons a CERNE for climate is needed now to gather scientists, experts and resources.

We need to move up a gear in the science from just being able to warn in general terms about climate change on a global basis to being very specific about what climate change will bring to individual regions and countries. The current generation of climate models are not capable of making very specific, very detailed predictions and projections, their resolution is too coarse. Why? Because universities and national institutions have had to tailor their ambitions to their computing capabilities – to their resources. So, unfortunately today, we just cannot answer key regional questions about climate change with confidence and clarity.

I and other climate scientists argue that getting climate models to the stage where they can really, reliably address questions about regional climate change will require a similar level of international collaboration and coordination as CERN. We need answers these questions in the next 5 to 10 years, not in the next 50 years.

Bulletin: *Could you give us examples of answers that km-scale modelling could provide?*

Professor Palmer: We are recording many extreme events like the incredible 50 °C temperatures in British Columbia, Canada, a couple of summers ago, extraordinary flooding in Pakistan, prolonged drought in southern Africa. We cannot answer precise questions about how climate change affected those extreme events simply because the models can't simulate them. But it is not just extreme local events: over the last year or so, global mean temperatures have been higher month on month than predicted by the Coupled Model Comparison Project and other standard models, at over 1/10 to 2/10 °C, which is quite significant.

Bulletin: *What are the roadblock to a Climate-CERN solution?*

Professor Palmer: Climate models started to be developed in the late 1950s into the 1960s largely

WMO Secretary-General Prof Celeste Saulo, WMO President Abdulla Al Mandous with IMO Prize Lecturer Tim Palmer

on the back of national weather forecast models. Today, manynational centres have global models. The roadblock is getting the existing institutions to realize that the resolution of their models is too coarse to help with the important problems that I mentioned, and that national resources are unlikely to be able to move the problem forward, at least on a timescale that is relevant to the climate crisis. The only solution is to work together internationally now to do this. You could say it's a political problem rather than a scientific problem.

Bulletin: *What resources would we need for km-scale global Earth System Model?*

Professor Palmer: Dedicated exascale computing – a million billion arithmetic calculations per second – is needed. Available exascale computing power – for science at least – is currently shared between many different applications, a whole range of people are queuing up to use them. To demonstrate unambiguously that km-scale models will produce more reliable forecasts with lower systematic errors, and with more accurate representations of extreme events and so on, climate scientists need dedicated access to exascale computing.

So funding is the biggest issue with launching a Climate-CERN. Countries and philanthropists would have to contribute to the international effort. The finer the resolution of the climate models, the more accurate the representation of the laws of physics and the more specific and precise the information science can provide. But a sizeable initial investment is required – comparable but no bigger than CERN.

Bulletin: *Time is of the essence. Could Climate-CERN be up and running in a short window of time?*

Professor Palmer: I do strongly believe that if the politics can be solved and financing can be found, then scientists will do the job in a very short time. There are plenty of precedents. Just think of the Apollo program to put a man on the moon. Or much more recently, the production of COVID vaccines.

Bulletin: *Other than physics, what kind of expertise would be required?*

Professor Palmer: Km-scale modelling of the climate system is one small part of Climate-CERN. Climate-CERN would also be about the impacts of climate on people and the environment, finding how to mitigate those impacts and identifying solutions. It would be critically important to have the whole spectrum of impact and application models, which would go from health through to agronomy, water resources, energy, food... To answer questions on what types of plants should be grown on a year-to-year basis, to planning urban environments... pretty much everything that is impacted by climate change. Even agent-based economic modelling should be fully integrated.

Artificial Intelligence would play a crucial role in identifying key variables in the wealth of climate data and how they should be fed into impact models to produce meaningful plain language outputs for policy and other decision-makers.

An international approach, funding and a wealth of expertise that exists across the world is needed to develop the next generation of climate models.

Bulletin: *Professor, do you have any final words for our readers?*

Professor Palmer: I started my research career in abstract theoretical physics. Then I thought, I don't really want to spend that rest of my career doing stuff that doesn't help many people. At the time, it was easier to do to pivot into a different field, such as weather and climate science, than it is today. We need to fund schemes to allow scientists (for example, at the postdoc level) to pivot from pure science to applied science. Fellowships to allow pure scientists to spend a year getting up to speed in their chosen applied field should be created.

Let me conclude with this. I cannot say how honoured I was to get the IMO Prize. When I read the list of prize winners over the years, it was of all my greatest heroes in meteorology and climatology. It is unbelievably humbling to be on such a list of esteemed people.

The Pearl of Climate Action: Gender equality and women's empowerment

by Nilay Dogulu, Claire Ransom, Maria Julia Chasco - WMO Secretariat

Earth's geographical and climatic conditions shape its weather systems, climate zones and river networks. This rich diversity has been the key to human development and enjoyment of life. For example, waterways are used for commercial purposes, such as agriculture, electricity generation, travel, shipping and fisheries, and for leisure activities such as swimming, sailing and windsurfing. But what can be said when it comes to equality and justice in the opportunities for all to benefit from this rich diversity?

Diversity[1], equity[2], inclusion[3] and justice[4] (aka DEI&J or JEDI) are widely used terms that are garnering greater awareness. Policies are being implemented to promote the representation and participation of groups with diverse identities, age, cultures, backgrounds and perspectives in almost every sector. Climate change is a key area with strong commitment to diversity, equity, inclusion and justice from the legislative level down to personal initiatives.

Climate change has highlighted environmental injustices: its impacts occur disproportionately high across regions and within communities (Ngcamu, 2023; Otto et al., 2017; Thomas et al., 2019) that are not major greenhouse gas emitters. To prevent further heightening of vulnerability and inequality, global climate justice must be manifest by protecting and empowering marginalized populations – youth, indigenous people, minorities and women – for climate action. Within the context of the United Nations 2030 Agenda, SDG 5 (gender equality) and SDG 10 (reduced inequalities) specifically address gender diversity, equity and inclusion. SDG 13 (climate action) supports these causes and has attracted innumerable youth and indigenous people thanks to events like Climate Week and movements like Fridays for Future. However, more emphasis is needed on gender equality and equity[5] and women's empowerment for climate action, especially in relation to hydrometeorological services such as early warning systems for floods and droughts.

Gender equality and equity for climate action

Gender[6] inequalities between women and men remain. Conscious and subconscious biases hinder societal progress, even in areas such as climate mitigation, adaptation and resilience. This societal problem is becoming more visible and consequential as the impacts of climate change intensify around the world and further exacerbate pre-existing social inequalities and current climate vulnerabilities (Parsons et al., 2024).

The climate crisis is not gender neutral. Women are among the most vulnerable to disasters and bear a heavy climate burden (Ngcamu, 2023; Parsons et al., 2024). Women and girls are often disproportionately impacted during extreme weather, climate and water-related events, which further amplifies existing gender inequalities and

1 *Diversity* refers to the characteristics of a person.

2 *Equity* acknowledges that circumstances (opportunities) available to each person are different and need to be accounted for.

3 *Inclusion* is about creation of space for everyone to have a say.

4 *Justice* highlights the need for equal and fair access to opportunities.

5 In this article, "gender" related terms and concepts are used in alignment with instruments, norms and standards adopted in United Nations frameworks and intergovernmental agreements where they hold a binary context. However, WMO acknowledges that individuals may not identify as man or woman.

6 Gender refers to the roles, behaviours, activities, and attributes that a given society at a given time considers appropriate for men and women

poses unique threats to their livelihoods, rights, health and safety. When climate change impacts result in the displacement of people, women and girl migrants experience a double vulnerability as they are particularly easy victims for human traffickers, forced labor, unsafe and unhealthy working conditions as well as of sexual and gender-based violence.

Limited or lack of gender equality and equity for climate action manifests itself in many forms, levels and places: from the classroom to work environments, from academia to policy realms. For instance, women are not represented adequately in critical United Nations climate talks (Alcobé & Harty, 2023; Nathanson & Jaffe, 2022) and women scientists' participation in IPCC[7] assessments and leadership has been low (Huyer et al., 2020).

Regardless of where, when and how inequality, injustice and unfairness occur, the fact remains the same: without the empowerment of women, climate action will not be sustainable.

Women's empowerment in science, policy and practice

Climate action – which often functions at the interface of science, policy and practice (SPP) – should be rooted on principles of gender diversity, equity and inclusion (DEI; Figure 1). Women's leadership is a key pillar of climate action. In this respect, the National Meteorological and Hydrological Services (NMHSs) have a fundamental responsibility in enhancing the scope, quality and level of women's participation in their organizational policies and decision-making.

The momentum in academia towards nurturing a culture of gender mainstreaming in science has been exemplary. For example, despite statistics on perceptions and impacts of gender inequality in the Earth and space sciences that indicate substantial room for improvement (Popp et al., 2019), greater awareness on gender biases (and the level of concern on its impacts) is driving more change and long-term cultural transformation.

In the context of climate change and development, integration of gender equality into climate policy has been slow at both global and national levels (Huyer et al., 2020). Women's political leadership in global climate diplomacy can allow for more integration of DEI principles and encourage gender-sensitive climate policy making while tackling gender inequalities in climate mitigation and adaptation (Lau et al., 2021). It should be noted that improving the underrepresentation of women in climate negotiation talks requires government action backed by finances.

7 IPCC: Intergovernmental Panel on Climate Change

Women and hydromet services

Achieving gender equity in operational hydrometeorological services – both in the design and the delivery of the services – is crucial for disaster risk reduction and sustainable development. Women's talents, energy and skills are underused assets for the support of climate action and must be harnessed universally across all geographies and institutional contexts. The WMO photo album Women in Action highlights the various roles and responsibilities of women working at NMHSs.

Women interact in various ways with the five essential elements of the value chain for effective hydrometeorological services: (i) observations and monitoring, (ii) research, modelling and prediction, (iii) services information system, (iv) engagement between users and providers of services, and (v) capacity development. For example, the inclusion of women in the development of hydrometeorological services leads to more successful co-designed gender-responsive weather, hydrological and climate services, which improves the efficiency and use of services by women (as public citizens).

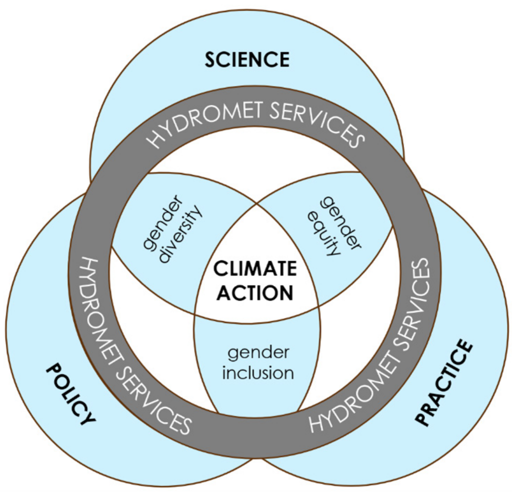

Figure 1. The central role of hydrometeorological services in climate action should be based on gender diversity, equity and inclusion to promote women's empowerment.

WMO vision and strategy on women

Building weather and climate resilient societies while ensuring gender equality and empowering women is a priority for WMO. As an intergovernmental organization, WMO has a key role in empowering women in hydrometeorology nationally and globally for climate action. First and foremost, it can participate actively in wider United Nations efforts towards gender-responsive climate action to enable women's full, equal and meaningful participation in the processes of the United Nations Framework Convention on Climate Change (UNFCCC) – for example, in the Lima Work Programme on Gender and its Gender Action Plan (GAP).

Secondly, it can push for accelerating the inclusion of women within the Secretariat and among WMO Members. The 2015 WMO GAP brought many positive changes through the adoption of WMO Gender Equality Policy. The 2023 updated WMO GAP raised the minimum target from 30% to 40% for gender composition – women's participation – in governance bodies and their working structures. The gender statistics presented at the Nineteenth World Meteorological Congress were promising in this respect.

The most recent GAP approved by the third session of the Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (SERCOM-3) in March aims to further accelerate the momentum. SERCOM-3 included a *Gender Action Day*, which defined the next steps for mainstreaming gender-responsive and inclusive services, especially multi-hazard early warning systems in the Early Warnings for All initiative.

Thirdly, WMO promotes gender equality and inclusiveness as essential components of project design planning and implementation. Guidance materials to assist Members with making weather, hydrological and climate services more gender-sensitive are widely available (see Congress report, Cg-19/INF. 4.5(1)).

NMHSs and WMO GAP

In alignment with WMO vision and strategy, NMHSs too have a major role in climate action. Most importantly, NMHSs must keep working towards a gender-balanced approach in their governance structures and work environments. All WMO Members and partners should contribute to advancing women's empowerment in disaster risk reduction through the design of gender-responsive multi-hazard early warning systems. The above listed resources on gender-responsive weather, hydrological and climate services are available for that purpose.

Let's keep the discussion going! Is your NMHS addressing gender equality or mainstreaming gender in its strategy? How so?

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Empowering the Next Generation: WMO Youth Climate Action

By Claire Ransom and Maria Julia Chasco – WMO Secretariat

The role of youth in shaping a sustainable future has never been more crucial. In recognition of this, the WMO Executive Council (EC-78) meeting in June took a significant leap forward in empowering young people to take decisive action against climate change by solidifying the Organization's commitment to engaging youth. The decision of EC-78 recognizes the vital role that young people play in driving climate solutions and calls for the development of a comprehensive Youth Action Plan. Following on the successful WMO Gender Action Plan, this WMO initiative aims to institutionalize youth representation, engagement and outreach. As a technical scientific organization in the United Nations system, WMO has a unique role in equipping youth with the right level of reliable scientific information on climate change.

Why a Youth Action Plan?

Youth are particularly vulnerable to the impacts of climate change – Youth represent a significant portion of the global population. About a quarter of the world's population – 1.8 billion people are between the ages of 15 and 24 – however, their voices are often underrepresented in climate decision-making processes. This is particularly concerning given that children typically account for 50%–60% of those affected by disasters. Furthermore, according to the United Nations Children's Fund (UNICEF), approximately one billion children are at extremely high risk from the impacts of climate change. Worse, their recent report "The Climate Crisis is a Child Rights Crisis" highlights that climate and environmental hazards, shocks and stresses do not occur in isolation, leaving millions of children exposed to multiple and compounding events. Such vulnerability makes youth engagement not just an option but a necessity in global climate efforts.

Harmonizing existing WMO work with youth – WMO already engages with children and youth through various partnerships, initiatives and events. We list a few below.

- WMO regularly supports lectures on weather, climate and water in academia such as degree courses in the Brown University (USA) and the Master programme in "European and International Governance (MEIG)" at the University of Geneva (Switzerland)
- WMO was a scientific adviser for the COPE book series, which aims to enhance the disaster resilience of children worldwide
- There is a strong relationship between Young Earth System Scientists (YESS) and the World Weather Research Programme (WWRP)
- WMO joined the "Weather Kids" campaign in collaboration with the United Nations Development Programme (UNDP) and the Weather Company.

A more cohesive, integrated and bottom-up strategy built with Members would maximize the impact of WMO's engagement. A Youth Action Plan is needed to optimize the use of resources, minimize duplication of efforts, and ensure alignment with the broader strategic goals and objectives of WMO.

Providing new opportunities for innovation through improved engagement – Young people often bring new perspectives and innovative ideas to the table. Their creativity and willingness to challenge traditional approaches can lead to new solutions and approaches to climate action. As future leaders and decision-makers, it is essential that youth are given the platform, support and formal recognition they need to be able to contribute meaningfully to climate initiatives. Addressing the current lack of proportional youth representation in WMO projects, expert teams and decision-making bodies will ensure that their voices are heard and acted upon.

55 Agencies are implementing the United Nations's Youth Strategy – The United Nations established a Youth Strategy in 2018, which 55 entities are currently implementing. As a specialized agency, WMO work on youth engagement should align with and contribute to this strategy. The absence of WMO among the implementing entities points to the need for a more structured approach to youth empowerment within the Organization. The EC-78 decision serves as a catalyst for this alignment, pushing WMO to integrate youth engagement into its core strategies.

What's next?

Developing the Youth Action Plan – The EC-78 decision is not just an acknowledgement of the importance of youth – it is about opening doors of opportunity for youth to contribute to climate action.

Consultation process for an inclusive approach – To ensure the Action Plan is as tangible, inclusive and effective as possible, the Secretariat is involving focal points across the WMO community to provide diverse perspectives. Consultations will also be held with other United Nations agencies and youth organizations to learn from their experience. The consultation process focuses on:

- *Youth participation in decision-making*: Creating platforms and opportunities for young people to participate in national and international climate-related decision-making processes so that youth voices are heard and considered in the formulation of climate policies and strategies.

- *Training and capacity building:* Offering capacity building activities that equip youth with the skills to engage in climate mitigation and adaptation activities. This includes workshops, online courses and hands-on experiences in climate monitoring and data analysis.

- *Support for youth-led initiatives:* Providing funding, mentorship and technical support for youth-led climate projects. This will help young innovators to turn their ideas into impactful actions that contribute to global climate goals.

- *Educational programs:* Developing and enhancing educational resources that provide young people with a deep understanding of meteorology, climate science and the impacts of climate change. This will enable them to make informed decisions and advocate effectively for climate action.

United Nations events to support youth climate action – In parallel, WMO has started to engage with youth events, such as the recent Summit of the Future and the upcoming Conference of the Parties (COP 29) of the United Nations Framework Convention on Climate Change (UNFCCC), to expand its youth network and learn from the incredible work already being done. For example, a recent consultation session enttitled COP29 Presidency Youth Climate Champion Consultations with Youth in UNFCCC Constituencies established several areas of work relevant to WMO:

- Youth Climate Forum
- Global Youth Statement
- Creation of spaces for intergenerational dialogue, especially with scientists
- Education and training on climate change for children and youth attending COP
- Establishment of an "open national youth delegates programme".

Going forward

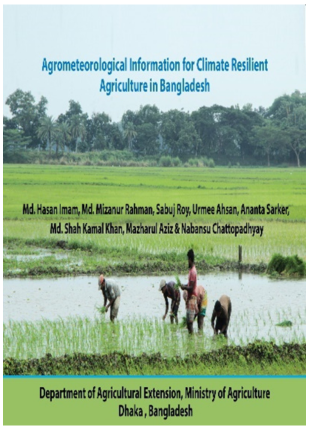
The draft Youth Action Plan will be presented for consideration to EC-79 in June 2025.

It will be a testament to WMO's unwavering commitment to empowering the next generation of climate leaders. By providing youth with the tools, knowledge and platforms they need to make a difference, WMO is fostering a more inclusive approach to climate action and ensuring that the voices of those who will inherit the planet are heard and acted upon. As we move forward, the active participation of youth in climate action will be crucial in shaping a sustainable and resilient future for all.

WMO urges all stakeholders, from governments to civil society, to support and amplify youth-led climate initiatives. Together, we can empower young people to lead the change in the global fight against climate change for a brighter, more sustainable future for generations to come.

Agrometeorological Information for Climate Resilient Agriculture in Bangladesh

By Md. Hasan Imam, Md. Mizanur Rahman, Urmee Ahsan, Ananta Sarker, Sabuj Roy, Md. Shah Kamal Khan, Mazharul Aziz & Nabansu Chattopadhyay - Agrometeorological Information Systems Development Project, Department of Agricultural Extension, Ministry of Agriculture, Dhaka, Bangladesh



Agriculture has always been under constant threat due to weather variability and climate extremes, today it has become increasingly insecure due to climate change. Bangladesh, a country prone to natural weather, climate, and water-related hazards, is frequently affected by floods, drought, and tropical cyclones and now it is likely to be one of the most vulnerable countries to climate change. Extreme weather events have long been a great concern for the Bangladesh economy and business sector. Over the last decades, the Government of Bangladesh, with support from the World Bank, has invested over US$ 1 billion in coastal infrastructure and cyclone shelters, making Bangladesh a model for community response to tropical cyclones through its Cyclone Preparedness Program (CPP) in the coastal districts. But despite these investments, the country's hydrometeorological information infrastructure over land, atmosphere and ocean, its basic public weather services, its forecasting, and its multi-hazard end-to-end early warning systems have remained weak. In consequence, the agriculture sector has suffered repeated setbacks as their need for such services has grown greater with climate change.

Weather and climate dependent sectors – such as agriculture, livestock, and fisheries – need tailored weather and climate data, products, information, and services to improve planning and decision-making and to mitigate the adverse impacts of weather and climate extremes. Accurate information on meteorological parameters has great potential to increase farming outputs. Such information can be used to modify crop environments, to protect plants from frost and strong wind and to schedule irrigation and more efficient water management and drought preparedness. The provision of needs-based climate information to farmers can support the management of agricultural resources – land, water, and genetic resources – to avoid physical damage to crops and soil erosion. Better understanding of the climate in a location provides opportunities to design various measures to reduce impacts. The lack of reliable agrometeorological information for farming communities is an opportunity lost that impacts the entire country. Agrometeorological information for sustainable agricultural development was urgently needed along with reliable dissemination methods using language that farmers could understand.

Bangladesh's Department of Agricultural Extension (DAE), Ministry of Agriculture started to address the problem in 2017 through the Agrometeorological Information Systems Development Project, funded by the World Bank. The Project aimed to advance climate services, including the monitoring of the extreme weather events, in order to disseminate tailored advisories to farming communities. State-of-the-art instruments and technology would be installed along with efficient delivery mechanism for the timely information delivery to farmers.

At the time, Bangladesh had no systematic way of combining meteorological information and forecasts with agriculture related information to produce tailored agrometeorological advisories for farmers. Today, agromet advisory bulletins are prepared at the district and national levels twice a week. A robust database and Decision Support System for generating automated crop and location-specific advisories reduces drudgery and errors, minimizes dependency on specialist inputs, reduces costs and creates a data bank and repository of valuable information and knowledge. Some 30 000 lead farmers are direct beneficiaries of the Project and 300 000 farmers are indirect beneficiaries. The Project's modernized agrometeorological advisories, early warnings and forecasts have sustainably increased agricultural production by informing decision-making processes in the farming community, thus reducing losses. And DAE, in collaboration with other organizations, is providing early warning services for extreme events to the rural farmers in Bangladesh. This is how it happened.

The Project structure

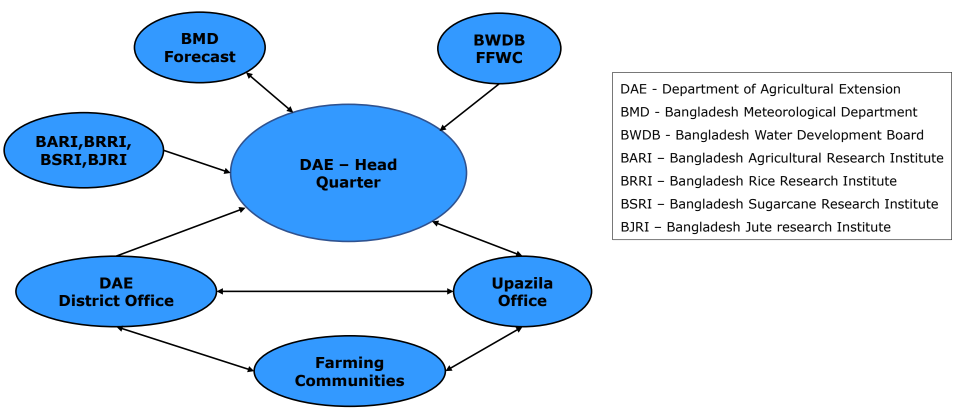
The Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD) and various research institutions came together to support DAE on the Project. This provided DAE with access to agrometeorological databases and ultimately permitted the development of the agrometeorological advisories and products. The Project's Joint Technical Working Group (JTWG) on Agrometeorology included experts from DAE, Bangladesh Agricultural Research Institute (BARI), Bangladesh Rice Research Institute (BRRI), Bangladesh Sugar Crop Research Institute (BSRI), and Bangladesh Jute Research Institute (BJRI). BMD and BWDB support is the effective functioning of the Working Group and the implementation of the decisions taken by the group.

The effectiveness of agricultural meteorology services is dependent on the availability of qualified, competent technical and professional agrometeorological personnel. Some products, for example, the determination of best dates for planting based on expected climate conditions, require specific expertise and research, and cannot be implemented without adequate capacity building. The Project identified an urgent need to upskill and train personnel. Agrometeorological teaching programs were developed with Bangladesh's agriculture universities. As and when the universities launch their agrometeorological departments, these will link with the DAE and BMD agromet services to augment research and development as well as extend components of the services. Funding has already been identified to launch the agrometeorological departments in two universities.

Agromet database, products, pools

BMD maintains various observation networks to monitor and assess the extreme events: conventional observation network, agromet observatories, soil moisture stations, Automatic Weather Stations (AWS), cyclone detection radars, Doppler weather radars and satellites observations. Satellite and radar observations are crucial for monitoring and assessing hazards, especially in areas prone to extreme weather events. The DAE Project completed the BMD network by installing 4 501 handheld automatic rain gauge units (see Figure 1). A number of Agro-AWS were also installed.

In addition, the BMD Project has so far installed 125 subdistrict levels AWS to provide real-time data on all the important weather variables. Historical and current agricultural data, such as land holdings, crops/cropping systems cultivated by farmers, and average crop yields in different districts, have been digitized. AWS, agricultural and other agrometeorological databases have been integrated for 487 districts. These databases are being used to carry out a variety of agrometeorological analyses and to



An Overview of Operational Agromet Services in Bangladesh

Recording of rainfall using handheld automatic rain gauges

generate information and products for tactical decisions by the farming communities in the different subdistrict.

Given the frequency of weather and climate extremes and their adverse impacts on the agriculture sector, the identification of vulnerable farming communities was critical. The Project undertook agricultural disaster risk analysis at the agroecological zone level, based on weather and climate information and socioeconomic factors such as farmer land holdings, indebtedness, soils information, and crops/cropping patterns. The natural characteristics of each climate risk were recorded, including the time of that year that it is most likely to occur, its severity and likely impacts in each geographical area. Climate risk vulnerability maps were developed for all the subdistricts, identifying the areas at risk and the vulnerable members of the community.

To improve the quality of agrometeorological bulletins, operational research and development was required to synthesize next level agromet products, such as drought and flood related information services, indices for different extreme events, and stress indices for crop, livestock, poultry and fishery. Agromet advisories require drought and flood related data for different crops. At this stage of the BMD Project, all of the products are not yet readily available but several are in operational use. It is proposed to develop indicators for aridity anomaly, Standardized Precipitation Index (SPI) for seasonal updates and the last four weeks, SPI forecasts, Quantitative Precipitation Forecasts (QPF), basin level forecasts, rainfall distribution using Markov Chain Model, assured rainfall using incomplete gamma distribution, soil moisture estimation, and many more.

DAE has also started to incorporate satellite-based agrometeorological components, particularly Normalized Difference Vegetation Index (NDVI) composite images developed by National Oceanic and Atmospheric Administration (NOAA), to generate information on crop vigour and agricultural progress. This information along with the rainfall data are being used in stress monitoring and to track crop growth from sowing to harvesting for all major crops. In the meanwhile, strategies have been worked out so that other remote sensing parameters can be used for monitoring of different weather parameters and events and, ultimately, the preparation of advisories.

Detailed lifecycle information for each important crop is presented in pictorial form on Crop Weather Calendars that can be used for planning, irrigation scheduling and plant protection measures. The broad indications in the calendars may also be useful for formulating policy matters regarding plant breeding, crop adoption, drought proofing, supplemental irrigation, and maximizing crop yields. The information may be especially useful for mitigating the loss of crop due to pests and diseases. Agricultural solutions for pests and diseases, require approaches that are scientific, methodological and socioeconomic. The Crop Calendar early warning models/guidelines permit farmers to implement protective measures in time for the security of their livelihoods as well as for national food security.

Dissemination

Considering the merits and progress of Agromet Advisory Services, widespread dissemination and adoption was a priority. One of Project's first dissemination goals was the establishment of the Bangladesh Agro-Meteorological Information (BAMIS), a dynamic web portal for agrometeorological services and related information for various users, especially farmers. Meteorological data from BMD and hydrological data from BWDB are displayed in the portal. After being translated and validated by the DAE Agromet Technical Committee, the information is disseminated to the 30 000 lead farmers and made available to other relevant stakeholders. DAE officials and farmers are also connected through the portal, which includes:

- Weather and climate information across Bangladesh
- Twice weekly updated agromet advisories for 64 districts and one weekly national/regional agromet advisory
- Agromet information on crops, weather sensitivities on crops, pests and diseases information with linkages to weather and other measures of control, crop weather calendars, pest and disease weather calendars, and more
- Developing agrometeorological products, including satellite products to help different users to make tactical and strategic decisions
- Information on extreme events
- Special Agromet Advisory Services for livestock, poultry and fishery
- A feedback mechanism on the services provide for farmers and others.

Other user-friendly dissemination platforms expand access further, including traditional media outlets, social media, mobile Apps, digital display boards, community radio and kiosks. The mobile Apps provide farmers to instant access to information on current weather, expected weather and related impacts on crop as well as advice on controlling any emerging pests and diseases. District Agricultural Offices have so far set-up 65 agrometeorological kiosks with digital display touch-screens, computers and printers to provide the specific information to their farming community. These kiosks provide one-stop access to information even to those with minimum literacy, allowing users to navigate through current weather data, agrometeorological advisories, crop cultivation practices, agriculture inputs, a crop diagnostic kit, crop management timetables, farm machinery, market information, and much more. This is the first such network in Bangladesh.

Dissemination also comes in the form of training for users of the services: farmers and DAE Cadre Officers, Agricultural Researchers and Subassistant Agricultural Officers, including training of trainers. Some 25 targeted training modules were developed so that each group would receive targeted training.

The learning formats developed for farmers include two single-day training modules and six sequential

Agromet information/advisories are disseminated by 12 community radio stations.

modules to be conducted before, during and after the cropping season. The modules are designed to build knowledge and understanding on farm management strategies and on the use of agromet information and advisories for decision-making to increase agricultural resilience and productivity. In addition, a support component was created to raise the awareness of weather and climate-related crop issues and of projected climate change and its impacts through roving seminars in farming communities. The seminars help farmers to better understand how weather and climate information can be used to improve their decision-making and provide an opportunity to DAE and BMD to interact directly with farmers and to demonstrate the BAMIS decision support tools and feedback mechanism. The direct interactions between farmers and agricultural weather information providers educates both groups on their needs and requirements. In addition to the seminars, the support component posts agromet bulletin boards and distributes rain gauges throughout the farming communities to further encourage decentralized collection and use of agromet information.

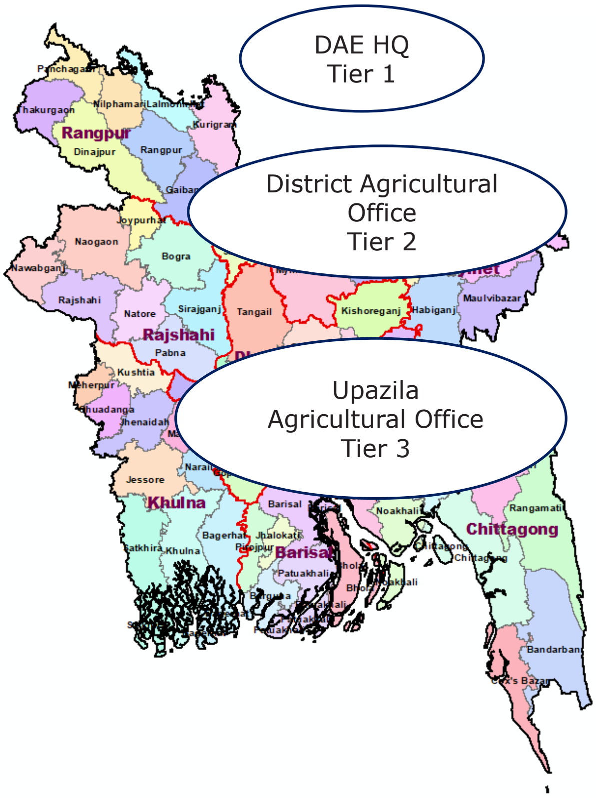
Feedback on the usefulness of the agrometeorological advisories and products is an important aspect of the Project. Feedback assessments are planned every five years to verify that farmers' feedback have been used to make changes and improvements to the agrometeorological advisories and products.

Future activities

The agromet services have significantly contributed to reducing risks and improving agriculture productivity and farm income in Bangladesh despite local weather vagaries. A comprehensive study on impact assessment and economic benefits of this service showed that farmers are availing themselves of the services and benefiting from them.

But DAE still sees a long way to go to establish a world-class agromet system for the underprivileged and farmers they have not yet reached. A number of future initiatives are planned to upgrade the services, including the establishment of a three-tier structure to operationalize services and applications for subseasonal to seasonal weather forecasts for agriculture. There is also the development of related contingency plans in case of significant climatic variability, preparation of crop and pest weather calendars for horticultural crops, prediction of lightning and thunderstorms, and much more.

All these required extensive training on the state-of-the-art technology and advanced training in different facets weather, climate and agrometeorology. Looking at these angles, such types of training programmes/courses have been proposed in suitable countries where such facilities are readily available.



Proposed Three Tier Structure of Optional AgrometServices in Bangladesh

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