WORLD
METEOROLOGICAL
ORGANIZATION

BULLETIN

Vol. 69 (1) - 2020

WEATHER CLIMATE WATER

Climate & Water

WMO BULLETIN

The journal of the World Meteorological Organization

Volume 69 (1) - 2020

The WMO Bulletin is published twice per year in English, French, Russian and Spanish editions.

Subscription rates

	Surface mail	Air mail
1 year	CHF 30	CHF 43
2 years	CHF 55	CHF 75

E-mail: pubsales@wmo.int

Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis avenue de la Paix Tel.: +41 (0) 22 730 8403
P.O. Box 2300 Fax.: +41 (0) 22 730 8117
CH-1211 Geneva 2 E-mail: publications@wmo.int
Switzerland

Contents

Weather, Climate, Water – The First 70 Years of WMO

WMO celebrates its 70th Anniversary in 2020. Activities to mark the Organization milestone anniversary start on 23 March – the date the WMO Convention came into force in 1950. One year later, WMO became a United Nations specialized agency and, today, WMO Member States and Territories number 193. But the history of international cooperation in meteorology dates back much earlier than 1950. The International Meteorological Organization (IMO), the predecessor of WMO, originates from the 1873 Vienna International Meteorological Congress decision to draft the rules and statutes of an international meteorological organization to facilitate the exchange of weather information across national borders. The 150 anniversary of that event will be celebrated with due pomp in 2023.

On 23 March, World Meteorological Day and World Water Day will be celebrated together for the first time. The Climate and Water theme is reflected in the slogan for the celebration: Count Every Drop, Every Drop Counts. More information, as well as outreach materials, are available online at worldmetday.wmo.int. We invite the WMO Community to make use of all the website and materials in their celebrations.

This issue of the WMO Bulletin on Climate and Water theme, underlines the importance of including water in climate policy discussions. The Geneva Water Hub, a Swiss initiative that promotes sound water management as an instrument for peace and a key WMO Hydrohub partner, highlights the evidence that water shortages have the potential to lead to political and social unrest. Water data is the basis of good water resource management and multi-hazard early warnings for water-related extreme events. Articles on WMO initiatives and projects –from HydroSOS, WMO Space-based observations, Flash Flood Guidance System to projects in Africa and the Americas – demonstrate the role of the Earth System Approach in addressing today's global challenges.

To mark its 70th anniversary, WMO will be holding an exhibit of National Geographic photos from its World's Water Towers and Highest Weather/Climate Stations series. The Weather, Climate, Water exhibit will run for 70 days until the WMO Executive Council, which has been postponed to autumn due to the COVID-19 pandemic. In parallel, the WMO Chronology of Weather Science online museum will run a social media slide show campaign. Readers are invited to join us on WMO social media channels to fly through the history of weather research on the traces of the people and institutions that have supported the progress of Earth System Science. The experts will accompany you from the beginnings of weather research in the early 20th Century to the advent of the first electronic computers and satellites then onward to the super computers that have revolutionized numerical weather prediction.

In addition, a series of special 70th anniversary publications are being produced in 2020 with inputs from leading scientists and experts around the globe. These publications are designed to be both retrospective and forward-looking. They will reflect on both the important historic milestones of the Organization, including its contributions to meteorology around the world, as well as anticipated transformations and innovations as we enter a new decade and beyond. In Origin, Impact and Aftermath of WMO Resolution 40, the first in the series released in January, former WMO President (1995–2003) John W. Zillman shares his rich memories of that crucial period of WMO history. Interestingly, the Eighteenth Session of the World Meteorological Congress in June 2019, established a task to review WMO data policies and practices, including those of Resolution 40, and called for WMO to convene a global Data Conference in 2020. In view of these developments, the historical review of the WMO data policies is timely and useful.

WMO has facilitated seventy-years of progress in weather, climate and water. The work of the WMO community has impacted the lives of countless millions at home, work and play. Building on the success of its first seventy years, WMO and its partners in all sectors will continue to work together to secure a better future for mankind and our planet.

Petteri Taalas
Secretary-General
World Meteorological Organization

Why is water so often missing from discussions around climate change?

By Sonja Koeppel[1] Anil Mishr[2] and Claudio Caponi[3]

All around the world, billions of people feel the impacts of climate change through water. The frequency of water-related disasters is on the rise due to the increase in the intensity of natural events such as storms, high winds, heavy precipitation and dry spells. Floods, droughts, landslides, glacier lake outbursts and storm surges are impacting lives and infrastructure in coastal zones and mountain tops, in arid plains and deserts, along river banks and in floodplains. The poorest and least developed are the most vulnerable. And yet, when the world talks about mitigation and adaptation to the new reality of climate change, water is rarely on the agenda. This has to change, and fast.

Climate change is increasing variability in the water cycle, inducing a greater number of extreme weather events, reducing the predictability of water availability and affecting water quality. In turn, this cascade of consequences threatens sustainable development, biodiversity and the enjoyment of the human right to water and sanitation worldwide.

Growing demand is putting pressure on a system that is already under stress. There is no time to lose.

2020 vision

This year, the United Nations (UN) system is focusing on climate change and water. UN-Water is seizing the opportunity to put water at the heart of climate action plans and at the front of people's minds when they think about climate change.

1 The United Nations Economic Commission for Europe (UNECE)

2 The United Nations Educational, Scientific and Cultural Organization (UNESCO)

3 WMO Secretariat

In 2019, the UN-Water Expert Group on Water and Climate – co-coordinated by WMO, the United Nations Economic Commission for Europe (UNECE) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) – produced a policy brief[4] on climate change and water. This brief outlines five key actions:

1. Acting now - Climate change is threatening lives and human rights. Securing water for communities, economies, and ecosystems is critical for poverty reduction, green energy transformation, and creating a buffer from disasters.

2. Considering water as part of the solution - Climate-resilient water management is an essential component of successful climate mitigation and adaptation strategies, and can accelerate progress towards achieving the goals of the 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction.

3. Improving water management practices - Communities, governments and basin authorities need to be empowered to make confident, risk-informed decisions that can help increase climate resilience, improve ecosystem health, and reduce the risk of water-related disasters.

4. Ensuring transboundary cooperation in adaptation - Transboundary cooperation in adaptation is needed to manage climate impacts that cross national boundaries, but can also help to harness the potential co-benefits of improved regional cooperation, such as exchange of data, and improved peace and stability.

4 unwater.org/publication_categories/policy-and-analytical-briefs/

5. Rethinking financing - Climate finance for water resource management and sanitation supports community climate resilience, job creation at local levels through green jobs, and help to improve sustainable development outcomes.

The policy brief also provides key actionable recommendations in two main focal areas: (1) global and regional climate and water negotiations and processes and (2) national and subnational capacity-building, planning, implementation and monitoring. The recommendations include:

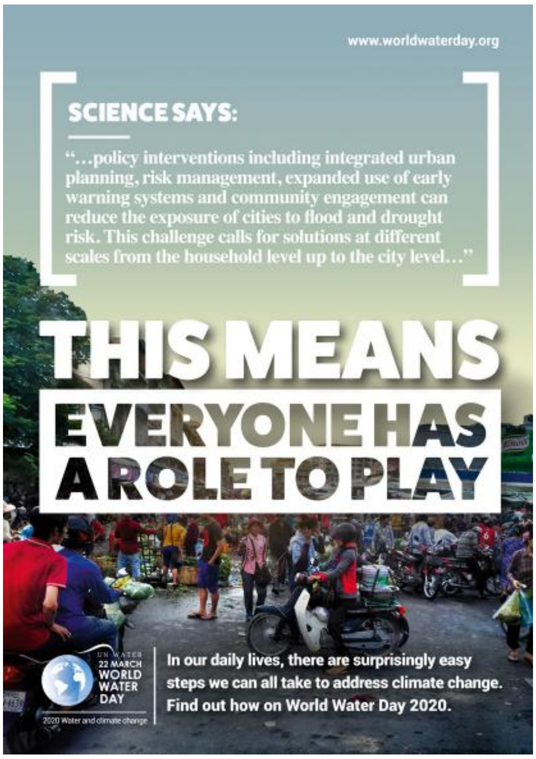
- A call for establishing criteria, and to develop a set of global priorities, for climate-resilient water and sanitation interventions in specific hotspots
- Support for the refinement of climate change projections and downscaling of relevant climate information as well as support for countries to overcome the "observation gap"
- Development of regional and basin-wide adaptation strategies to maximize the effectiveness of adaptation
- The stimulation of innovation and fostering of capacity-building for, as well as better awareness of, adaptive water management
- Calls for engaging and empowering youth and young water professionals – including indigenous youth as leaders and knowledge holders who provide solutions for water security and climate action.

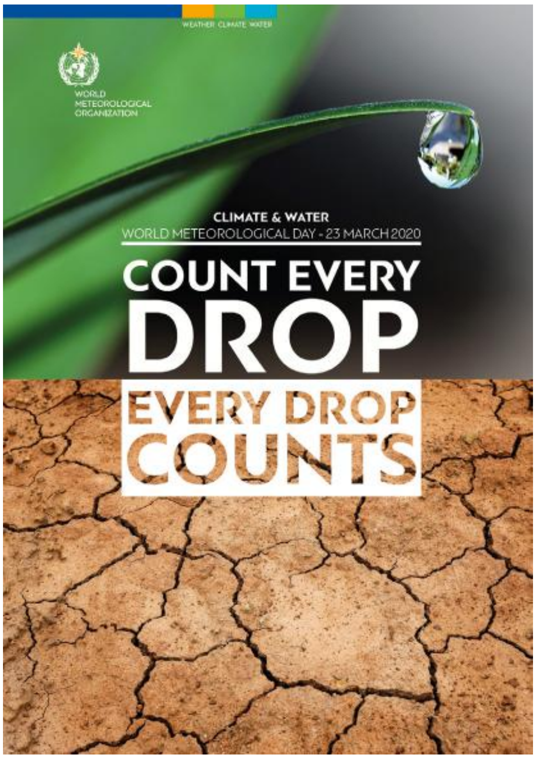
These five approaches and key recommendation should be promoted and widely implemented in national and international river basins. But none of these solutions can fully succeed without wider – global – public participation. Everyday people need to be inspired into action with concise, clear and practical messages.

World Water Day and World Meteorological Day 2020

To amplify the messages around climate change and water, both World Water Day and World Meteorological Day in 2020 will focus on climate change and water and aim to inspire people around the world to take action. In order to inform and engage people, World Meteorological Day and World Water Day will highlight how water can help fight climate change.

The Intergovernmental Panel on Climate Change (IPCC) states that "the relationship between climate change mitigation measures and water is a reciprocal





One of three World Water Day 2020 campaign posters (left) and World Meteorological Day 2020 poster (right).

one." Measures introduced to reduce greenhouse gas (GHG) emissions have direct implications for water resource use and management. Conversely, water extraction and management measures have an impact on carbon emissions due to the energy intensity of water treatment and distribution systems. At the same time, water plays a central role for adaptation to climate change since efficient and sustainable water management enables more effective adaptation of water-related sectors to climate change and improves the resilience of ecosystems. The role that governments and other actors, including the private sector, must play in water stewardship to achieve a sustainable, low-carbon future is acknowledged in the Sustainable Development Goals (SDGs) and the Nationally Determined Contributions (NDCs) of the United Nations Framework Convention on Climate Change (UNFCCC). However, this awareness is still incomplete.

This 22 and 23 March, everyone can get involved and take action. World Water and World Meteorological Day websites provide practical tips on how each of us can act and make a difference on climate change and water. Together we can make the following messages resonate with everyone, everywhere:

1. We cannot afford to wait. Climate policy-makers must put water at the heart of action plans.

2. Water can help fight climate change. There are sustainable, affordable and scalable water and sanitation solutions.

3. Everyone has a role to play. In our daily lives, there are surprisingly easy steps we can all take to address climate change.

The key role of water management and data for peacebuilding

By François Münger, Natasha Carmi, Caroline Pellaton, Jean Willemin of the Geneva Water Hub

As the climate change crisis becomes a global reality, so does the importance of water. Accessible, potable water is critical for stable human societies and sustainable ecosystems. What's more, it is now evident that water shortages have the potential to lead to political and social unrest. In Asia, the 1960 Indus Water Treaty between India and Pakistan is currently being challenged by both nations due to recent changes in rainfall patterns and increasing rates of "water withdrawal" that have resulted from dam developments in both nations.[1] In Australia, a different sort of water crisis is developing: devastating bushfires are occurring at the same time that algae blossoms are threatening freshwater ecosystems and diminishing the quality of drinking water.[2] In Russia, the government has been compelled to issue a climate change plan of action in response to extreme weather patterns; water shortages are increasing the demand for the development of drought-resistant crops and of new dams.[3] Tellingly, the Netherland Judiciary recently maintained that government inaction on climate change violates human rights.[4] In short, sustainable water resources management is a critical and universal challenge in the 21st century.

Addressing such a challenge is complicated – and it is exacerbated by the fact that the human population is continuously growing. Water-related issues are becoming a recurrent factor in fomenting local, national and regional fragility.[5] Water scarcity and deteriorating water quality are widely viewed as conflict-risk multipliers.[6] Thus, it is not surprising that challenges related to water resources management have now reached the top of political agendas. For the past five years, the Annual Global Risks Report of the World Economic Forum has reported that world business and political leaders consider water crises as one of the top global risks.[7] In its 2020 report, it stated that extreme weather events, failure of climate change mitigation, natural disasters, and water crisis rank among the top 10 most likely and impactful risks to global stability: "Over a ten-year horizon, extreme weather and climate-change policy failures are seen as the gravest threats."

Climate change impacts are often manifest through flooding or droughts. Further, climate change is expressed by greater climate variabilities and successive, major extreme weather events that dramatically weaken sustainable development. Therefore, great deficiencies or inundations of water are its key impacts. According to the High-level Experts and Leaders Panel on Water and Disasters (HELP), water-related disasters have comprised 90% of the 1 000 most severe disasters that have occurred since 1990. Water-related disasters in 2018 resulted in a death toll of 6 500 and affected the livelihoods of over 57 million people, with an economic loss of US$ 140 billion worldwide. (HELP, 2019).

It is also important to recognize that climate change will have a disproportionate impact on fragile states and regions first, increasing their existing social, economic, environmental and governance challenges. Vulnerable regions often prove to be fertile ground for conflicts and violent extremism. Therefore, the response to climate change should take into account the other factors that render nations and regions unstable. By mitigating these, the most vulnerable countries may be better prepared to deal with their changing climates.

To this end, water resource management has untapped diplomatic potential. Floods and droughts ignore political boundaries. Managing water effectively requires international collaboration. Thus, it can be used as a key vehicle for cooperation and peace. It is with this positive vision that the Geneva Water Hub (GWH) was established in 2014 with the support of the Swiss Agency for Development and Cooperation and

1 www.ooskanews.com/story/2019/03/india-stops-water-flow-three-rivers-pakistan_177836

2 www.ooskanews.com/story/2020/01/australia-bush-fires-and-threat-drinking-water-ecosystems_179125

3 www.ooskanews.com/story/2020/01/new-russia-climate-change-plan-acknowledges-extreme-weather-patterns-looks-drought

4 amp.wbur.org/hereandnow/2020/01/13/netherlands-climate-change-human-rights

5 FAO 2018: Water Management in Fragile Systems: Building Resilience to Shocks and Protracted Crises in The Middle East and North Africa

6 harvardnsj.org/2018/05/water-scarcity-the-most-understated-global-security-risk/, www.weforum.org/agenda/2016/05/lack-of-water-will-raise-the-risk-of-conflict-heres-what-we-need-to-do

7 The Global Risks Report 2019, www.weforum.org/reports/the-global-risks-report-2019, last accessed on 8 January 2020

the University of Geneva. The aim of the GWH is to foster a better understanding and prevention of water-related tensions at intersectoral and transboundary levels – thereby promoting sound water management as an instrument for peace and cooperation. GWH works to build bridges between different communities of practices and to leverage resources available in the International Geneva in order to develop a "hydro-politics" agenda.

The relevance of data for water cooperation and peace

Devastating flood and drought events across the globe have received extensive international media coverage and underscored the need for comprehensive water data. Two major political endeavours – namely the High Level Panel on Water (HLPW) and the Global High Level Panel on Water and Peace (GHLPWP) – have collaborated to put water issues at the top of the political agenda during the last three years. They have promoted a united message concerning the need for water data, recommendations for water management, and the importance of water management in promoting peace and sustainable development.

In 2017, the GHLPWP published "A Matter of Survival." This report contains analyses and recommendations adopted by the Panel following two years of consultations and discussions with stakeholders. One of its recommendations is to strengthen "knowledge-based decision-making and cooperation on data," as well as to improve the "level of knowledge relating to water quality and quantity issues at all levels. Knowledge on groundwater and aquifers, representing more than 90% of unfrozen global freshwater reserves, should be enhanced as a matter of priority."[8]

In March 2018, the HLPW released its own outcome report, "Making Every Drop Count – An Agenda for Water Action." This included another set of key recommendations, one of which emphasizes the need to develop national water data policies and systems using open-data approaches wherever possible, with support from the World Water Data Initiative.[9]

In 2019, HELP published its first global report as well for governments and stakeholders. The report urges leaders and users to learn from major water-related disasters and to invest in information systems. Water data, the report asserted, is a key factor for disaster-preparedness.[10]

The Coalition for Water Data and Peace

To address the importance of comprehensive water-data for both resource-management and peace – and in support of the Sustainable Development Goals and the United Nations Framework Convention on Climate Change (UNFCCC) agenda – two events have been organized jointly by WMO and GWH:

The first event, "Coalition for Water Data and Peace," was organized by WMO and GWH with the support of the German permanent mission to the United Nations in Geneva. The purpose of this event was to explain the importance of international data-collection and sharing, and to create a coalition of Geneva International Mission Champions to help raise awareness about the importance of water data and to promote the issue in their national governments.

The second event was a panel discussion, "Hydrology for Sustainable Development and Peace," held during the opening segment of the WMO Hydrological Assembly, subtitled Aiming at Further Developing the WMO Vision and Strategy for Hydrology, in June 2019 during World Meteorological Congress. The panel was attended by several missions that had participated in the first event, and it helped to set the stage for the deliberations of the Hydrological Assembly. Participants discussed the importance of water for sustainable development, as well as the relevance of water data-collection and sharing as mechanisms for peace. The panel emphasized the need for policy-makers to understand the connection between science and policy, which is essential for

8 Global High-Level Panel on Water and Peace. (2017). A Matter of Survival (Report). Geneva: Geneva Water Hub

9 High Level Panel on Water (1018) Making Every Drop Count- An Agenda for Water Action- Outcome Report

10 HELP Global Report on Water and Disasters 2019

better decision-making and better governance if the sustainable development goals are to be reached.

The Global Observatory on Water and Peace

Many existing organizations and mechanisms are contributing significantly to water cooperation on an international level. However, these efforts are constricted by the limited capacity of international actors to work together collectively and effectively at political and diplomatic levels. In response, GHLPWP has called for the establishment of the Global Observatory on Water and Peace (GOWP) to bridge and promote existing efforts and fill critical gaps in global water management.

GOWP, based in Geneva International, has been founded as an international platform for peace and diplomacy, with its central office at the Geneva Water Hub. GOWP is an inclusive network that unites and aligns regional and local partners with neutral and credible institutions committed to the agenda of water, peace and security.

GOWP promotes water-cooperation as a way to reduce tension and conflicts between various stakeholders and to promote peace. GOWP has adopted diplomatic tools such as "the knowledge management approach" and "discreet facilitation" rather than traditional dispute settlement, peacemaking or peace building approaches.

GOWP has various goals designed to promote sharing access to water data:

- To conduct data-collection and research-supported analysis of global efforts in terms of water, peace and security, and provide an annual overview of these findings
- To create a "safe space" in pre-negotiation consultations for project development and for proactively addressing major water, peace and security issues – with the acknowledgment that the first milestone in any negotiation process and consultation is agreed-upon data
- To encourage the production and use of innovative approaches and tools to better understand and meet water, peace and security challenges – using water-data.

The role of data in transboundary groundwater management: first diplomatic steps on the Senegalo-Mauritanian Aquifer Basin

A specific example of how water-management collaboration can build peace and good-will between nations can be found in West Africa. In order to address the challenge of managing water in a sustainable manner, the Gambia, Guinea Bissau, Mauritania and Senegal initiated a discussion for the joint management of a shared aquifer system essential to the economic and social development of their region. The four states sharing the Senegalo-Mauritanian aquifer basin (SMAB) met in Geneva on 6–7 February 2019 for a roundtable on strategic, transboundary cooperation for managing water resources. Jointly organized by GWH and the Secretariat of the Convention on the Protection and Use of Transboundary Watercourses and International Lakes hosted by UNECE, this diplomatic meeting was convened expressly to enable the water ministries of the four countries to establish a first exchange on the state of knowledge of this complex system of aquifers. The issues of data production, sharing information and sustainable financing were key components in this exchange.

With an area of approximately 350 000 km2, the SMAB is the largest basin in the Atlantic margin of northwest Africa. The groundwater it contains is a strategic resource for all four aquifer states, whose populations – more than 24 million people in total – depend on the basin to a large extent for their access to drinking water and various sectoral uses. The SMAB is the water supply for such major cities as Dakar and Bissau. However, today, all four aquifer basin nations face challenges to their water supply including: salinization, pollution and the impact of climate change on the precipitation necessary for groundwater recharge. The precariousness of the aquifer basin situation demands cooperation at regional levels and the development of greater knowledge about the aquifer systems.

In addition to the four SMAB states, the roundtable included the main transboundary basin organizations of the region: the Senegal River Basin Development Organization and the Gambia River Development Organization. These basin organizations were able to illuminate innovative ways they could potentially be involved in groundwater management, in addition to their current surface-water management mandate. The meeting also benefited from active contributions from experts and technical and financial partners.

The meeting highlighted that cooperation around the SMAB should go beyond aquifers located in the Maastrichtian layer to other layers – sometimes shared only by a sub-group of the SMAB's riparian States. SMAB's governance should thus eventually adopt an integrated hydrogeological approach that takes into account the interactions between surface- and groundwater. A partnership between both transboundary basin organizations therefore has great potential for the sustainable management of the SMAB. An institutional arrangement between them could build upon other examples of regional cooperation, such as the groundwater management practices of the Orange-Senqu River Basin Commission in Africa; the International Commission for the Protection of the Danube River; and the International Commission for the Protection of the Rhine in Europe.

As an outcome of this meeting, the riparian nations proposed setting up a working group to promote transboundary cooperation on the SMAB. The working group would develop specific, user-friendly institutional mechanisms to ensure permanent data production and exchange, elevate and equalize the states' capacities and expertise and implement a regional strategy for the sustainable management of the SMAB.

The role of 21st century river basin organizations for sustainable development – and the need for data in joint investment plans

Strengthening the water-peace-security nexus around the globe requires strong institutions and political will. Collective efforts are needed to create and implement efficient intersectoral, transboundary and territorially-inclusive approaches. To this end, several institutional arrangements can serve as models for the way forward, such as those of the River Basin Organizations (RBOs).

RBOs range from small or local watershed-user associations to large, transboundary water agencies. RBOs have huge potential on a number of fronts: to contribute to inclusive water-management approaches; to provide multiple perspectives on water management as developers and equalizers; to prevent and adapt to climate change and water-related disasters; and to act as informal diplomats or peacemakers. GWH considers RBOs to be uniquely positioned as global connectors for building water-management networks; for addressing the growing gaps in development between fragile and stable nations; and for helping regions overcome the disconnect that often occur between different levels or sectors of local or national authorities. As demonstrated by the well-documented Senegal River Basin Organization example, RBOs can play a critical role in leveraging innovative financing solutions and generating new investments in transboundary and multisectoral water-related projects. One word of caution, however: Historically, financial focus has been placed primarily on global- and national-level investments. Financing for water management efforts must integrate local (subnational) and regional – supranational – efforts too in order to be effective.

In its report, GHLPWP recommended that joint investment plans in river basins become standard practice in the financial community. Such plans have the potential to reduce risks and mobilize political and financial wills – and to translate broader cooperation objectives into concrete results for the benefit of basins' populations. Unfortunately, too many "master plans" or investment strategies have remained on paper because they lacked a policy or a strategic framework or a sound blueprint for operations, financing and implementation. Our objective is therefore to support subnational or supranational organizations – such as RBOs – to meet 21st century challenges and propel the world forward on collaborative water-management. A fundamental part of this goal also depends upon nations having access to – and a consensus on – water data.

Data production for water and climate diplomacy

Within the past two years, the European Council has adopted conclusions on both water diplomacy and climate diplomacy.[11] These demonstrate that water and climate are becoming priorities in discussions of foreign policies and preventive diplomacy.

Diplomatic engagement, however, needs to build upon a solid set of data-production mechanisms. Simply put, nations cannot agree on shared goals or shared actions if they are not operating with a shared set of facts. This is all the more true in contexts in which political institutions and multilateralism are being challenged – sometimes, it would seem, in reaction to limited capacities to address and prevent environmental crisis. In light of this, data production mechanisms should be designed in user-friendly ways that are conducive to political engagement and public mobilization. As acknowledged during the 2020 World Economic Forum, new technologies have the potential to develop data systems in such a way as to restore some level of public trust in science, diplomacy, and cooperation. Thereby, they can help us to meet the societal challenges of the 21st century and adopt more inclusive approaches to sustainability and diplomacy.

Ideally, where water management is concerned, information systems should not only be based on hydrometerological data, but combine social, economic and environmental data as well. They should take into account transboundary water legal frameworks and the human right to water and sanitation. Data production – and information access – are essential investments for protecting our natural resources and global stability, and for promoting public trust and constructive participation.

As such, the GWH strives to contribute to shape the global hydropolitical agenda. Although much effort has been concentrated on the implementation of the recommendations of the GHLPWP, even greater effort is needed. Mobilizing a coalition for data on water and peace is crucial for meeting the challenges of our century.

---

11 On 19 November 2018, the Council adopted conclusions on water diplomacy, in which it stressed the essential link between water and climate. "The Council notes the potential of water scarcity to affect peace and security, as water related risks can have grave human and economic costs, all of which can have direct implications for the EU, including through migration flows."

On January 20th, 2020, the Council renewed its commitment to its conclusions on climate diplomacy adopted on 18the February 2019 » the Council recalls that climate change is an existential threat to humanity and biodiversity across all countries and regions, and requires an urgent collective response. For this reason, EU leadership through example is crucial for raising the level of global climate ambition. »

HydroSOS – The Hydrological Status and Outlook System towards providing information for better water management

By Alan Jenkins[1], Harry Dixon[1], Victoria Barlow[1], Katie Smith[1], Johannes Cullmann[2], Dominique Berod[2], Hwirin Kim[2], Michael Schwab[2], Luis Roberto Silva Vara[2]

Water-related hazards and threats are a source of deepening concern globally. Tens of millions of people worldwide are affected by these events, and damages are estimated to cost in the order of magnitude of billions of US dollars per year[3]. Water hazards are consistently identified as among the highest global risks in terms of impact (World Economic Forum (WEF), 2020). And scientists expect water-associated risks to intensify in the coming years due to climate change, population growth and increasing economic activities.

Some of the principal water challenges include: securing water supplies; designing appropriate water governance schematics; sustaining the management of transboundary basins; managing flood and/or drought; and ensuring ecosystem- protection and conservation. One of the main difficulties in trying to effectively manage water resources and address such challenges is the lack of hydrological information products targeted to serve the needs of different sectors. This information deficiency is often driven by three factors:

- insufficient local-scale data
- a lack of regional to global coherence in hydrological information and modelling systems
- limited dialogue between the multitude of actors, which renders the understanding of stakeholders' water management needs unclear.

Because of these shortfalls, water managers and stakeholders cannot properly assess the availability of water resources on different spatio-temporal scales. They also cannot foresee how the availability of water might change over the near future, thus rendering water management and planning difficult, if not impossible. A framework is needed that can bring regional and global monitoring data together with locally collected data, analyses and basin-scale modelling systems. The WMO Global Hydrological Status and Outlook System (HydroSOS) is that mechanism. HydroSOS aims to fill in the shortfalls in order to facilitate the tasks of water managers and stakeholders in the face of intensifying water threats and risks.

Addressing Water Challenges through HydroSOS

A global framework for the production and sharing of water-related information products could produce a unified assessment and prediction system. This, in turn, could help us understand the current status of surface and groundwater hydrological systems as well as predict their evolution over the coming weeks to months. The main objective of HydroSOS is to develop such a system by bringing National Meteorological and Hydrological Services (NMHS) together to improve the provision of reliable, timely, accurate and relevant

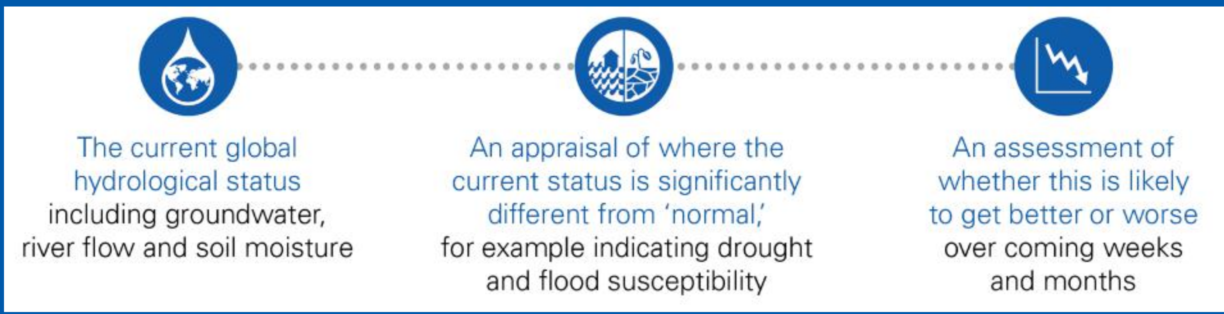
1 UK Centre for Ecology and Hydrology

2 WMO Secretariat

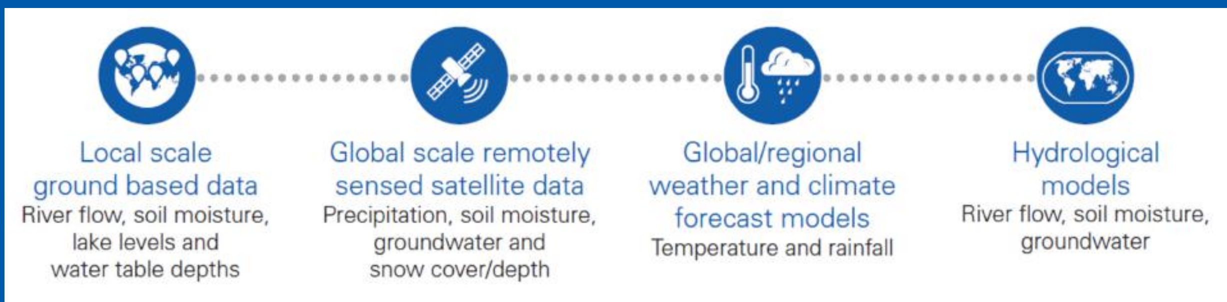
3 The United Nations World Water Development Report 2019: Leaving No One Behind. Paris, UNESCO World Water Development Report 2019: Leaving No One Behind. Paris, UNESCO

HydroSOS elements

The intent of HydroSOS is to help countries assess their current water resources relative to “expected” or “normal” conditions for a particular location and time of year. Using this information, countries can then develop outlooks on how the resource status may change over the coming weeks and months:



The information will be provided for a range of spatial scales including global, regional, national and local (river basin) scales. The status and outlook will be determined using observed data and/or from model outputs using meteorological models to drive hydrological models, particularly in areas where observations have gaps or are scarce:



hydrological status assessments and outlook products to inform water resources management.

Such products need to be derived from systematically collected, comparable and trustworthy local-scale data. This information needs to be consistent with national, regional and global information. HydroSOS will thus permit NMHSs to respond to pressing questions from decision-makers, such as: “How much water is there available in my basin/region at the moment?”; "Is the current situation normal?"; and "How might the local and regional flood/drought situation change in the coming weeks to months?”

HydroSOS will support national capabilities to assess current hydrological status- and forecast-outlooks, as some WMO Members still do not have the tools and skills to undertake such analysis. Moreover, it will provide consistent hydrological status and outlook information, which is not often available at present across transboundary basins or regions of shared hydrological interest. Finally, it will bridge the information gap between locally-informed hydrological and information products and those developed globally.

HydroSOS within WMO

In December 2016, the WMO Commission for Hydrology initiated HydroSOS and approved the formation of an Expert Task Team to oversee the pilot phase of this initiative. In June 2019, the Eighteenth World Meteorological Congress recognized the HydroSOS initiative as a fundamental component of the WMO Strategic Plan (Resolution 25, Cg-18). HydroSOS will support eight of the long-term ambitions for an operational hydrological community (Resolution 24). It will directly address Long-term Ambition Six, which states: "We have thorough knowledge of the water resources of our world" (for more information see WMO Long-Term Ambitions for the Operational Hydrological Community). It will do this by enabling a monitoring system that produces information that can be used to optimize existing services as well as future policies and services and decision-making from the local to the global scale.

HydroSOS supports the full value-chain for services by focusing on the development and sharing of inter-operable hydrological status and outlook information products and by drawing upon existing WMO initiatives. First, it will enhance hydrological monitoring and data exchange such as the Global Hydrometric Support Facility (HydroHub), through three of its components: the World Hydrological Cycle Observing System (WHYCOS), the WMO Hydrological Observing System (WHOS), and the World Water Data Initiative (WWDI). Secondly, it will advance hydrological forecasting, water resources assessment and early warning capabilities such as the Flood Forecasting Initiative (FFI), the Flash Flood Guidance System (FFGS), and the Dynamic Water Assessment Tool (DWAT).

National Hydrological Services at the centre of HydroSOS

The WMO HydroSOS will be designed for, and operated by, National Hydrological Services (NHSs). It will enable them to better support a range of stakeholders – including government bodies, different socioeconomic sectors such as energy and agriculture, regional and international aid agencies, and the public – in decision-making related to water management.

HydroSOS will build capacity to undertake hydrological status assessments and develop outlooks within NHSs; it will directly draw upon existing and planned WMO initiatives in relation to hydrological monitoring, data sharing and sub-seasonal to seasonal hydrological and meteorological forecasting, together with different partners.

The working structure of HydroSOS

A set of work packages – addressing coordination, standardization of technical approaches, implementation and delivery – have already been established for the pilot phase of HydroSOS.

Work Package 1 (WP1), coordination, focuses on programme management, communications and resource mobilization. Furthermore, it considers linkages with other WMO initiatives such as WHOS, WHYCOS, WWDI, and the Global Data-Processing and Forecasting System (GDPFS).

Work Packages 2a, 2b and 2c focus on the standardization of technical approaches and aim to develop the technical protocols needed for HydroSOS. Furthermore, WP2 compares the different methodologies that could be recommended to NMHSs (and others) that do not currently have well-developed hydrological status assessment and outlook capabilities but want to provide information services.

In 2019, WP2a performed a review of the climate, hydrology and terrain data available at the global, regional and country levels. While WP2b compiled a series of hydrological status assessment methodologies from around the world, including consideration of the definition of "normal" hydrological conditions for both streamflow and groundwater. Whereas WP2c made important advances in evaluating the technical performance of sub-seasonal to seasonal hydrological forecast methods. Thus, WP2c resulted in a greater understanding of the strengths and weaknesses of different outlook-generation methods on local and global scales – and of the causes of the contrasting performances among them.

Implementation of WP3 and WP4 is now ongoing at regional and global levels. WP3a and 3b are implementing two Regional Capacity Development pilots: one in the Lake Victoria Basin, the other in South Asia (Ganges-Brahmaputra-Meghna Basin). The two proof-of-concept pilots aim to assess how shared HydroSOS capabilities can be developed in transboundary basins or regions of shared hydrological interest. The assessments of regional needs and capabilities were already carried out in the two pilot basins in 2019 through in-depth discussions with NMHSs and other stakeholders.

In the meantime, WP4 is assessing the role of large-scale (global/continental) status and outlook products in supporting and supplementing local-scale (basin/national/regional) products. NMHSs often have difficulty reconciling local information with the large-scale products of global modelling centres and research organizations. WP4 aims to assess such products, analyse their possible use in HydroSOS and determine how new WMO products can be developed specifically to support NMHSs locally. So far, work has focused on comparing global hydrological models to see if any of them can be used for specific basins – and under what conditions one product might perform better than the others.

Delivery, the final stage of the pilot project, includes two work packages. WP5 covers Product Communication and Dissemination, while WP6 deals with Capacity Development and Training. An early-stage prototype, HydroSOS Global Portal, is being developed as part of the delivery stage to show how hydrological status and outlook products from around the world could be brought together. In November 2019, the Nanjing Hydraulic Research Institute (NHRI) hosted the first HydroSOS Technical Workshop in Nanjing, China. The Workshop took stock of progress-to-date and determined the steps needed in order to present the pilot phase findings to the Extraordinary Session of the World Meteorological Congress in 2021.

The South Asia (Ganges-Brahmaputra-Meghna Basin) Pilot

WP3a conducted national HydroSOS capacities and needs assessments in four of the countries along the Ganges-Brahmaputra-Meghna basin: Bangladesh, Bhutan, India and Nepal. The focus was on the national institutional capacities of NMHSs, the availability of hydrometeorological data, mapping stakeholder needs and the challenges to implementation of HydroSOS.

All four countries had good networks of hydrometeorological data and easily-accessible digitally-formatted historical data. Their real-time hydrometeorological data networks are being expanded and will be adequate for HydroSOS. However, the sharing of river discharge data between some countries is limited and some NMHSs in the basin are bound in the activities by low staff, budget and technological capacity.

There is a significant need for a regional HydroSOS in the basin, especially for agriculture, energy and navigation. Demand for water resources is growing in the basin, which currently has one million hectares of irrigated land, one hundred thousand Megawatts (MW) of hydro-electric capacity and an extensive criss-cross of river navigation. In addition, the basin suffers from frequent floods, landslides and droughts.

Improvements in the management of water resources – which will better the livelihood of about 750 million people and increase the economic development of the region – will be underpinned by HydroSOS. Many sectors will benefit from HydroSOS, including hydropower operators, water supply management, river navigation operators and disaster management agencies. Most notably, agricultural output would increase with improved management of groundwater, irrigation water and drought risks.

The Lake Victoria Basin Pilot

In 2019, WP3b assessed HydroSOS capacities and needs assessments in five countries of the Lake Victoria Basin: Burundi, Kenya, Rwanda, Tanzania and Uganda. Its goal was to gain a thorough understanding of the operations and capacities of NMHSs and regional institutions and to identify needs and opportunities for taking HydroSOS forward. Consultations were carried out with NHSs; National Meteorological Services (NMSs); selected national institutions responsible for disaster management and hydropower management; and regional institutions responsible for water, climate and governance.

Data collection infrastructure for both meteorology and hydrology exists in all the countries. However, the potential use of data for real-time water resources management is not realized in all of them – except to some extent in Rwanda – because of a lack of operational telemetry and insufficient data processing and management systems. Staffing levels and financial constraints do not permit any to operate and maintain a complete national network of stations. Many NHSs and NMSs around the world face similar problems; WMO efforts under the HydroHub will focus on addressing them.

Despite the observation network issues, the WP3b assessment concluded that significant steps forward can be made through HydroSOS. If needed resources are provided to the region to develop and deliver status and outlook products, there can be significant benefits for all stakeholders: delivery of such products would finally bring real value from the many projects, past and present, that have supplied instrumentation and capacity building to stakeholders in the region to generate usable data and information.

The beneficiaries of both status and outlook products in the Basin include the hydropower sector, agricultural producers and those operating irrigation systems – whose work would benefit especially from rainfall, soil moisture, and temperature outlooks. These products are also essential for public health managers and those controlling reservoir storage and groundwater pumping for domestic, agricultural and industrial water supplies. The WP3b assessment also indicates that most of the users of status products are interested in short-term weekly and monthly outlooks – thus, the region has a large and receptive number of users of hydrological outlook products.

Path forward

HydroSOS is still in its pilot phase. Work continues on the analysis of the methodologies to define hydrological status and create local, basin-scale hydrological outlooks that can be integrated across regions and the globe. This will help to define the initial technical protocols and standards on which HydroSOS will be based.

Implementation plans to extend the WP3a and WP3b pilots to other regions are currently being drafted. The plans will include technical protocols and standards and stakeholder workshops to better understand user needs. It will aim to enhance cooperation between participating NMHSs and regional organizations in order to produce more meaningful hydrological products for the populations living in the two basins.

Work is also ongoing to determine how global hydrological models perform in comparison to regional/local models and on how a regionally-informed global system might be built.

HydroSOS is on course to develop a demonstrator portal, where hydrological data from different countries, including the pilot countries, is being incorporated into a web interface of hydrological indicators. This portal will be tested and perfected to better understand how the delivery mechanism of HydroSOS will work.

Once the pilot phase has produced more substantive results, WP6 on capacity development will begin to define and create the materials required for a successful transfer of technology and know-how to participating countries. WP6 will ensure that hydrological products are created to the highest standards possible.

Who we are

The HydroSOS global team is comprised of a multidisciplinary and multi-cultural group of experts from NMHSs, academia and research institutions. Many international and regional organizations have donated in-kind to HydroSOS with their expertise and time. At present, HydroSOS experts represent five NMHS, four NMS and eight NHS from fifteen countries, nine research/scientific institutions in seven countries, three regional organizations in Africa, and four international organizations. Furthermore, the community of WMO Regional Hydrological Advisers have provided inputs to the initiative since its inception.

The current Work Package leaders are:

- WP1 - Coordination: United Kingdom Centre for Ecology and Hydrology (UKCEH)
- WP2a-Data Sources and Exchange Methods-Nanjing Hydraulic Research Institute (NHRI)

- WP2b- Current Status Assessment and Modelling Methods: United States Geological Survey (USGS)
- WP2c - Hydrological Forecasting and Modelling Methods: Australia's Bureau of Meteorology (BoM)
- WP3a - South Asia Pilot: Independent consultant from Nepal
- WP3b - Lake Victoria Pilot: Uganda's Ministry of Water and Environment (MWE)
- WP4 - Global Pilot: UKCEH
- WP5- Product communication and dissemination: United States National Center for Atmospheric Research (NCAR)
- WP6 - Capacity Development and Training: Currently vacant

Get involved

As HydroSOS pilot phase moves to implementation, enhanced skills are sought for the project. For example, groundwater and soil moisture experts are needed to help the team to better understand these processes and properly include them in the development of the system. Additionally, the meteorological community is encouraged to help establish links between sub-seasonal and seasonal meteorological forecasts. Also, experts in capacity development in the hydrology domain are sought to help HydroSOS to develop comprehensive materials for NMHSs such as guidelines and training manuals.

HydroSOS is looking specifically for methodology cases from NMHSs about how they generate and use hydrological status and outlooks. Moreover, HydroSOS seeks to develop greater links within the WMO Regional Associations by engaging with regional working groups on hydrology.

HydroSOS aims to bring operational and research hydrologists and meteorologists together at national, regional and global levels. By engaging with HydroSOS, the research and global modelling communities will be able to co-design and refine products with the WMO network of NHS, increasing their utility to operational water managers and the contribution they make to future water security.

WMO and the HydroSOS team are looking forward to engaging with more Members and their experts in developing a framework for the System. HydroSOS is looking for contributions, both in-kind and financial, for the implementation of its pilot phase.

Innovating global hydrological prediction through an Earth system approach

By Shaun Harrigan[1], Hannah Cloke[2, 3] and Florian Pappenberger[1]

Climate change, population growth and human intervention within river channels and catchments make it more challenging than ever to provide reliable information on the current and future state of water in the world's rivers. Yet society urgently needs timely, dependable information for early warning of floods and droughts, which still today surprise and devastate entire communities. Scientific progress must accelerate to meet this challenge. This article argues that an Earth system approach to global hydrological prediction will spark the innovation and stronger interdisciplinary collaboration needed for breakthrough scientific progress.

Traditional hydrological prediction

Hydrological prediction has a rich past. Its basic principles were already well-established over 50 years ago (Nash and Sutcliffe, 1970). But since then, despite significant investment, progress has been slow and vast scientific, data and operational limitations remain.

The lack of river discharge observations around the world is a major obstacle for hydrological prediction systems (Lavers et al., 2019). But traditional prediction approaches also have limited capability to exploit the range of available, and planned, Earth system observations – for snow, soil moisture, evapotranspiration, groundwater and river discharge – especially with the proliferation of remote sensing. In addition, traditional models struggle to extrapolate predictions of extremes outside the ranges to which they were tuned. This problem is exacerbated as catchments, and their river flow, change over time in response to land-use and climate changes. Given the complexity and scale of the problem, it is pertinent to ask whether an alternative and more interdisciplinary approach would accelerate scientific progress.

1 European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK
2 University of Reading, Reading, UK
3 Uppsala University, Uppsala, Sweden

The advantages of the Earth system approach

The Earth system approach, the basis of the European Centre for Medium-Range Weather Forecasts (ECMWF) Strategy 2016–2025 and the WMO governance reform which is now in implementation, models the Earth as a whole. This includes interactions between the atmosphere, oceans and land as well as the biosphere and human activities. Such an approach is inherently interdisciplinary, spanning many fields of science and demanding closer collaboration.

The advantages of exploiting Earth system modelling for the task of global-scale hydrological prediction are many. Allowing for interactions between all components of the Earth system leads to improved and consistent predictions between all variables. For example, a correct water budget[4] would not only provide the optimum land surface conditions to drive surface weather, it would also provide the best freshwater influx to the ocean, which in turn would improve the atmospheric predictions which would positively impact the hydrology. This physical and technical consistency provides the basis for seamless prediction from short-to-seasonal lead times without

4 The water budget is the relationship between the inflow and outflow of water.

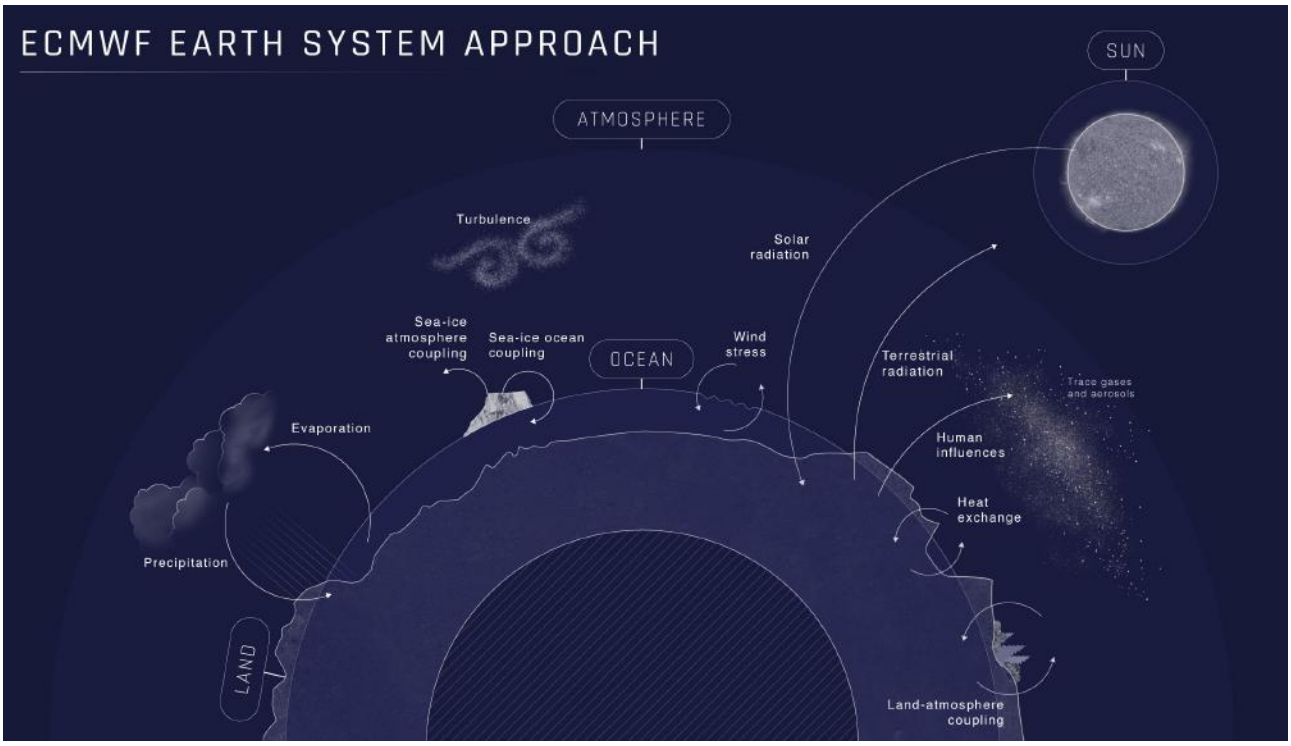


Figure 1. The Earth system approach is central to the ECMWF Strategy 2016–2025

any need for separate flood and drought systems, as is currently the case (e.g. Global Flood Awareness System (GloFAS; Alfieri et al., 2013) and GloFAS-Seasonal (Emerton et al., 2018)).

Large-scale hydrological prediction services must be sustainable in terms of scientific, technical, and computational expertise and resources. Operational numerical weather prediction (NWP) centres have already embraced the Earth system approach. Therefore, performing hydrological prediction at NWP centres allows unparalleled access to resources and expertise. These include advances in Earth system observations and data assimilation, high performance computing and cloud infrastructure, delivery of 24/7 operational predictions, and collaboration on new developments in areas such as artificial intelligence and machine learning at scale. Together, these foster collaboration and innovation and provide significant cost saving.

ECMWF's Earth system approach

At ECMWF the comprehensive Earth system model, known as the Integrated Forecasting System (IFS), forms the basis for all the data assimilation and forecasting activities. Progress in the modelling of interactions between Earth system components is at the core of the ECMWF 2016–2025 Strategy (Figure 1).

The ECMWF vision is to use the Earth system approach to take global hydrological prediction to the next level. Closing the water budget[5] in operational models remains a major scientific challenge (Zsoter et al., 2019). As stated earlier, improving the representation of hydrology would benefit the prediction of other interconnected atmospheric and oceanic components. But it will not be an easy task. It will require close collaboration between scientists from many fields. Many scientific questions remain open, and there are just as many barriers when it comes to the availability of hydrological data. However, the use of Earth system modelling for flood forecasting is a clear proof of concept. The Global Flood Awareness System (GloFAS, www.globalfloods.eu/), for which ECMWF is the computational centre, is the fully operational 24/7 forecasting component of the European Commission's

5 Closing the water budget would imply measuring all inflows and outflows of water.

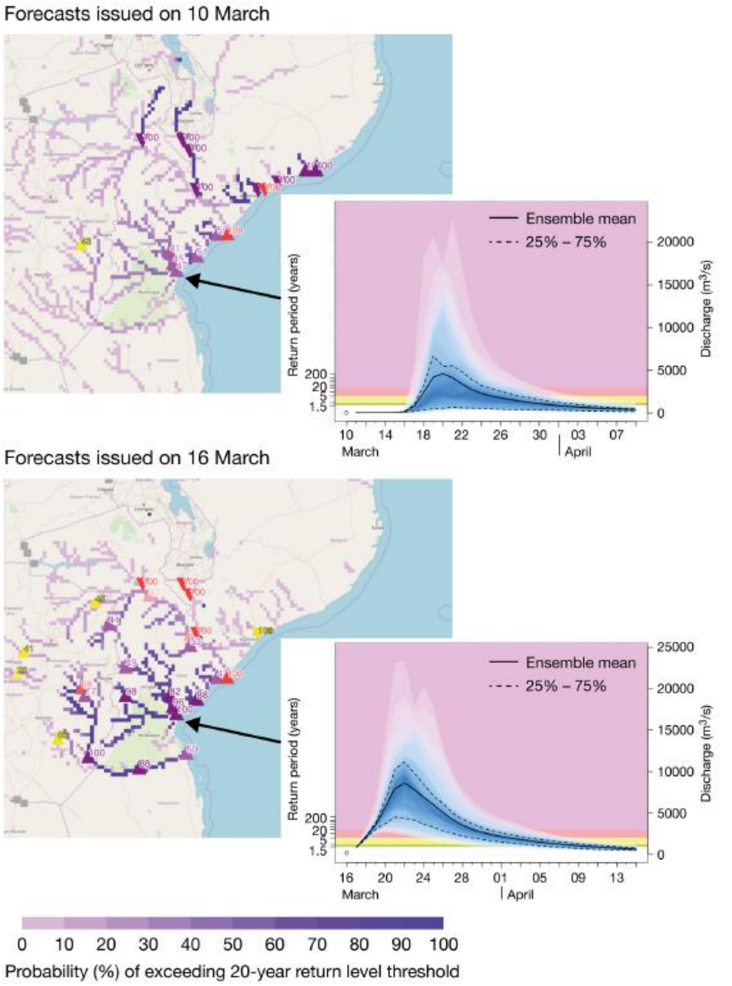


Figure 2. GloFAS flood risk forecasts derived from ECMWF Earth system model output. The shading of the rivers in the maps shows the predicted probability (in %) of the river discharge exceeding the severe flood alert threshold (20-year return period) over the next 30 days in forecasts starting on 10 March 2019 (top) and 16 March 2019 (bottom). The inset charts show the discharge evolution for the Pungwe River at Beira, Mozambique (source: Magnusson et al., 2019).

Copernicus Emergency Management Service (CEMS). GloFAS provides information to support early warning of floods around the world. Figure 2, for example, presents the GloFAS flood forecasts used in Mozambique in March 2019 during the destructive tropical cyclone Idai.

Challenges for the Earth system approach in hydrology

The spatial resolution of Earth system models is currently rather coarse for hydrological prediction in small catchments. For example, GloFAS, with its horizontal gridded resolution of approximately 10 km, is recommended for use in medium and large catchments with areas larger than 1000 km^2. In comparison, where in situ observations are available, traditional models can be set up in much smaller catchments. A "hyperresolution" target in the order 1 km globally is required for Earth system based hydrological prediction to be useful at local scales (Wood et al., 2011).

It much more straightforward to reduce water budget errors in traditional hydrological models because they only seek to predict river discharge correctly. The closing of the water budget within Earth system models must be done in a way that does not worsen predictions of other components that are essential for weather and climate prediction.

The tracking of progress made by any new hydrological prediction developments, as well the ground-truthing (measuring) of new river discharge remote sensing capabilities, is dependent on access to real-time and historical hydrological observations in a standardized data framework. Initiatives such as the WMO Hydrological Observing System (WHOS, www.wmo.int/pages/prog/hwrp/chy/whos/index.php), which would make such data available, are crucial for advancement of global hydrological perdition (Lavers et al., 2019).

Making the vision a reality

The substantial progress in hydrological prediction made within the field of hydrology with traditional models cannot be ignored. It is essential that such progress continues. However, the Earth system approach is more effective for global scale prediction as it provides a clear framework and vision for closer interdisciplinary collaboration, advanced data assimilation and Earth system observation capabilities, access to high performance computing, and offers service sustainability. As we face the pressures of climate change and a growing population, it is our ambition and responsibility as a community at the service of society to be prepared and to provide prediction systems capable of meeting global challenges. The Earth system approach promises to deliver this.

With the right leadership, resources and a group of interdisciplinary scientists willing to step outside their comfort zones and embrace a different way of doing things, pushing the boundaries of hydrological prediction towards an Earth system approach is achievable. Progress has already begun, as demonstrated by GloFAS. With even more powerful supercomputers allowing ground-breaking kilometre-scale global Earth system models to be tested (ECMWF, 2020), the vision of fully coupled hydrological prediction within Earth system models is reachable within the next decade.

References

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J. and Pappenberger, F., 2013: GloFAS - global ensemble streamflow forecasting and flood early warning, Hydrol. Earth Syst. Sci., 17(3), 1161–1175, doi:10.5194/hess-17-1161-2013.

ECMWF, 2020: ECMWF scientists to simulate global weather at 1 km resolution, accessed 23 January 2020, ECMWF news article, available: https://www.ecmwf.int/en/about/media-centre/news/2020/ecmwf-scientists-simulate-global-weather-1-km-resolution

Emerton, R., Zsoter, E., Arnal, L., Cloke, H. L., Muraro, D., Prudhomme, C., Stephens, E. M., Salamon, P. and Pappenberger, F., 2018: Developing a global operational seasonal hydro-meteorological forecasting system: GloFAS-Seasonal v1.0, Geosci. Model Dev., 11(8), 3327–3346, doi:https://doi.org/10.5194/gmd-11-3327-2018.

Lavers, D., Harrigan, S., Andersson, E., Richardson, D. S., Prudhomme, C. and Pappenberger, F., 2019: A vision for improving global flood forecasting, Environ. Res. Lett., doi:10.1088/1748-9326/ab52b2.

Magnusson, L., Zsoter, E., Prudhomme, C., Baugh, C., Harrigan, S., Ficchi, A., Emerton, R., Cloke, H., Stephens, L. and Speight, L., 2019: ECMWF works with universities to support response to tropical cyclone Idai, ECMWF Newsletter, 160, 2–3.

Nash, J. E. and Sutcliffe, J. V., 1970: River flow forecasting through conceptual models part I — A discussion of principles, Journal of Hydrology, 10(3), 282–290, doi:10.1016/0022-1694(70)90255-6.

Wood, E. F., Roundy, J. K., Troy, T. J., Beek, L. P. H. van, Bierkens, M. F. P., Blyth, E., Roo, A. de, Döll, P., Ek, M., Famiglietti, J., Gochis, D., Giesen, N. van de, Houser, P., Jaffé, P. R., Kollet, S., Lehner, B., Lettenmaier, D. P., Peters-Lidard, C., Sivapalan, M., Sheffield, J., Wade, A. and Whitehead, P., 2011: Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, Water Resources Research, 47(5), doi:10.1029/2010WR010090.

Zsoter, E., Cloke, H., Stephens, E., de Rosnay, P., Muñoz-Sabater, J., Prudhomme, C. and Pappenberger, F., 2019: How Well Do Operational Numerical Weather Prediction Configurations Represent Hydrology?, J. Hydrometeorol., 20(8), 1533–1552, doi:10.1175/JHM-D-18-0086.1.

Integrated approach to Flood and Drought Management in the Volta Basin

By Robert Dessouassi[1], Armand Houanye[2], Hwirin Kim[3], Giacomo Teruggi[3] and Ramesh Tripathi[3]

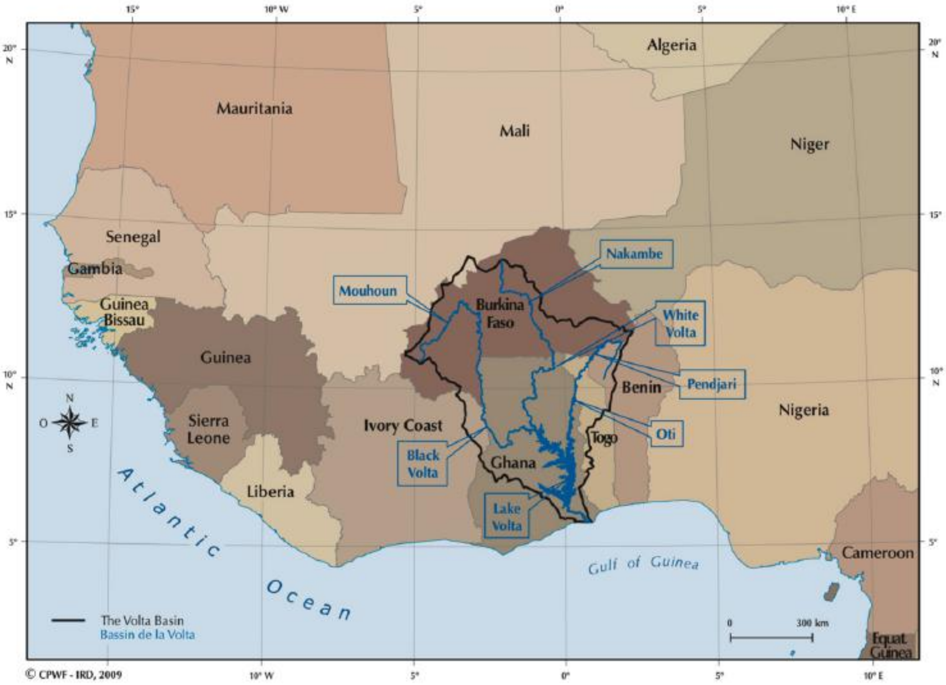
The Volta River Basin covers a region of about 400 000 km2 with a population of approximately 29 million. The Volta Basin runs through the semi-arid to sub-humid areas of six countries: Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali and Togo. The Basin is highly vulnerable to meteorological and hydrological events. Baseline socio-economic issues in the region are today exacerbated by considerable changes in the climate over recent decades – a reduction in precipitation and temperature increase. And the climate is expected to keep changing. Scientists predict that the dry seasons will be longer and drier, while the monsoon seasons will become shorter with more intense precipitation. If climate change adaption measures are not implemented, food security will be threatened, farmers will lose their livelihood and the number of people living in informal settlements in the high-risk flood prone zones of urban centres will increase.

National agencies in the Volta Basin countries, mainly National Hydrological and Meteorological Services (NMHSs), are acutely aware of the need to prepare the region for the socio-economic and environmental impacts of climate change. They identified the implementation of an integrated water resources management strategies and the development of risk maps and early warning systems as priorities to increase resilience and ensure sustainable development in the region. Other needs identified include the integration of disaster risk reduction strategies into national development and climate adaptation plans, the enhancement of synergies and coordination mechanisms at regional, national and local levels to foster integrated flood and drought management and the availability of standardized data, especially real-time data, and the development of coordinated information channels and procedures for end-to-end early warning system. At the ground level, communities at risk requires training and knowledge on early warning systems and strategies to manage disaster risks and get actively involved in preparedness and contingency plans.

WMO, in partnership with the Volta Basin Authority and the Global Water Partnerships (GWP)-West Africa, with the support of the national agencies of the six riparian countries developed and submitted a regional climate adaptation project proposal covering all of these aspects to the Adaptation Fund. The proposal, for US$ 7.92 million, was endorsed by the Adaptation Fund Board for implementation in October 2018.

The Volta Basin project uses an integrated approach to strengthen targeted national agencies and community level resilience and adaptation capacity to the impact of climate change events – floods and drought. It is based on the framework for Integrated Flood Management (IFM) and Integrated Drought Management (IDM), which has been promoted by the Associated Programme on Flood Management (APFM) and Integrated Drought Management Programme (IDMP) for the past 17 years.

1 Volta Basin Authority
2 GWP-WA
3 WMO Secretariat



Over the last 20 years, some two million people along the stretch of the Volta have been affected by floods – mainly the 68% of the population working in the agricultural sector.

The four-year Volta project, officially launched in June 2019. The main objective is to assist the six countries in the implementation of coordinated and joint measures to improve their existing flood and drought management plans at regional, national and local level. This will be achieved by building on the lessons learned from the past as well as on current and ongoing projects related to disaster risk reduction and climate change adaptation.

Project objectives and components

The project has three specific objectives:

1. Develop capacity and established frameworks at the local, national and regional levels to ensure risk informed decision-making

2. Develop concrete adaptation and environmentally-friendly actions using an integrated approach

3. Strengthen policy and institutional capacity for integrated flood and drought management at the local, national and trans-boundary levels.

These will be delivered through three components: risk prevention, concrete adaptation and stakeholder engagement, and governance.

Current and future areas of vulnerability, capacities for flood and drought management, exposures and risks (defined as VCERs in the project proposal) information will be identified in the **first component** in order to develop local, national and regional flood and drought risk maps. During capacity building sessions, climate scenarios will be gathered and disseminated to stakeholders, together with the risk maps, to study the possible impact of climate change on the zones identified. Stakeholders recommendations on these will be integrated into the climate change adaptation approaches and disaster risk strategies. Indicators and tools will also be provided to stakeholders to raise awareness of how the ecosystem functions to our benefit as human well-being and the importance of protecting and restoring them. These tools will help stakeholders to contribute to preserving wetlands and other areas of transboundary importance such as biodiversity hot-spots.

The **second component** will provide the basis for an integrated flood and drought management approach in the region, through the data and information systems and the early warning systems that will be put in place in the Basin. The development and implementation of the End-to-End Early Warning System for floods and drought at the scale of the Volta Basin is the key output of the project. The open-source myDewetra.world[4] platform will be used to connect the meteorological, hydrological, climatological, VCERs databases and other validated outputs, such as hydrological modelling systems, decision support and early warnings, from related projects and initiatives at the local, national and regional level. To improve the sharing of information, the Early Warning System will cover the complete risk reduction value chain – from vulnerability and risk mapping to forecasting, warning dissemination and decision support. The operational use of the new End-to-End Early Warning platform will be supported by a series of pilot tests in various sub-basins and vulnerable areas, which have diverse socio-environmental conditions. Capacity development activities will be carried out to ensure an adequate uptake of the new products, services and tools. Moreover, self-help modules on nature-based solutions and gender-sensitive participatory approaches will be developed at the local and national levels.

"...each of the Volta Basin countries must have Hydrometeorological information to prevent and manage the harmful effects of climate change. But also and above all take steps to offer better living conditions to the populations living in the Volta Basin."
- Colonel Martial Mé, representing the Minister of Water and Forests, Côte d'Ivoire at the project Inception workshop

Component 3 will explore the benefits of the project's implementation in order to revise or develop new policies, plans and guidelines on disaster risk reduction and climate change adaptation. Adaptation measures and strategies that align with environmental and social policies as well as with gender principles will be discussed at local levels to increase resilience to floods and drought. The participation and engagement of local stakeholders will facilitate the adoption of the strategies for the disaster risk reduction and climate change adaptation and result in long-term sustainability.

4 CIMA Research Foundation and Department of Italian Civil protection have jointly developed the myDEWETRA. world open-source platform contributing to the hydro-meteorological and wildfire risk forecasting and mitigation.

Status and expected results

Implementation of the Volta Basin Flood and Drought management project started at the Inception workshop held in Abidjan, Cote d'Ivoire, on 25 and 26 June 2019. The first step was to understand current capabilities and needs for the End-to-End Early Warning System for Floods and Drought through the carrying out of national consultation meetings with stakeholders in the six countries. The MyDewetra.world platform – fully integrated with existing information and products for floods and drought management – will be rolled out to stakeholders at the end of the first year, in June 2020.

The project will develop the underlying capacity of national and regional institutions to maintain long-term sustainability and to scale up the results. It will support stakeholders at all levels by providing policy and management guidance and by sharing scientific information, knowledge and best practices for Integrated Disaster Risk Reduction and Climate Change Adaptation. The six riparian countries will benefit from a basin-wide transboundary management framework to ensure long-term environmental and economic development. The region will have concrete solutions to alleviate a potential increase of vulnerability due climate change and to build an effective network of actors to address climate adaptation issues.

The project's wide training curriculum – covering aspects ranging from hazard and risk mapping, water resources management, hydrological outlooks, community-based flood management, agrometeorology, integrated drought management, etc. – will provide technical support and new decision-support tools for national operational centres.

The joint activities of the partner organizations, such as requirements specifications, installation of equipment in the NMHSs and provision of new information to

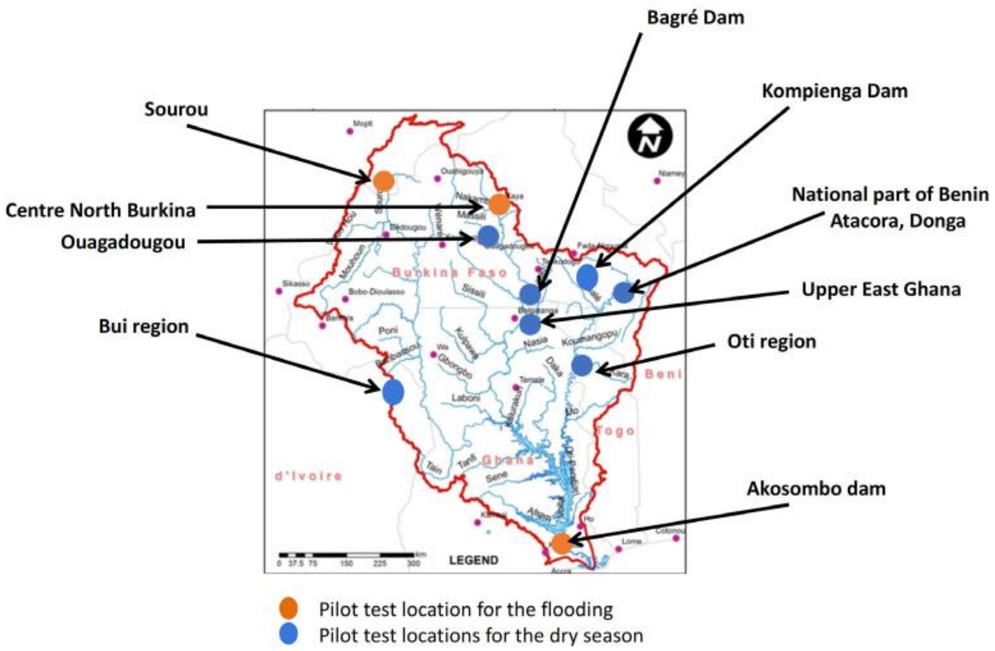


Figure 2: Tentative pilot sites for testing the End-to-End Early Warning System

the public, field work in the pilot testing locations will also foster exchanges, create groups of users and form trainers, who will take up project ownership in the future and prolong the project efforts.

Sustainability

The long-term sustainability of the project achievements will be dependent on the meteorological, hydrological and climatological data and related products from the NMHSs of riparian countries. Several – as well as other agencies in charge of environmental protection – have already provided support letters to ensure the long-term transfer of information from the national databases to continue operations of the forthcoming transboundary Early Warning System coordination unit.

International organizations and financial institutions will be invited to follow the project success stories and to identify other needs at local, national and regional levels. These will potentially lead to new funding sources or develop synergies with other on-going and future projects in the six countries.

Project Donors and Partners

Flash Flood Guidance System: Response to one of the deadliest hazards

By Milica Dordevic, Petra Mutic and Hwirin Kim, WMO Secretariat

Flash floods are among the world's deadliest natural hazards. They cause more than 5 000 deaths annually and have severe social, economic and environmental impacts[1]. Flash floods account for approximately 85% of all floods and have the highest mortality rate among all categories of flooding. Flash floods are sudden and short, with a time frame of less than six hours between the observable causative event and the flood itself, which tends to have a high peak discharge. Flash floods have enough power to change the course of rivers, bury houses in mud, and sweep away or destroy whatever stands in their path. They are complex hydrometeorological events that are hard to predict. Therefore, preparing for them requires expertise in hydrology and meteorology combined with knowledge of local conditions.

When Hurricane Mitch struck Central America in 1998, it caused more than 11 000 casualties and destroyed hundreds of thousands of homes. Flash floods, floods, landslides and mudslides brought on by heavy rainfall destroyed entire villages, and the majority of the countries' crops and infrastructure were destroyed. Total damages amounted to more than US$ 5 billion.

In the wake of these catastrophic events, the U.S. Agency for International Development's (USAID) Office of Foreign Disaster Assistance (OFDA) initiated a project to coordinate the development of an early warning system for flash floods in the region. In 2001, the Hydrologic Research Center, in collaboration with U.S. National Oceanic and Atmospheric Administration (NOAA), began the development of the regional Flash Flood Guidance System (FFGS) to generate flash flood warnings. Then in 2007 World Meteorological Congress approved the implementation of FFGS worldwide through projects developed jointly by the WMO in collaboration with NOAA, the Hydrologic Research Center, and USAID/OFDA.

Today, FFGS is providing early warnings in over 60 countries to some three billion people – 40% of the world's population – as a result of 13 regional and 2 national FFGS projects. And more projects are under development worldwide. Environment and Climate Change Canada is funding the implementation of FFGS as part of the ongoing Building Resilience to High-Impact Hydrometeorological Events through Strengthening Multi-Hazard Early Warning Systems in Small Island Developing States and Southeast Asia project. The CREWS[2] Initiative's Seamless Operational Forecast Systems and Technical Assistance for Capacity Building in West Africa project, launched in 2019, is developing FFGS in three countries in that region.

Objectives of the System

FFGS was developed to improve the capacity of National Meteorological and Hydrological Services (NMHSs) to issue flash flood warnings and alerts in order to mitigate the adverse impacts of hydrometeorological hazards. The FFGS enhances collaboration between national meteorological and hydrological services, disaster management agencies and other stakeholders and implements state-of-the-art hydrometeorological forecasting models and technology. It provides extensive training to the hydrologists, meteorologists and disaster managers. Since flash floods often cross-national boundaries, regional FFGS projects and cooperation are essential: thus FFGS fosters national, regional and global development and collaboration.

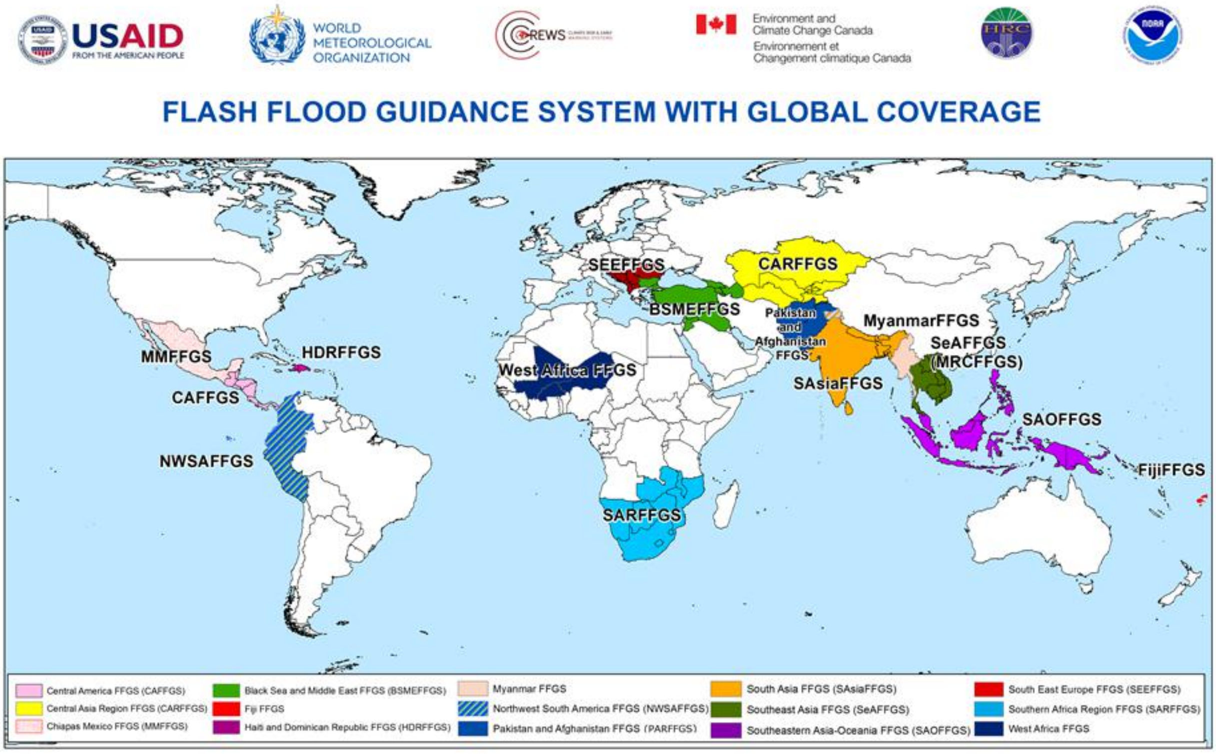
FFGS has been developed as a tool to provide meteorological and hydrological forecasters with both real-time information and diagnostic products to improve their capacity to produce and issue timely and accurate flash flood warnings. Since the implementation of FFGS, most of the countries using it have had access for the first time to products that enable them to issue flash flood warnings and provide response-agencies with the ability to mobilize rapidly.

FFGS products include:

- Quality-controlled precipitation estimates gathered from radar and satellites
- Rainfall measurements from rain-gauges

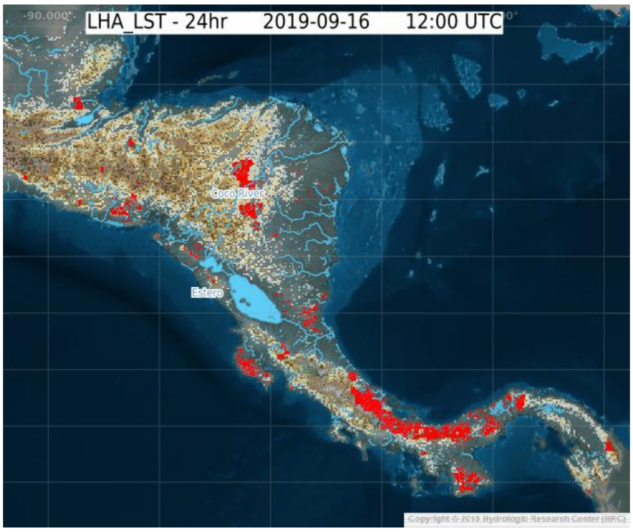
1 www.wmo.int/pages/prog/www/CBS/Meetings/MG_7/Doc5(7)_CHy.doc

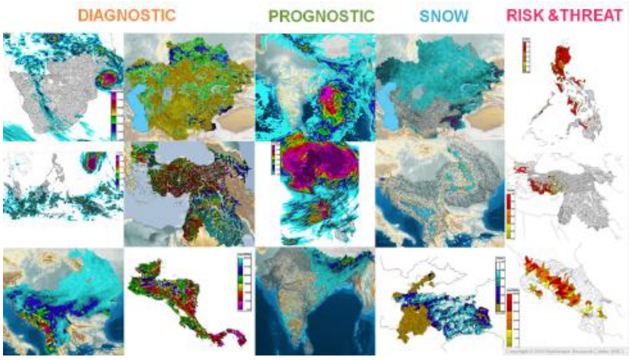
2 Climate Risk and Early Warning System



Flash Flood Guidance System with Global Coverage

Flash Flood Guidance System' Objectives





Landslide Threat Index showing the likelihood of landslide occurrence in Central America (left) and Flash Flood Guidance System Products (above).

- Average soil-moisture and flash flood guidance
- Prognostic products such as quantitative precipitation forecasts from Numerical Weather Prediction models
- Snow products that provide data on snow coverage, snow melt and snow water equivalent;
- and risk- and threat-assessment products related to flash floods.

Special FFGS modules and components are available to assess landslide threats, flash flood events in urban areas and riverine routing. The world's urban population is expected to increase from 55% in 2018 (some 4.2 billion people) to 68% by 2050[3]. With this significant rise in concentrated population centres, it is essential that cities around the world invest in reducing flash flood risks.

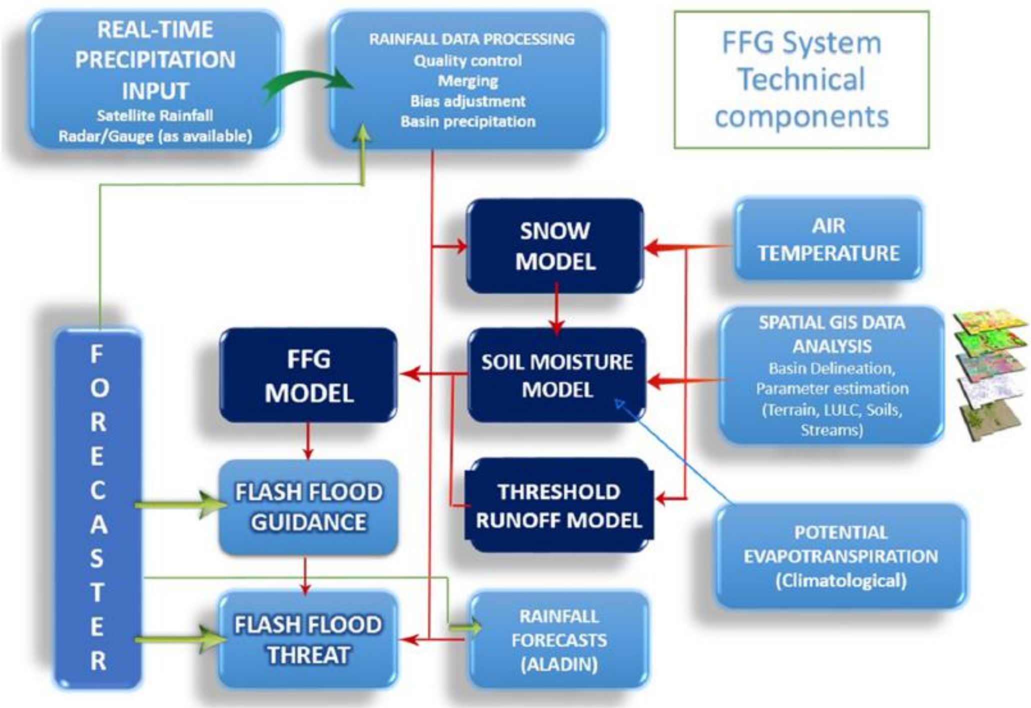
Antalya Statement

Training of hydrologists, meteorologists and disaster managers is an integral part of implementing FFGS and critical for establishing sustainable, local capabilities within the participating NMHSs. Since its implementation started a decade ago, more than 400 meteorological and hydrological forecasters have received extensive FFGS training. An international FFGS Global Workshop, hosted by the Turkish State Meteorological Organization in November 2019 in Antalya, Turkey, gathered 169 experts from 59 countries[4] to share experiences, showcase accomplishments, determine challenges, identify service gaps and establish recommended practices. Their goal was to augment the sustainability of FFGS.

Poster session from the FFGS Global Workshop

3 United Nations, Department of Economic and Social Affairs www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

4 community.wmo.int/meetings/hydrology-and-water-resources/flash-flood-guidance-system-ffgs-global-workshop



Flash Flood Guidance System Technical Components.

Participants recognized that the implementation of FFGS over the last decade had led to a significant reduction in the loss of life and property. They called upon national governments to recognize FFGS as an effective means of safeguarding their countries from flash floods – particularly as the global population increases, urban areas grow, and societies continue to encroach upon regions prone to flash floods. The need for flash flood early warning systems is paramount.

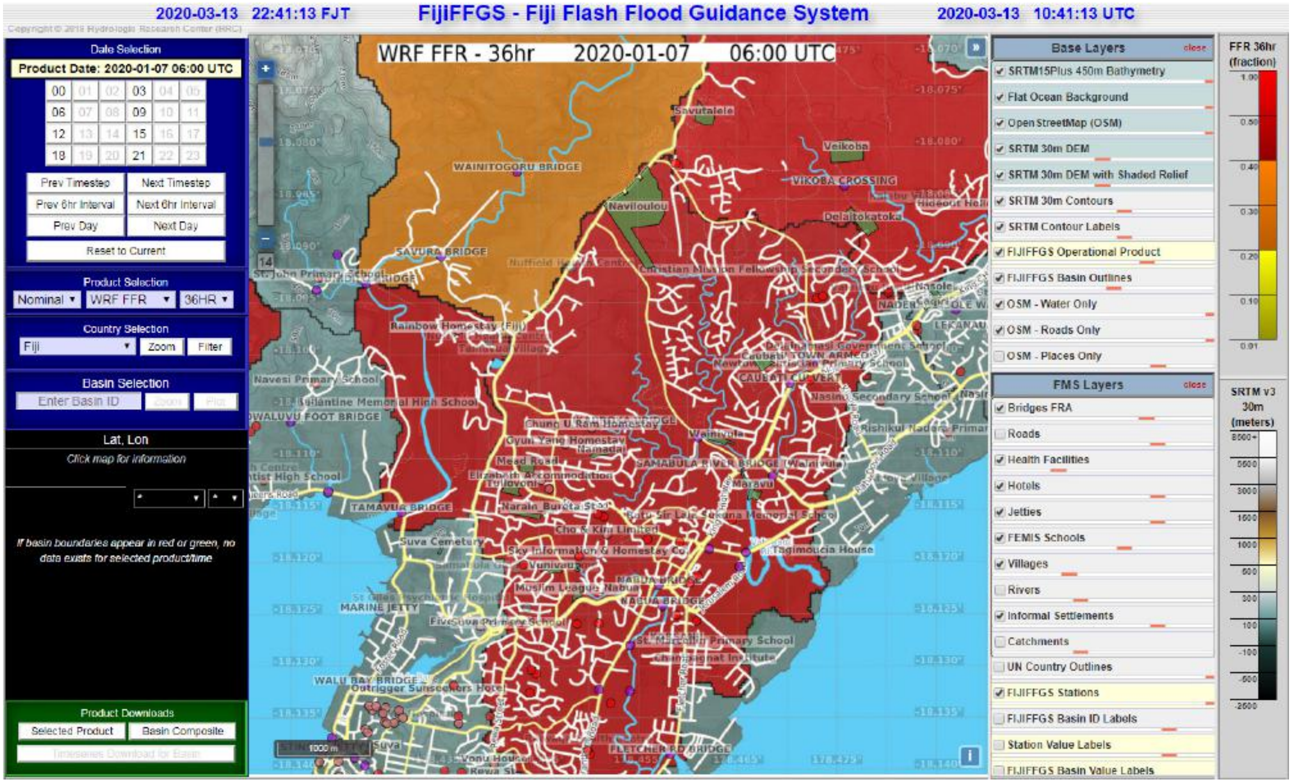
The Antalya Statement details the main findings of the workshop and outlines recommendations for implementing FFGS in the future. It highlights that further investments are needed in emerging science and technology in order to strengthen and sustain FFGS. Efforts also have to be directed towards: Improving governance; improving training and capabilities; increasing visibility of the role and benefits of FFGS; and mobilizing additional resources. To help ensure FFGS' sustainability, participants recommended that technical issues be better addressed. Among their recommendations were calls to adopt a more formal, inclusive, research-to-operations process and to make it easier to access and distribute digital data from automated rain gauges to the Flash Flood Guidance System.

The Antalya Statement

For the well-being and prosperity of their citizens, national governments should recognize that the Flash Flood Guidance System has achieved a state of maturity that merits their expenditure of resources to implement and maintain its operational readiness. A concerted global effort is needed to ensure that the advances made to date are strengthened for the benefit of current and future generations.

Integration into multi-hazard system

FFGS has used data from WMO Severe Weather Forecasting Project as an input to create flash flood risk and threat products wherever geographically alignment made it possible. Work is already underway



Fiji FFGS MapServer interface showing flash flood risk product including vulnerability of infrastructure.

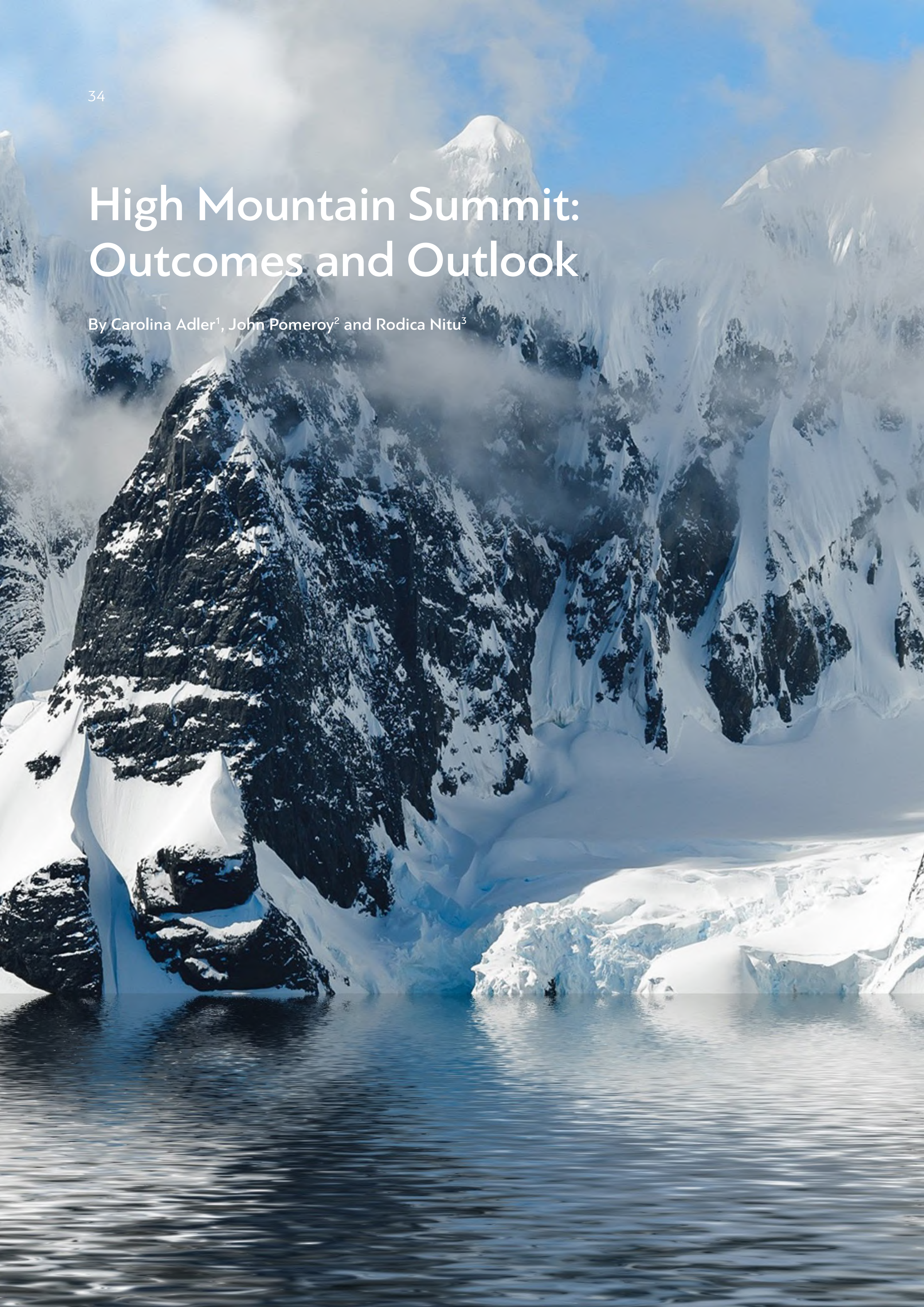
to improve FFGS' predictive capabilities by providing more accurate forecasts with longer lead times – both are critical for disaster risk reduction.

Based on these positive results, the 2019 World Meteorological Congress decided to integrate three projects – FFGS, Severe Weather Forecasting Project, and Coastal Inundation Forecasting Initiative – into the larger Multi-Hazard Early Warning System. Thereby, it will create a system that integrates coastal flooding, flash flooding, and severe weather prediction capabilities. In accordance with that decision, the Hydrological Coordination Panel recommended the preparation of a strategic outline to ensure a smooth integration of the three projects and the support of sub-projects by relevant experts.

The FFGS MapServer interface already provides meteorological and hydrological forecasters with the ability to overlay FFGS products with Geographic Information System (GIS) data, including: Demographic data, vulnerability maps, evacuation facilities, infrastructure, and educational and health facilities. By providing hydrometeorological and disaster management agencies with information about the vulnerabilities of infrastructure, NMHSs could help minimize the adverse impacts of weather-related disasters and reduce fatalities, damage and loss[5].

Scientists expect the frequency and severity of flash floods to increase due primarily to climate change, population growth and land-use changes. Development and implementation of FFGS is, therefore, more crucial than ever to protect communities, safeguard economies and save countless lives. Together, FFGS partners, participating countries and regions will continue to mitigate the impacts of flash floods by enhancing early warning capabilities.

5 WWMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services, WMO-No.1150



High Mountain Summit: Outcomes and Outlook

By Carolina Adler[1], John Pomeroy[2] and Rodica Nitu[3]

The WMO High Mountain Summit on 29-31 October 2019 concluded with a Call to Action and a roadmap of priority activities. The priority actions aim to support more sustainable development, disaster risk reduction and climate change adaptation both in high-mountain areas and downstream.

Mountain regions cover about a quarter of the Earth's land surface. They are important sources of freshwater, centres of biological and cultural diversity as well as traditional knowledge, being home to a quarter of the world's population. High-mountain areas include all mountain regions where glaciers, snow or permafrost are prominent features of the landscape (IPCC[4]). River basins with headwaters in the mountains supply freshwater to over half of humanity, thus mountains are often referred to as "the water towers" of the world.

However, rising global temperatures are causing changes to mountain meteorology, hydrology, and ecology, including the cryosphere – snow, glaciers, frozen ground. Natural hazards, environmental alterations and the loss of critical mountain ecosystems are increasing the risk of local and downstream disasters. Large mountain regions play a key role in the evolution of large-scale weather systems. The anticipated increase in uncertainty in water availability from mountain rivers is a significant risk factor for local and downstream agriculture, forestry, food production, fisheries, hydropower production, transportation, tourism, recreation, infrastructure, domestic water supply and human health.

The WMO Summit highlighted that – in spite of the above facts – Earth system processes over complex mountain terrain are insufficiently observed and understood to confidently model their behaviour. Consequently, the resulting impacts of those changes on people and economies have not been well-articulated in major international policy frameworks such as the Sendai Framework for Disaster Risk Reduction or the Paris Agreement on Climate Change. As water security is becoming one of the greatest challenges for humanity, and a source of political tension within and between nations, the absence of such references makes the task of developing and implementing relevant policies much more difficult.

Call for more scientific understanding

The available scientific evidence is very heterogeneous across and within mountain regions. Often, new observations, learning, thinking and experiences are acquired by international research initiatives with limited or no engagement with local scientific or operational communities.

The scientific understanding of social-ecological systems in high mountains needs to be substantially strengthened. In addition, amplified knowledge is needed of the ecosystem services and goods provided by the cryosphere and other critical systems in mountain regions, and their human uses.

Participants at the Summit repeatedly cited the findings of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, which includes a dedicated chapter on high mountain areas. The IPCC report notes that current trends in cryosphere-related changes in high-mountain ecosystems are expected to continue, and their impacts to intensify. Snow cover, glaciers and permafrost are projected to continue to decline in almost all regions throughout the 21st century. The findings of this report convey a sense of urgency in addressing the hydro-climatic changes in high mountains, their impacts and their downstream effects.

High Mountain Summit Call to Action

Following engaging presentations and inter- and trans-disciplinary dialogues, the Summit participants committed to opening access to and use of 'fit-for-purpose' hydrological, meteorological and climate information services for people living in and downstream of mountains. This would help address their need to adapt to and manage the threats caused by unprecedented anthropogenic climate change,

1 Mountain Research Initiative (MRI)

2 Global Water Futures programme, Global Institute for Water Security & Centre for Hydrology, University of Saskatchewan, Canada

3 WMO Secretariat

4 www.ipcc.ch/srocc/

recognizing the importance of mountain regions as home of the cryosphere and source of global freshwater.

An Integrated High-mountain Observation, Prediction and Services Initiative was deemed essential to achieve this objective. The Initiative would have user-centred goals, build on existing knowledge and activities, international coordination and multidisciplinary approaches. It would include a series of collective, intensive campaigns of analysis and forecasting demonstration projects in key mountain ranges and headwaters around the world, including those with transboundary foci. The Initiative would make it possible to co-design solutions, build capacity, support and facilitate investments by actively engaging information users, providers and producers to address the most pressing issues of climate, cryospheric and hydrological change. Its results would support the management of water resources and adaptation to the risk of natural hazards downstream of large rivers – thus affecting large segments of the Earth's human population and ecosystems. It would foster exchanges and interactions between populations, users, science and services, and provide relevant input to policymakers.

Summit co-chairs – Ms Carolina Adler, Executive Director, Mountain Research Initiative, and Mr John Pomeroy, Canada Research Chair in Water Resources and Climate Change, Director, Centre for Hydrology, Global Water Futures Initiative – presented these outcomes at the 2019 United Nations Framework Conference on Climate Change (COP25) in Madrid, in a side events organized on 11 December, the UN International Mountain Day, at. The United Nations General Assembly Resolution A/74/209 on Sustainable Mountain Development, approved on 19 December, recommends that Member States "Develop and implement measures to strengthen the adaptive capacity and climate resilience of mountain communities and to reduce exposure to climate risks through increased generation and use of climate and disaster risk information, development of hazard risk maps and platforms, improvement of early warning systems and application of the risk-based approach in all development planning;" as a mean to build resilience to climate change and disasters and protecting biodiversity.

The way ahead

Integrated mountain prediction systems are needed to comprehensively model scenarios and predict mountain-specific climate, meteorology, hydrology, ecology, human system and cryospheric change in mountain regions, and for mountain-sourced river basins. Additional mountain observations are critical to integrated mountain prediction systems. These in turn will yield more reliable products and information on the changing risks due to climate change. Such information will underpin adaptation strategies to reduce the impacts of and exposure to natural hazards and related disasters.

The translation of the Call to Action into practice requires a consortium of national and international institutions and networks representing policy, practice, scientific research, academia and funding agencies. The Call requires a joint and collective response to support the proposed Integrated High-mountain Observation, Prediction and Services Project and to organize coordinated observation and prediction campaigns, potentially, within the scope of a Year of Mountain Prediction (YMP).

WMO plays an important role in addressing the need identified in the Sendai Framework to "Strengthen technical and scientific capacity to capitalize on and consolidate existing knowledge and to develop and apply methodologies and models to assess disaster risks, vulnerabilities and exposure to all hazards."

WMO Deputy Secretary-General Elena Manaenkova stated at the conclusion of the Summit, "WMO will provide leadership and guidance in the Integrated High Mountain Observation and Prediction Initiative. We need to improve observations, forecasts and data exchange in mountain ranges and headwaters around the world. This is needed to address accelerating climate change which has increasing impacts on vulnerable populations."

To do so, WMO appeals to national and international institutions and networks representing policy, practice, scientific research, academia and funding agencies, to join efforts and support the proposed Integrated High-mountain Observation, Prediction and Services Project. Additional resources are needed as well as coordinated observation and prediction campaigns. The 2007 International Polar Year, coordinated by WMO, was a testimony of the its ability to stimulate action in the international community towards the achievement of important scientific goals. The success of such campaigns depends on the strong commitment of leading organizations around the world, which are invited to join WMO in translating into practice the priority actions of the Call to Action.

Sponsors of the High Mountain Summit include the World Bank Global Facility for Disaster Reduction and Recovery and Central Asia Water and Energy Program, and Swiss government agencies (MeteoSwiss, the Federal Office of the Environment, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, and the Swiss Agency for Development and Cooperation). The over 150 participants represented academia, the scientific and operational communities, users of hydro-meteorological services, policy-makers, and representatives of the civil society, from 45 countries and several international organizations.

Donors and Partners

Third Pole climate warming and cryosphere system changes

By Tandong Yao[1], Yinsheng Zhang[1], Ninglian Wang[2], Lin Zhao[3], Tao Che[4], Guangjian Wu[1], Qiuhong Tang[5], Walter Immerzeel[6], Tobias Bolch[7], Francesca Pellicciotti[8], Xin Li[1], Wei Yang[1], Jing Gao[1], Weicai Wang[1] and Baiqing Xu[1]

Mountains are sources of water, energy, minerals, forest and agricultural products as well as popular recreational areas. High mountain regions are the largest reservoir of ice and snow after the Arctic and Antarctic. Asia's high mountain region hosts the world's 14 highest peaks and some 100 000 km2 of glaciers. This so-called Third Pole (TP) encompasses the Tibetan Plateau, the Himalayas, the Hindu Kush, the Pamirs and the Tien Shan Mountains. Melt-water from ice and snow in the Third Pole feeds many of Asia's large lakes and rivers, including the Indus, Brahmaputra, Ganges, Yellow and Yangtze. Known as the Asian Water Towers (AWT), this mountain region is critical for the water security and socio-economic sustainability of many nations. It supports a population of 1.7 billion and gross domestic product (GDP) of US$ 12.7 trillion (Figure 1).

The Third Pole has experienced significant environmental changes over the last five decades. The conditions and stability of the Asian Water Towers are impacted by warming-induced glacier retreat, ice collapse, glacial lake expansion and frequent Glacier Lake Outburst Floods (GLOFs) with repercussions on the socio-economic progress of countries in the region. The rapid changes in Third Pole glaciers, permafrost, snow cover, lakes, rivers and their downstream effects have been studied since 2010 under the Third Pole Environment (TPE) programme with funds from the Chinese Academy of Science. This key international research initiative addresses the multi-sphere interaction of the Earth system across the Third Pole. Mountain cryosphere changes and their impacts on regional hydrology and water resources are important research aspects of the TPE programme.

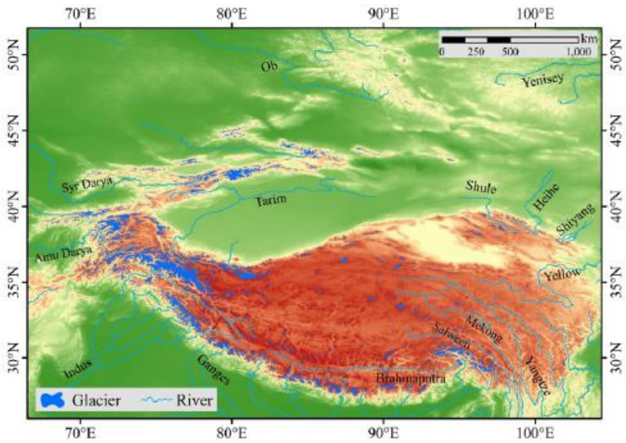


Figure 1. Glaciers distribution over the TP and its surrounding areas.

Ten years into the study, it is useful to synthesizes the research results and to discuss water availability and the social-economic implications over the broader mountain regions. This report, the 1st part of synthesis, focuses on climate warming and changes in the Third Pole cryosphere system, that is to say changes in snowcover, glacier and permafrost conditions. The 2nd part (to be published in the next issue of the Bulletin) will cover hydrologic response to the Third Pole cryosphere changes, water security and social-economic sustainability.

1 Institute of Tibetan Plateau Research, Chinese Academy of Sciences
2 Northwest University
3 Nanjing University of Information Science & Technology
4 Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences
5 Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences
6 University of Utrecht
7 University of St Andrews
8 Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Climate warming over the Third Pole

The Third Pole is one of the most sensitive areas to climate change. It has been considered as the place to observe for early warning signals of global warming (Yao et al., 2019; You et al., 2019). The region has warmed by about 1.8 °C over the past half century (Figure 2), significantly higher than the warming rates for the Northern Hemisphere and the globe mean (Kang et al., 2010; Liu and Chen, 2000; Yang et al., 2014). Annual and seasonal temperatures increased more at higher elevation zones across the Third Pole (Figure 3; Gao et al., 2018; Liu and Chen, 2000; Liu et al., 2009; Yao et al., 2019). This elevation dependent warming is especially pronounced during the winter and fall seasons (Yao et al., 2019) in areas below the 5 000 metres above sea level (m asl) mark.

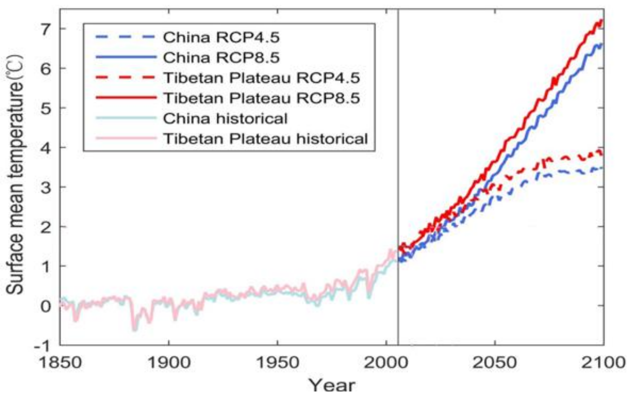


Figure 2. Regionally mean surface temperature for China and Tibetan Plateau in the period from 1850 to 2100 from the multi-model ensemble means of 21 Coupled Model Intercomparison Project (CMIP) 5 under the IPCC's Representative Concentration Pathway (RCP) 8.5 and 4.5. The vertical brown line marks the boundary between the historical and the RCP CMIP5 simulations (You et al., 2019)

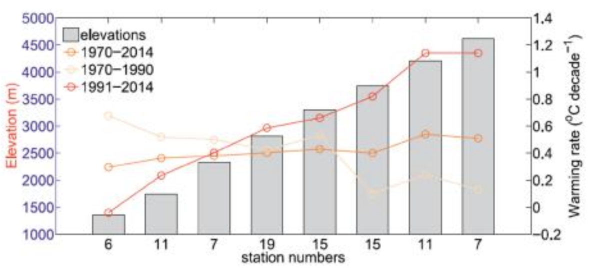


Figure 3. The elevation dependence warming of winter mean air temperature over Tibetan Plateau in the period from 1970 to 2014 (Yao et al. 2019).

The Third Pole climate is characterized by a wet and humid summer and a cool and dry winter. Approximately 60% to 90% of annual precipitation falls between June and September. Since 1960, annual precipitation, with significantly high inter-annual variability, slightly increased in most parts of the Third Pole, except the southern and southeastern regions (Gao et al., 2015) (Figure 4a,b). Because of inaccessibility and the complex terrain, precipitation in most parts of the northwestern Third Pole remains largely unknown due to lack of observations (See Figure 4b). Similar to the elevation dependent warming, there is a significant increasing trend in summer precipitation with elevation over the Third Pole (Figure 4c), that is by 0.83% $decade^{-1}$ km^{-1} during 1970 to 2014, and 2.23% $decade^{-1}$ km^{-1} for 1991–2014 (Li et al., 2017). Third Pole precipitation is projected to increase in the 21st century particularly over the north and west regions.

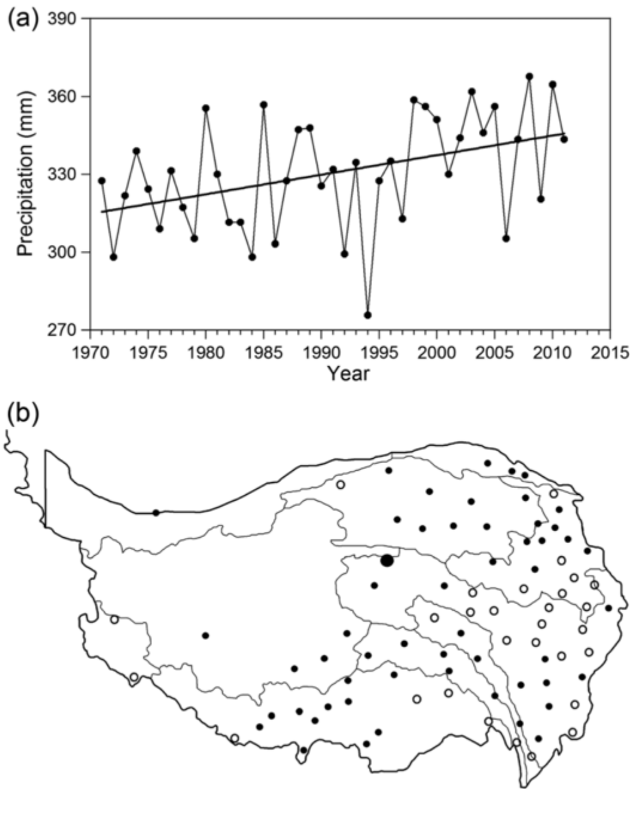


Figure 4 (a) Variations of annual mean precipitation averaged over the Third Pole from 1971–2011 (Gao et al., 2014) (b) Spatial pattern of the trends in annual precipitation on the Tibetan Plateau from 1979–2011. The filled symbols indicate increasing trend, while the hollow symbols indicate decreasing trend. Larger symbols represent significant trends (Gao et al., 2015).

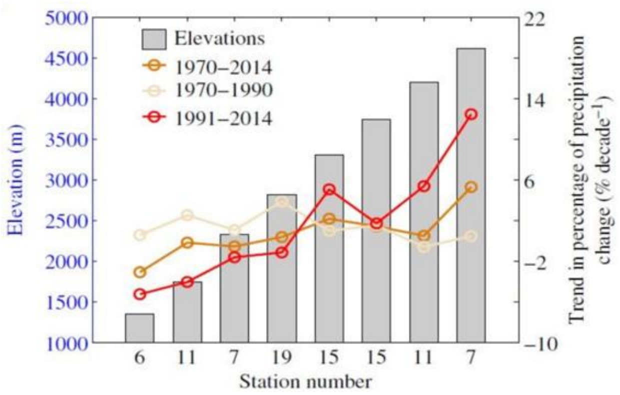


Figure 4 (c) The elevation dependence of trends (% decade–1) in summer precipitation for three time periods (1970–1990, 1991–2014, and 1970–2014) over Tibetan Plateau.

Snow cover characteristics and changes

Climate warming directly affects the Third Pole's cryosphere system, leading to significant glacial retreat, snow cover changes, and permafrost degradation (Yao et al., 2019). Remote sensing data reveal changes in snow cover conditions from 1980 to 2018. The average, maximum and minimum snow extent in the accumulation period (November to March) were large in 1980s and 1990s, but have consistently decreased since 2000 (Che et al., 2008). Maximum snow extent was approximately 2.5 × 106 km2 in the winter of 1994/1995. Most of the Tibetan plateau experienced less snow cover days from 1980–2016, with an average decrease of less than 2 days/year over almost half of the region, and more than 4 days/year in some areas. The decrease in snow duration is also evident in the Tibetan plateau since 1980s. Similarly, snow depth decreased from 1980 to 2018, with large inter-annual fluctuation before 2000 and less variation after 2000 (Che et al., 2019). Spatial inconsistencies exist in snow depth change across the Tibetan plateau, with a clear decrease by 0.1-0.2 cm/a in the Nyenchen Tanglha Mountains, and a slight increase (less than 0.1cm/a) in the Qilian mountain, the HohXil Mountain and the North slope of the Himalayas (Figure 5).

Snowmelt processes vary over space and time across the Third Pole. Although spring snowmelt is not the dominant contributor to river flow, it comes at the end of spring, the critical period for irrigation and plant growth. Therefore, snowmelt is an important water supply to soil moisture and river runoff in Third Pole. Climate change significantly affects hydrological processes across the Tibetan Plateau. In recent years, an increase in runoff and an earlier peak of snowmelt runoff were found in several studies (Immerzeel et al. 2010; Wang and Li 2006). Model results suggest regional differences in snowmelt process and runoff in response to climate warming in the Himalayas (Rees and Collins 2006). For example, increase of spring snowfall in the eastern part of Himalayas would reduce the increase in snowmelt runoff, and push back the timing of peak flows.

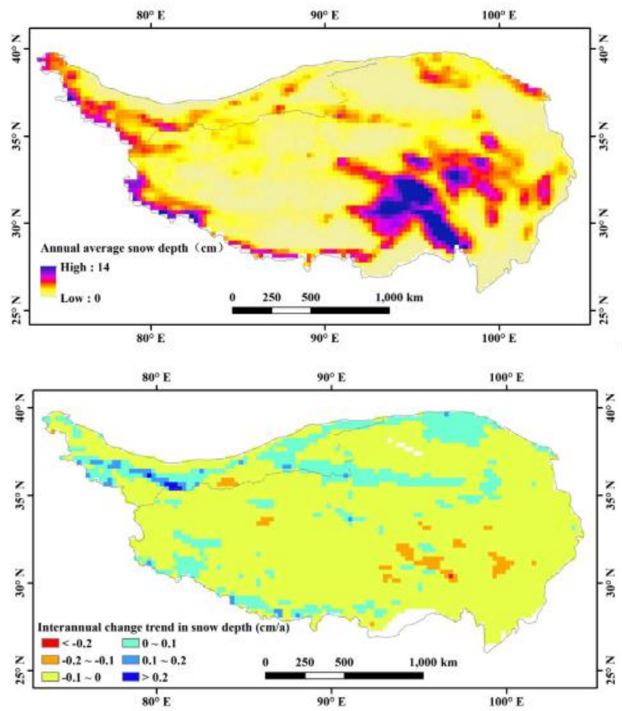


Figure 5. Snow depth distribution and change during 1980-2018 over the TP.

Permafrost condition and change

Permafrost is ground – soil or rock, including ice or organic material – that remains at or below 0 °C for at least two consecutive years (Harris et al. 1988). Permafrost covers approximately 40% of the Third Pole surface area, around 1.06 × 106 km2 (Zou et al. 2017). Permafrost exists at the source of many major river basins, its coverage in the watersheds vary from less than 10% to more than 60% in Qilian Mountains and in between Kunlun and Tangula Mountains. During the period of permafrost formation and repeated

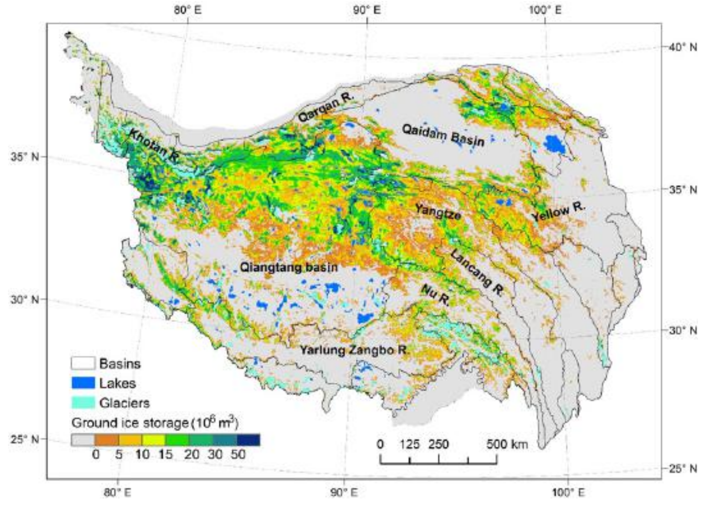


Figure 6: Distribution of permafrost and ground ice on the Third Pole.

ice segregation, a large amount of water is reserved underground and stored in the solid state as ground ice buried near the permafrost table. The ground ice reserve near the permafrost table on the Qinghai-Tibet Plateau is about 1.27 × 1013 m3 (Zhao et al. 2019) (Figure 6).

Global warming due to climate change has widely degraded permafrost across the Third Pole. In situ monitoring shows significant increases in active layer depth and ground temperature. Borehole observations along Qinghai-Tibet Highway from 2004 to 2018 show warming by 0.48 °C/decade, on average, at the bottom of the active layer, and by 0.02~0.31 °C/decade at depth of 10 metres (Cheng et al. 2019) (Figure 7). Modeled results also indicate a thickening trend in the active layer depth by 19.5 cm/decade (Hu et al. 2019). The change in the active layer displays spatial heterogeneity; it is more prominent in the cold permafrost regions, high elevation, high-alpine meadows and regions with fine-grained soils.

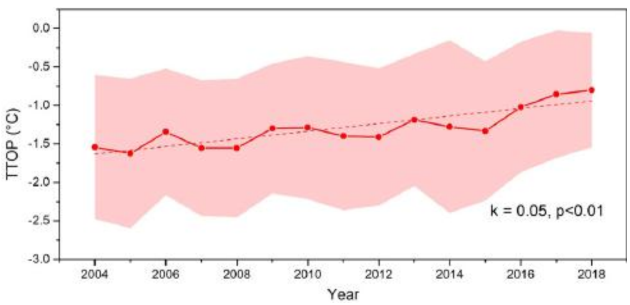


Figure 7: Soil temperature at the bottom of active layer during 2004-2018.

Permafrost degradation can lead to changes in hydrological processes, including alteration of water storage in surface reservoirs (e.g., lakes, wetlands), hydrological connectivity and surface water-groundwater interaction (Connon et al. 2014). In permafrost terrain, the interaction between groundwater and surface water is restricted because permafrost acts as an impermeable layer. With permafrost degradation, groundwater storage and recharge are expected to increase (Niu et al. 2011, Bense et al. 2012). Permafrost degradation has been identified as a potential associated cause for winter streamflow increase in the upper Heihe basin (Gao et al. 2018) and Lhasa River (Gong et al. 2006).

The thickening of the active layer affects production, convergence and ecological processes in permafrost regions; ground ice melt leads to additional water release and participation in the water cycle. In permafrost regions, during the thawing season, soil water content increased in the soil profile (Zhao et al. 2000). In response to the thickening of the active layer and ground ice melt, water content at the bottom of the active layer increased overall between 11%–32% from 2004 to 2018, while the surface soil moisture decreased or remain constant (Wu et al. 2017; Zhao et al. 2019).

Isotope studies reveal that the contributions of thawing permafrost to thermokarst lakes could reach 61.3% in the Beiluhe region (Yang et al. 2016). The contributions of meltwater from ground ice to runoff reaches 37.4% in the typical alpine river in

Kunlun Mountains Pass (Yang et al. 2016) and 13.2% to 16.7% in the source region of Yellow River (Yang et al. 2019). The amount of ground ice melt and its effect to regional water cycle is difficult to quantify, since the response of permafrost to climate warming is relatively slow. Consequently, the impact of permafrost degradation on the hydrological process is also gradual. The specific processes of permafrost changes/variations in warmer, wetter climate and their effects on the hydrological conditions in the Third Pole need further research.

Glacier change and mass loss

Glacier changes and their impact on water resources and sea level rise have attracted attention around the world [Immerzeel et al., 2019; Zemp et al., 2019]. In the middle latitudes, the Third Pole is the region with the most concentrated distribution of glaciers (Figure 1). According to the new version of the world glacier inventory Randolph v.6.0 [RGI, 2017], there were 97 760 glaciers with an area of 98 739.7 km2 in the Tibetan Plateau and its surrounding areas, including Hindu Kush, Pamir, Tien Shan and Altai. The ice volume of these glaciers was estimated to be about 7 481 km3 [Zemp et al., 2019]. It is important for downstream water resources management and sustainable socio-economic development to understand the glacier changes and their influences on river runoff.

Glacier changes is mostly reflected by changes in equilibrium line altitude (ELA), area and mass balance. The changes in glacier mass balance and area are directly controlled by the changes in ELA. In the Tibetan Plateau and its surrounding areas, there are only a few monitored glaciers. Over the past 50 years, all those glaciers displayed a general retreat trend, and their ELAs showed an increasing trend. For example, the ELAs of Glacier No.1 at the source of the Urumuqi River in Tien Shan, the Maliy Aktru glacier in the Altai Mountains and the Qiyi Glacier in Qilian Mountains have risen by about 110 m, 140 m and 250 m respectively since 1960s (Wang et al., 2010; Ye et al., 2016). Remote sensing data provide an important basis for the study of glacier changes and glacier inventory over the large spatial scale. Wang et al (2019) assessment of glacier area changes in the Tibetan Plateau and its surrounding areas via the synthesis of many studies results indicated a clear spatial pattern of glacier area changes over the past 40 years. That is glacier shrinkage of less than 0.2%/year in west Kunlun Mountains, Pamir and Karakoram – only 0.04%/year in central Karakoram – of 0.4%/year in east Altai, Tien Shan, Qilian, east Kunlun, Tanggula, Gangdis, southeast Tibet and Himalayas and greater than 0.7%/year in southeast Tibet. Wang et al. (2019) also summarized the results of studies on the changes of glacier mass balance obtained by geodetic and glaciological methods, and reported that the glacier specific mass balance over the past 50 years was close to zero and/or slightly larger or lower than zero in Karakoram, west Kunlun and Pamir, but was a significantly negative value in the other regions (Figure 8). On the other hand, glaciers were in a state of mass gain or less mass loss in Karakoram, west Kunlun and Pamir after 2000. Although other glaciers experienced accelerated mass loss in the other regions after 2000. This seems to imply that the "Karakoram anomaly" might partially extend to nearby west Kunlun and Pamir (Farinotti et al., 2020), and that water supply from the glaciers in the region of "Karakoram anomaly" to the downstream should be relatively stable.

The glaciers in the Third Pole are mostly concentrated in the Trim, Indus and Amu Darya basins (see Figure 1, about 60% of the total glacier area in these three basins). The large glaciers in these basins can lead to abundant glacier meltwater resources. For example, more than 40% of total runoff of Trim River comes from glacier meltwater. Even though the area of glaciers in the Trim Basin has shrunk, glacier meltwater runoff increased over the period of 1961–2006 (Gao et al., 2010). However, as glaciers recede further, the key question is when will annual glacier runoff reaches a maximum? This point is often referred to as "peak water," and beyond it runoff decreases as the reduced glacier cannot supply rising meltwater anymore. A recent study estimated that peak water in the most large rivers basins in the Third Pole will be reached from 2030 to 2050, depending on the different greenhouse gas emission scenarios (Huss and Hock, 2018). This timing is critical for to current and future water resources management in the lower reaches.

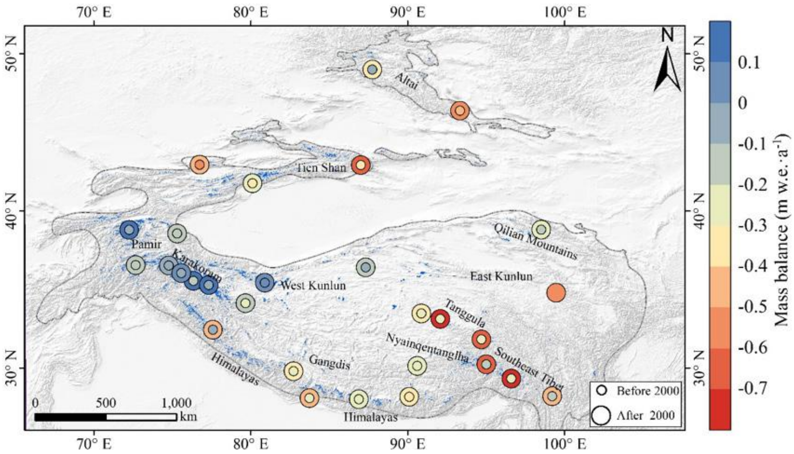


Figure 8. Spatial and temporal changes of glacier mass balance in the TP and its surrounding areas. Data used from [Bolch et al., 2017; Cao et al., 2014; Chen et al., 2017; Gardelle et al., 2013; Gardner et al., 2013; Kääb et al., 2012; Ke et al., 2015; Maurer et al., 2019; Neckel et al., 2014; Pieczonka et al., 2013; Scherler et al., 2011; Shangguan et al., 2010; Wang et al., 2008; Wang et al., 2013; Wei et al., 2015a; Wei et al., 2015b; WGMS, 2017; Wu et al., 2018; Xu et al., 2013; Zhang et al., 2016; Zhou et al., 2018; 2019].

Glacial hazard and disaster

Rapid glacier changes in the Third Pole may lead to disasters related to natural hazards such as glacier collapse, glacier surging, glacial debris flow, and glacial lake outburst flood (GLOF). These glacial events have their spatio-temporal distribution characteristics, dynamic processes and mechanisms. Glacier surging actively occurs in Karakorum, Himalayas and southeast Third Pole. The velocity of ice surface movement can reach hundreds of metres every year. There were 27 advancing glaciers in Third Pole in the period from 1978 to 2015 with significant increases in area and length. The speed of change for the western side of the Wood Stark glacier was 904 m/a from 1996 to 1998, 446 m/a for the eastern side of the K2 glacier from 2007 to 2009, and 238 m/a from 1978 to 1990 for the 5Y654D497 glacier (Xu et al., 2016). Surging glaciers can quickly move into glacial lakes and cause outburst floods. Glacier debris flow can be triggered by strong and quick glacier melt, GLOF, and glacier collapse or avalanche. High temperature and heavy precipitation are the two major meteorological factors that directly connect to the occurrence of glacier debris flow.

New types of glacier-related disasters are occurring the Third Pole. On 17 July and 21 September 2016, two massive ice collapses occurred in Aru Range, Ngari, west Third Pole (Kääb et al. 2017). The Aru glacier collapses caused nine human casualties – shepherds – and the lose of hundreds of livestock (Figure 9). On 17 and 29 October 2018, glacier collapse caused debris flow and blocked the Yarlung Zambo River at Sedongpu valley, southeast Third Pole. The fact that both the continental (Aru) and maritime (Sedongpu) type glaciers have experienced collapses seems to suggest that glaciers on the Tibetan Plateau might be in an unstable state.

Important implications

Over half of the world's population lives in watersheds of major rivers with mountains sources – from glaciers and snow melt (Kaltenborn et al., 2010). Third Pole cryosphere changes affect regional hydrology, ecosystem and humans living in the entire watersheds. For instance, due to the decreased contribution of glacier runoff, streamflows will be more sensitive to precipitation fluctuations, leading to more stochastic hydrological processes. In the long-run, glacial meltwater in the streamflow would decrease if mountain glaciers continue to lose mass or disappear.

In the greater Himalayan region, up to 45% of the total river flow comes from seasonally snow and ice meltwater (World Resources Institute, 2003; Kehrwal et al., 2008). The downstream areas of the High Himalaya have escalating demands for water due to rapid population and economic growth. Changes in glacial runoff – decrease is likely decrease in the future – would reduce irrigation water availability, diminish agricultural productivity and threaten food security in the region. Due to shortages in water supply, food

Figure 9. Rescue for potential survivors of the Aru glacier collapse, July 2016 (photo by Xinhua Net)

security for 4.5% of the population in the Brahmaputra, Indus, Yangtze, and Ganges basins will be threatened by reduced glacial runoff (Immerzeel et al., 2010).

It is clear that Third Pole cryosphere changes will have very broad implications. There is an urgent need to:

- monitor Third Pole cryosphere changes and understand their impacts to water resources

- develop adaption strategy, not just at the regional or national level, but at the basin scale involving all riparian countries, especially in the Third Pole region, in order to take account of and balance the demand for water from all the parties in the large watersheds.

References are available in the online version.

Glacier Lake 513, Peru: Lessons for early warning service development

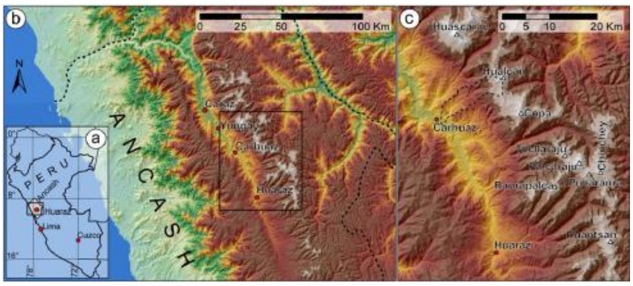
By Christian Huggel[1], Alejo Cochachin[2], Fabian Drenkhan[1,3,4], Javier Fluixá-Sanmartín[5], Holger Frey[1], Javier García Hernández[5], Christine Jurt[6], Randy Muñoz[1], Karen Price[7], Luis Vicuña[1]

Glacier shrinkage – accelerated over the last decades due to climate change – is exposing large areas in mountain regions worldwide. But an even dire consequence of the melting ice is the forming of more glacier lakes, which are increasing in size. Glacial lakes have caused some of the world's most devastating floods, for example, in the Andes, Himalayas and Alps, where thousands of human lives were lost and huge infrastructure damages reported (Carrivick and Tweed, 2013; Bajracharya et al., 2007; Carey 2005). Climate change is rapidly reshaping living conditions in high mountains – altering flood patterns and creating new flood hazards – leaving populations at imminent risk in several regions (Cook et al., 2016; Emmer et al., 2015; Frey et al., 2016; Drenkhan e al., 2019).

Climatic, glaciological and hydrological information and services can play an essential role for early detection of potential hazards and risks, and for effectively reducing risks. However, infrastructure for climate and associated services are poorly developed in many high mountain areas and need to be substantially strengthened. This report on the design, implementation, operation and circumstances around the setting up of an early warning system for glacier lake outburst floods (GLOFs) in the Peruvian Andes highlights the challenges related to accessing and installing equipment in many high mountains regions.

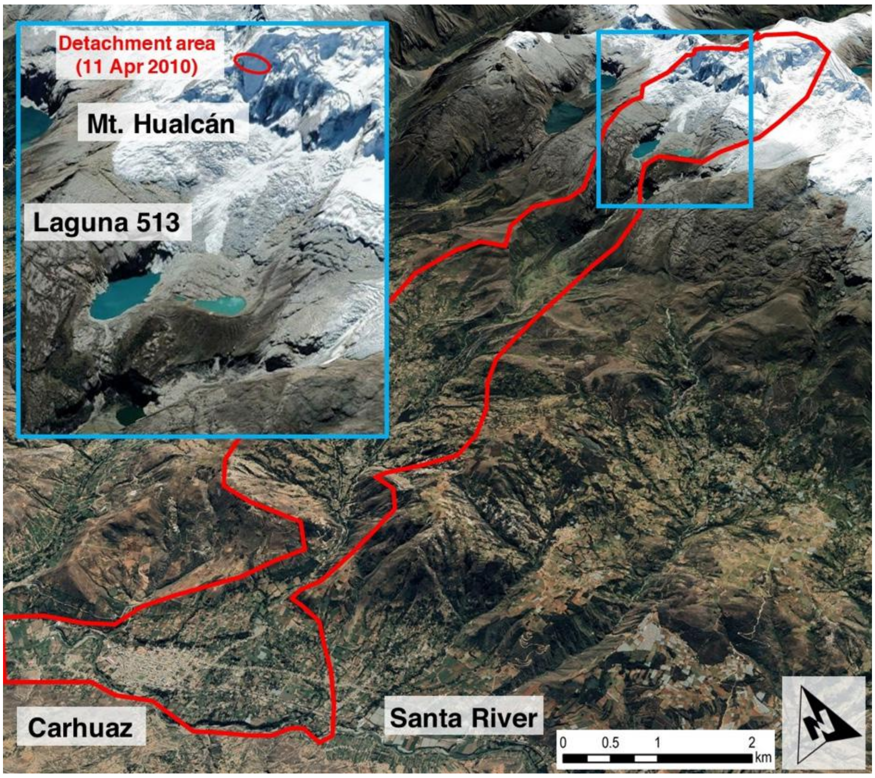
Laguna 513 disaster

The Cordillera Blanca in the tropical Andes of Peru is a glaciated mountain range with a long history of disastrous GLOF events (Carey 2005; 2010). GLOF risks result from considerable physical hazard levels and the high levels of vulnerability and exposure of downstream populations (Frey et al., 2018). The Laguna 513 glacier lake (9°12′45′′S, 77°33′00′′W) is located at 4 428 metres (m) above sea level at the foot of Mount Hualcán (6 104 m) in the Santa River basin (Figs. 1, 2). The lake, which formed in the late 1960s as a result of glacier shrinkage, was declared highly dangerous in 1988 and subjected to exhaustive security works to artificially lower its level by some 20 m until 1994. This did not reduce GLOFs risk to zero, though the probability of occurrence and magnitude of GLOFs was substantially lowered. In 2004, authorities and specialists produced a report indicating that the lake could be considered safe due to the infrastructure in place (INDECI 2004; Muñoz et al. 2016).



Site location: a) Peru, b) Cordillera Blanca and c) the Hualcán-Carhuaz area (in dashed line).

1 Department of Geography, University of Zurich, Zurich, Switzerland
2 Area de Evaluación de Glaciares y Lagunas, Autoridad Nacional del Agua (ANA), Huaraz, Peru
3 Pontificia Universidad Católica del Perú, Lima, Peru
4 Department of Civil and Environmental Engineering, Imperial College London, London UK
5 Centre de Recherche sur l'Environnement Alpin (CREALP), Sion, Switzerland
6 Bern University of Applied Sciences, School of Agriculture, Forest and Food Sciences (HAFL), Bern, Switzerland
7 CARE Perú, Lima, Peru



Overview map of Lake 513 and Carhuaz, indicating the 2010 ice avalanche source zone producing the GLOF that reached down to Carhuaz.

However, Laguna 513 was heavily impacted when a 450 000 cubic metres (m3) rock-ice avalanche detached from the southwest slope of Mt. Hualcán (Carey et al., 2012) (Fig. 2) on 11 April 2010, at about 8 a.m. local time. The avalanche caused a tsunami-like push-wave on the lake, resulting in a dam spillover despite the over 20 m freeboard. Traces of the wave indicate an overtopping of the dam by about 5 m – corresponding to a wave height of about 24 to 25 m – with a peak discharge of rate of several tens of thousands m3 per second (Schneider et al., 2014). The resulting GLOF damaged several bridges, water service infrastructure along its trajectory and eventually reached the debris fan of the city of Carhuaz (about 20 000 inhabitants), where the coarse material of the GLOF was deposited. A total of 0.7 km2 of agricultural land was buried and the Santa Valley highway was affected, but no lives were lost.

Local and national authorities, as well as Peruvian and international experts, met in the weeks following the disaster to discuss ways to better protect people and their assets in future incidents. As a result, plans for a GLOF Early Warning System (EWS) were initiated in 2011 and implemented within three years. The GLOF EWS, the first in the Andean region, was established in the framework of the Glacier Project (www.proyectoglaciares.pe) with financial support from the Swiss Agency for Development and Cooperation (SDC). CARE Peru and the University of Zurich jointly implemented the EWS in close collaboration with the municipality of Carhuaz and the National Water Authority of Peru (ANA) and its Office for Glacier and Lake Evaluations (former Glaciology and Water Resources Unit - UGRH) in Huaraz.

Development and implementation of a GLOF Early Warning System

The design, organization and operation of the GLOF was structured to adhere to internationally recognized EWS components (cf. Fluixá-Sanmartín et al., 2018):

1. risk knowledge

2. monitoring and warning

3. dissemination and communication

4. response capability.

Risk knowledge

Understanding the risks encountered at a particular location is fundamental for the design of an EWS. Risks can be assessed using established methods that analyze physical hazards by means of critical indicators and thresholds (in this case related to the different components involved in the GLOF process), exposure of people and assets (e.g. infrastructure) and the vulnerability (e.g. social, economic) of the elements at risk. Comprehensive risk assessments for GLOFs are rare (Allen et al., 2016) and complex because GLOFs are typically the results of a cascade of triggering and propagating mass flow processes (Schneider et al., 2014; Westoby et al., 2014).

The 2010 GLOF served as a reference to analyze the physical hazards by simulating the process cascade with an iterative approach of coupled, physically-based numerical mass movement and hydrodynamic models (RAMMS and IBER). This model chain was then used to simulate three potential future scenarios of different magnitudes (small, medium, large) and corresponding probabilities of occurrence (high, medium, low, respectively). This hazard assessment procedure followed international standards and was in line with the recently established guidelines of the International Commission on Glacier and Permafrost Hazards in Mountains (www.gaphaz.org), a joint commission of the International Association of Cryopsheric Sciences (IACS) and the International Permafrost Association (IPA). The modelling, together with field surveys, resulted in a GLOF hazard map for local communities and city of Carhuaz (Schneider et al., 2014) (Fig. 3). Exposure and vulnerability were assessed using publicly available data sources (such as census data) and additional surveys in the catchments.

However, risks are perceived in very different ways by different actors. It is a challenge to understand and take these differences in perception into consideration but this is essential for wide user acceptance and the long term success of risk reduction measures. Repeated workshops were conducted in the different communities of the catchment to learn about the risk perceptions and priorities of local leaders and people. At a later stage, ethnographic studies, which included longer (several months) research visits with the local communities, were also conducted in the catchment. These were important to gain more in-depth understanding of how local people perceive their natural environment, and the relationships they maintain with mountains, glaciers and lakes that surround them. This led to a deeper understanding of how they perceived the diverse types of risks and how they understood the connections between those risks and those involved in the GLOF EWS project. Thereby cultural and political aspects were highlighted and people's concerns about water came to the fore, that is water availability, mostly in terms of access to water (e.g. water rights, allocation).

Monitoring and warning

Monitoring and warning are central elements of an EWS. Monitoring instruments and technical measuring must be set up to detect hazards so that timely warnings can be issued. The challenge is to identify the environmental processes and variables that are critical to the early detection of an extreme event (such as a GLOF) – and that are measurable by sensors. The insights and improved understanding of the processes gained from the reconstruction of the 2010 outburst and the modelling of potential future scenarios (risk knowledge element) served to identify where and what to measure and monitor. Knowledge about GLOF travel times – from triggering to reaching population centres – are, for instance, critical for the design of an EWS and for later visualization and planning with local authorities and communities (see "Dissemination and communication").

Reference projects for GLOF EWS were rare at the time of the design for Laguna 513 (2011/2012), and completely non-existent for the Latin American region. The "art" in such a design is in taking account of all possible flood trigger processes while measuring the point that still allows for timely warning. The different types of flood trigger processes – ice avalanches, moraine instabilities, rock slope failures – strongly depend on local conditions. It is critical to adequately understand the physical environment and interplay of processes that can result in different GLOF scenarios.

The harsh, extreme physical environment in which glacier lakes (as origin of GLOFs) form are often the biggest challenge. At high altitudes, such as that

Stations and receiving centre of the Lake 513 EWS: from left to right: station at Lake 513, at Pampa Shonquil and repeater, and the data receiving centre at the municipality of Carhuaz.

of Laguna 513, there are large daily temperature fluctuations, long periods of cloudiness, heavy precipitation and high solar radiation as well as a steep topography in what is a remote environment. All of these factors need to be considered in the design and implementation. The GLOF EWS adventurer/scientists had to make provisions for reduced energy, for complications with data transmission from the sensors and the limited access for sensor installation and frequent following-up and maintenance.

Another crucial element for monitoring and warning, in particular for an EWS in extreme environments such as in this case, is the redundancy in the system. Even in a well-calibrated and tested EWS, a sensor or data transmission failure is likely to occur at some point, sufficient redundancy is indispensable to avoid that sensor failure results in EWS failure as a whole.

An addition problem is funding the long term maintenance of the EWS. Small municipalities with limited budget have other priorities like investing in health and education services.

With the knowledge and information gathered, the local and international team worked together, each contributing their expertise, to design an EWS that would overcome the challenges of Laguna 513. The design comprised two stations – a main station at the Laguna 513 dam and a station in the Pampa Shonquil, which would include meteorological measuring instruments – a data centre in the municipality of Carhuaz, a warning station in the community of Pariacaca, and a repeater station for transferring the signal from the lake to the data centre (Fig. 3).

The stations were equipped with the following instruments:

1. Data centre Carhuaz (2 640 m a.s.l.): receiving antenna, screen with real-time data access, server for data storage, infrastructure for launching alarms.

2. Repeater station (3 189 m a.s.l.): receiving and sending antenna.

3. Station Laguna 513 (4 491 m a.s.l.): 2 cameras taking photos every 5 seconds during daylight times, one looking at the face of Mt. Hualcán, one observing the dam. 4 geophones located close to the station, continuously measuring and sending data in 5 second intervals, in order to detect potential mass movements (e.g. ice avalanche) impacting the lake. Receiving and sending antenna and data logger.

4. Station Pampa Shonquil (3 600 m a.s.l.): river discharge station (using pressure sensor), meteorological station with sensors for measuring

air temperature and humidity, precipitation, wind speed, and solar radiation. Sending antenna and data logger.

5. Information receiving and warning station at Pariacaca (3 138 m a.s.l.): the monitoring system informs locals about events at Laguna 513 and sirens activated from the Data Centre Carhuaz to facilitate evacuation.

All stations were equipped with solar panels and batteries for energy generation and storage, however energy availability remained a limiting factor, in particular at the glacier lake station as the peaks of the Cordillera Blanca experience a high frequency of cloud coverage. Each station had a mast where most of the instruments were fixed, a concrete lockable box for the electronic equipment, and a protective fence. Emergency power aggregates were available in the municipal building to prevent data losses and interrupted access during blackouts.

The geophones (devices recording ground movements and converting them into voltage) were the principle instruments used for registering a potential GLOF trigger. The back-up cameras could be used to get an overview of the current situation and, particularly during the test phase of the system, for relating geophone measurements to the magnitude of (avalanche) events. The pressure sensor in the riverbed at the Pampa Shonquil station added redundancy to the system and, if calibration measurements were taken, could be used to continuously record runoff. Later, it was planned to install wire sensors in the river channel bed below Laguna 513 that would detect unusually high and dangerous river flow discharge, which could be applied in debris flow warning systems.

A permanently manned hut with wardens next to the station at Pampa Shonquil was an important element of the EWS, especially for consideration of redundancy. Its main purpose was to control the freshwater intake for the municipality of Carhuaz but the location gave the wardens a perfect view towards Laguna 513, they could radio warnings to the authorities in case of an event (as was the case in the 2010 event).

For security, all data is first stored in the data logger at each respective station, then transmitted at 5-second intervals to the data centre server, which has a cloud back-up. All data are directly transferred to a website that permits real-time remote access. In the data centre itself – a separate office in the municipality of Carhuaz – a screen continuously displays the data from this webpage.

Warning protocols represent essential elements of an EWS. The protocol documents and defines warning procedures, typically differentiating a number of warning levels and associated actions as well as the responsible institutions, organizations or committees and people. Local, regional and national laws, rules and guidelines had to be taken into consideration in the Laguna 513 warning protocol. The members of the Local Emergency Operation Centre, civil defense, selected government officials and the mayor, whose authority it is to launch the evacuation alarm, had to be involved. Accordingly, the protocol was accompanied by a list of responsible persons and their phone numbers. It defined three warning levels – yellow, orange and red – plus a normal green baseline level and how these warning levels are reached and what type of actions need to be taken. To this purpose, thresholds of physical variables and processes had to be determined based on sensor measurements. Definition of these thresholds is critical and involves an extended period of calibration and testing, typically of many months, especially if no prior measurements are available as in the case of Laguna 513.

Dissemination and communication

If measurements on a geophone surpasses a defined threshold, a short message to immediately check EWS data and information is automatically sent to the mobile phones of all the responsible personnel identified in the warning protocol. The subsequent steps to be taken are based on the action plan and on the available data. Alarms cannot be automatically launched by the EWS because, under Peruvian law, only the mayor can authorize an evacuation.

Carhuaz's alarm module has two long-range acoustic sirens and the capacity to send predefined text messages to community and district leaders and stakeholders such as school principals, hospital chiefs, the police and firefighters. Communities upstream of

Carhuaz receive warnings and associated information through the Local Emergency Operation Centre and the central authorities of Carhuaz. Pariacaca, which is on the flood pathway, has a warning station with sirens. Furthermore, the EWS protocols were adapted to fit with the Peruvian protocols for risk assessment, allowing communication with the National Emergency Operations Centre at Lima to ask for help (Muñoz et al. 2016).

Response capability

The ability of people at risk to appropriately respond to the levels of warning issued is possibly the most critical element of an EWS – it is also the most susceptible to failure as the last element of the EWS chain. Failures or errors along the monitoring and warning chain have to be accommodated such that this last element is not adversely affected or threatened.

For the Laguna 513 EWS, information sessions were held with the population at risk. During these, the concept and functionality of the EWS, as well as its potentials and limitations, and clear instructions on actions that have to be taken in case of an alarm were explained and discussed. The instructions include the directive to immediately escape the endangered zones, and a clear indication of the evacuation routes and safety zones. A detailed map with all evacuation routes was prepared by the civil defense of Carhuaz on the basis of the hazard map developed in the risk knowledge phase of the EWS GLOF design. Emergency simulations are scheduled several times a year for the entire country as Peru's seismic risk is very high. Such simulations, some of them taking place at nighttime, have been used to expose both the population as well as the responsible authorities to a test evacuation und near-realistic conditions, and to familiarize them with the EWS of Laguna 513.

Operational aspects and lessons learned

In 2010, when discussions and activities related to the GLOF EWS started, Carhuaz was the main local actor and the centre for data and information reception. However, the technical, operational and social dimensions of the EWS were beyond the capacity of such a small city. Long-standing national and international expertise – necessitating regular presence on site and permanent joint capacity building and exchange with local people and authorities – was indispensable to address the challenges. In July 2015, full responsibility of the EWS was handed over to the local authorities in a ceremony attended by representatives from the local, provincial and national governments of Peru, from the Swiss government, and from local communities and schools as well as national and international experts. By that time, the EWS had made headlines in the Peruvian, Swiss and international media.

In 2016, much of the central tropical Andes, including the Cordillera Blanca region, was affected by a strong drought. In normal years, after a long dry Austral winter season, farmers count on the start of the rainfall season in October. In 2016, no rainfall was recorded in October and November.

After first requests to remove the EWS by some local inhabitants (cf. Fraser, 2017), farmers got desperate and rumors started to spread that the rain gauges and antennas of the EWS at Laguna 513 were responsible for the lack of rainfall. In a rather dramatic turn of events – driven by community-level power policy factors and weak communications from authorities on the extraordinary meteorological events – a large number of locals gathered at Laguna 513 on 24 November and decided to dismantle the EWS station at the lake. Reactions at the local, national and international levels were vigorous. There was animated disorderly mix of supporters of the EWS on social media. Others expressed incomprehension, disgust, shame and critiqued the voluntarily exposure of lives at risk by this destructive action.

The destruction of the station affected the monitoring and warning components of the EWS from a technical and operational point of view. But service could be maintained thanks to the wardens located at the intermediate site (Pampa Shonquil). Response capabilities and institutional mechanisms were not affected. However, it was crucial to understand the root causes of this action.

The results of intensive research into the incident, which centred on social sciences, are summarized below. The lessons learned are relevant for the development of climate and warning services beyond Peru.

- The dismantlement of meteorological and EWS stations by local people is not unique to this site, nor to Peru. Similar incidents have occurred in other regions, such as Himalayas, Andes and Alps of Europe, though those experiences were poorly documented.

- Local intra and inter-community conflicts, as well as distrust and biases against the participation of, and installations from, external institutions, can have a strong, but invisible, impact on acceptance.

- The relation of local (risk exposed) people to their natural environment and their perceptions of different risks strongly determines their attitude towards risk reduction efforts. Local perspectives may differ substantially from government or technical and scientific perspectives. For instance, local people can have intimate relations with mountains, glaciers and lakes as places of spirituality and the origin of life. Hence, a GLOF may be understood as a reaction of, for example, a glacier (as a mountain spirit) and a lake (as a being) to human disturbance or inappropriate human behavior. Traditional knowledge and narratives have to be recognized and acknowledged as part of a constructive dialogue and in finding acceptable solutions.

- As a consequence, the acquisition of a profound understanding of the social, political and cultural conditions, particularly in terms of power dynamics, is a prerequisite for early warning as well as more generally for climate adaptation service development. It is necessary for collaboration among diverse people, actors and experts, including local populations, physical and social scientists, engineers, local governments, technical governmental institutions, and non-governmental organization (NGOs). It is encouraged to give the social sciences a more prominent role.

- Authorities often believe that an EWS is primarily a technical measuring and data transmission system. The recognition that an EWS also consists of institutional, social, cultural and political components is fundamental because an EWS can only be operational if all components fulfill their function. Furthermore, it is critical that the local authorities and people understand that an EWS cannot reduce risks to zero – its main objective is to avoid harm to human lives. Therefore, it needs to be accompanied by other risk reduction measures, in particular appropriate land-use planning.

Conclusion

EWS in extreme environments, such as glacier lakes, bring many challenges. The system needs to be carefully designed to achieve robust energy provision, smooth and reliable data transmission, measurement of critical physical variables and the required degree of redundancy. Many months of system calibration are indispensable. Local authorities must clearly understand this. In addition, maintenance of the EWS needs to be budgeted annually by the local authorities to guarantee the sustainability of the system.

The Laguna 513 EWS has become the model for several other EWS in the Peruvian Andes (e.g. Huaraz-Palcacocha, Urubamba-Chicón) and beyond. While the experience and capacity development can be replicated, it is also crucial to acknowledge that every location is an individual case with special characteristics that need appropriate attention.

References

Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P., Kumari, A., 2016. Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. Nat Hazards 84, 1741–1763. https://doi.org/10.1007/s11069-016-2511-x

Bajracharya, B., Shrestha, A.B., Rajbhandari, L., 2007. Glacial Lake Outburst Floods in the Sagarmatha Region. Mt. Res. Dev. 27, 336–344. https://doi.org/10.1659/mrd.0783

Carey, M., 2010. In the Shadow of Melting Glaciers: Climate Change and Andean Society. Oxford University Press, Oxford.

Carey, M., 2005. Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. Glob. Planet. Change 47, 122–134. https://doi.org/10.1016/j.gloplacha.2004.10.007

Carrivick, J.L., Tweed, F.S., 2013. Proglacial Lakes: Character, behaviour and geological importance. Quat. Sci. Rev. 78, 34–52. https://doi.org/10.1016/j.quascirev.2013.07.02

Cook, S.J., Kougkoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosph. 10, 2399–2413. https://doi.org/10.5194/tc-2016-140

Drenkhan, F., Huggel, C., Guardamino, L., Haeberli, W., 2019. Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. Sci. Total Environ. 665, 465–483. https://doi.org/10.1016/j.scitotenv.2019.02.070

Emmer, A., Merkl, S., Mergili, M., 2015. Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. Geomorphology 246, 602–616. https://doi.org/10.1016/j.geomorph.2015.06.032

Fluixá-Sanmartín, J., García Hernández, J., Huggel, C., Frey, H., Cochachin Rapre, A., Gonzales Alfaro, C.A., Román, L.M., Masías Chacón, P.A., 2018. Highlights and Lessons from the Implementation of an Early Warning System for Glacier Lake Outburst Floods in Carhuaz, Peru. Technol. Dev. 187–200. https://doi.org/10.1007/978-3-319-91068-0_16

Fraser, B., 2017. Learning from flood-alarm system's fate - Carhuaz, Peru. EcoAméricas April 2017, 6-8.

Frey, H., Huggel, C., Bühler, Y., Buis, D., Burga, M.D., Choquevilca, W., Fernandez, F., García Hernández, J., Giráldez, C., Loarte, E., Masias, P., Portocarrero, C., Vicuña, L., Walser, M., 2016. A robust debris-flow and GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru. Landslides 1–15. https://doi.org/10.1007/s10346-015-0669-z

Frey, H., Huggel, C., Chisolm, R.E., Baer, P., McArdell, B., Cochachin, A., Portocarrero, C., 2018. Multi-Source Glacial Lake Outburst Flood Hazard Assessment and Mapping for Huaraz, Cordillera Blanca, Peru. Front. Earth Sci. 6, 1–16. https://doi.org/10.3389/feart.2018.00210

INDECI (2004) Mapa de peligro, plan de usos de suelo y medidas de mitigación ante desastres Ciudad de Carhuaz, Primera. INDECI, Lima, Perú

Muñoz R, Gonzales C, Price K, Rosario A, Huggel C, Frey H, García J, Cochachin A, Portocarrero C, Mesa L (2016) Managing Glacier Related Risks Disaster in the Chucchún Catchment, Cordillera Blanca, Peru. In: Climate Change Adaptation Strategies – An Upstream-downstream Perspective. Springer International Publishing, Cham, pp 59–78

Schneider, D., Huggel, C., Cochachin, A., Guillén, S., García, J., 2014. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. Adv. Geosci. 35, 145–155. https://doi.org/10.5194/adgeo-35-145-2014

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J., Reynolds, J.M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth-Science Reviews 134, 137–159. https://doi.org/10.1016/j.earscirev.2014.03.009

Measurement-Model Fusion for Global Total Atmospheric Deposition, a WMO initiative

By Lorenzo Labrador[1], Claudia Volosciuk[1] and Amanda Cole[2]

The Earth's atmosphere's main cleansing mechanism removes chemicals from the air and deposits them onto land and water surfaces. While the effects of these removal processes are mostly beneficial, some can have negative impacts on human health, ecosystems and food security. For example, acid rain – the acidification of rainwater due to nitrogen and sulfur emissions – damages forests, kills insects, corrodes industrial metal structures, etc. Such adverse impacts of deposition are of great interest to society as a whole and more particularly to policymakers, thus, WMO decided to undertake the Measurement-Model Fusion for Global Total Atmospheric Deposition Initiative.

With changes in emissions of atmospheric pollutants, atmospheric deposition has changed dramatically over the past decades. Without a proper understanding and assessment of the amount of atmospheric pollutants deposited onto land and water surfaces, atmospheric deposition could have even more detrimental unknown effects on the well-being of society and ecosystems and the functioning of the atmosphere-land-ocean system. In view of this, many global and national scientific, ecosystem, human health and food security stakeholders have a keen interest in better understanding of atmospheric deposition at all spatial scales in order to better assess its deleterious effects and devise the necessary mitigation measures. The Measurement-Model Fusion Initiative proposed by the WMO Global Atmosphere Watch (GAW) will overcome the limitations and maximize the benefit of existing approaches to mapping deposition on a global scale.

Atmospheric deposition

The Earth's atmosphere, composed primarily of nitrogen and oxygen, is a complex medium. Besides these two main constituents, it is the carrier of a diverse range of additional trace gases and particles, some emitted by natural sources, others emitted by human activities, and still others created by chemistry within the atmosphere. Many of these trace species are considered "pollutants" due to their negative impacts on human health or on the natural or built environment. Pollutants are removed from the atmosphere and deposited onto the Earth's terrestrial and aquatic surfaces through a process known as atmospheric deposition. Atmospheric pollutants can be removed by either wet deposition – precipitation – or dry deposition. Dry deposition can include gravitational settling of particles, or diffusion and turbulent transfer to the surface and subsequent uptake by plants or adsorption to surfaces.

Atmospheric deposition is the primary removal process for most reactive chemical compounds in the atmosphere. In many regions, it is the primary mechanism for pollutants to enter an ecosystem, representing a key process in the Earth system.

The rates at which atmospheric pollutants are deposited onto the Earth's land and water surfaces are determined by meteorological factors such as temperature, precipitation, humidity and wind, the deposited gas or particle's properties (both physical and chemical), and the characteristics of the surfaces onto which these compounds are deposited. The combination of all of these factors determines how long a given atmospheric pollutant will remain in the atmosphere, how far away from its source it will be

1 WMO Secretariat

2 Environment and Climate Change Canada

transported by the wind and how much of it will be removed from the atmosphere.

Relevance to the Sustainable Development Goals

Atmospheric deposition is linked through various Earth-system impacts to several United Nations Sustainable Development Goals (SDGs). Deposition of certain atmospheric pollutants, such as reactive nitrogen, sulphur, ozone, mercury and black carbon, has the potential to affect human health and cause severe damage to ecosystems and vegetation, negatively impacting agricultural productivity and compounding the effects of climate change.

Ozone deposition to vegetation, for example, seriously affects the sustainable provision of food, feed and fibres worldwide (SDG 2- Zero Hunger). In addition to its direct contribution to radiative forcing, ozone can also affect radiative forcing indirectly through damage to vegetation, which reduces plant productivity, thereby leading to decreased carbon dioxide uptake resulting in more carbon dioxide in the atmosphere (SDG 13 – Climate Action) (IPCC, 2013; WMO, 2018). Ozone damage has been estimated to cause worldwide economic losses in the range of US$ 10–20 billion due to its deleterious effects on staple food crops such as wheat, soybean and maize (Avnery et al., 2011). The estimated annual yield loss due to ozone (ozone yield gaps, mean of 2010–2012) is by 12.4%, 7.1%, 4.4% and 6.1% for soybean, wheat, rice and maize, respectively, adding up to 227 Tg of lost yield (Mills et al., 2018). An example of ozone-induced plant damage and how it gets worse over time is shown in Figure 1. The older leaves on a plant will show more damage than the younger ones as the former will have been exposed to ozone for a longer period.

Similarly, atmospheric deposition of reactive nitrogen has a direct effect on ecosystem health, agricultural production on both managed and unmanaged lands, and climate change. High levels of nitrogen deposition have been shown to cause soil and surface water acidification, water quality degradation and eutrophication and to affect vegetation growth and plant and animal species diversity. Cumulative nitrogen deposition can lead to nitrogen saturation of soils, which in turn can lead to biodiversity loss, soil acidification, water degradation and forest growth reduction. Thus, understanding and mapping atmospheric deposition on a global scale is extremely important, particularly since atmospheric deposition is linked to 7 of the 17 United Nations' SDGs.

Figure 1: Ozone injury to common bean leaves (Black Turtle) increases when ozone exposure continues: initially, the level of damage is small (left), then symptoms get worse (centre and right)

Figure 2: During the GAWTEC training course on total atmospheric deposition at Hohenpeißenberg GAW station. (left) Precipitation samplers and (right) different samples of collected atmospheric deposition on filters.

Measurements of atmospheric deposition and the Measurement-Model Fusion technique

Wet deposition of atmospheric pollutants is measured by collecting precipitation samples and measuring the concentrations of the targeted pollutants and the depth of the precipitation (Figure 2). Dry deposition is commonly estimated by measuring the concentrations of gases and particles near the Earth's surface and using computer models to calculate their associated dry deposition velocities, that is, the speed at which these pollutants are deposited to the Earth's surface. Both methods require expensive and sophisticated measurement networks that operate over large areas, such as those coordinated by GAW. Wet and dry deposition are also estimated by chemical transport models (CTMs), which combine emission inventories with meteorological and atmospheric process models over regional and/or global scales. Both the measurement and modelling approaches have specific advantages and disadvantages but neither is perfect.

Current maps of atmospheric deposition on a global scale are based on a limited set of measurements or the predictions of CTMs. Both types of maps contain large uncertainties: Deposition measurements are sparse or non-existent in large areas of the world, that is, Africa, Asia, Australia and South America and over the oceans, and chemical transport models are necessarily reliant on assumptions and simplifications in their emission budgets and parametrizations.

In order to overcome the limitations and maximize the benefit of both approaches, a new method of creating deposition maps, called Measurement-Model Fusion (MMF), has been developed. MMF merges best-available measurements of both wet and dry deposition, including atmospheric concentrations, with best-available CTM estimates of deposition using statistical methods.The technique "nudges" or adjusts model estimates closer to true values by incorporating or "assimilating" measurement values, much in the same way that observations of meteorological variables, such as temperature, wind speed, wind direction and relative humidity, are assimilated into numerical weather prediction (NWP) models in order to improve the accuracy of weather forecasts. Unlike NWP, however, atmospheric deposition measurements cannot be incorporated into deposition models in real or near-real time as deposition-related measurements need to be processed and analysed post-collection. Instead, observations are assimilated at a later stage or retroactively.

The result of this process are maps of atmospheric deposition that provide more accurate estimates of both wet and dry deposition than could be achieved with either observation or model estimates alone.

Figure 3 (a)

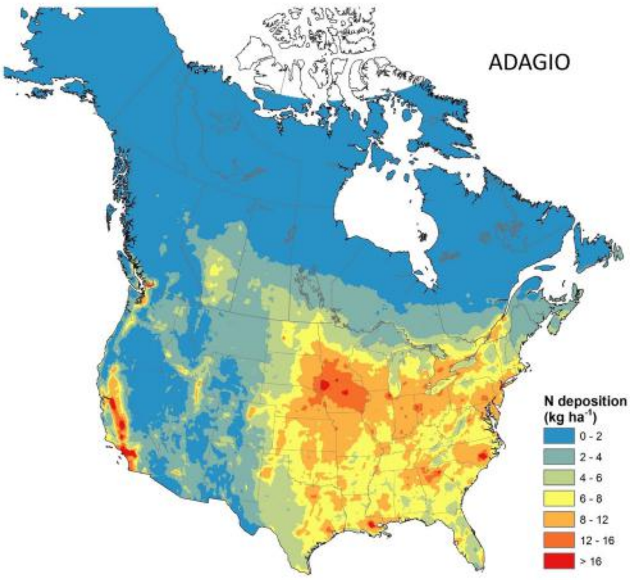
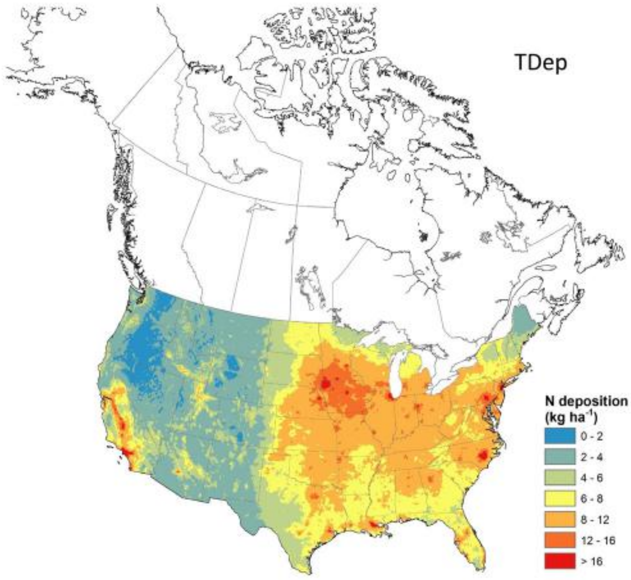


Figure 3 (b)



Figures 3 (a) and (b): Current measurement-model fusion maps of total atmospheric deposition. Figure 3 (a) (Left) 2010 nitrogen total deposition in kg N ha^{-1} yr^{-1} produced by Environment and Climate Change Canada (Schwede et al., 2019), Figure 3 (b) (Right) 2010 nitrogen total deposition in kg N ha^{-1} yr^{-1} produced by the United States Environmental Protection Agency (Schwede et al., 2019).

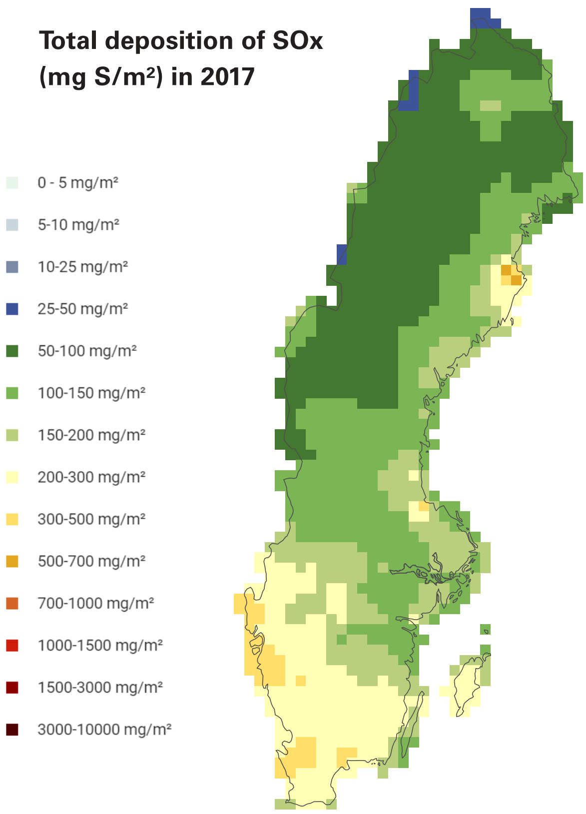


Figure 4: 2017 sulphur deposition in Sweden in mg S m^{-2} yr^{-1} produced by the Swedish Meteorological and Hydrological Institute (Leung et al., 2019).

MMF methods have been developed and applied successfully in several countries including Canada, Sweden and the United States but have yet to be applied on a global scale. Figures 3 (a-b) and Figure 4 show examples of high-resolution MMF deposition maps produced by Canada, the United States and Sweden, respectively. These methods provide the scientific and methodological basis for expanding deposition maps from national and regional scales to global scales.

WMO Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD) Initiative

GAW is now in a position to engage and coordinate leading experts on atmospheric deposition and MMF from around the world to develop and apply MMF techniques to produce global deposition maps. They will build on recent advances in chemical transport modelling and use satellite observations of atmospheric deposition as well as the network of surface measurements of concentrations and deposition fluxes coordinated by the WMO Scientific Advisory Group on Total Atmospheric Deposition.

The goal of the initiative is to use a combination of regional and global atmospheric deposition models and observations to produce high-quality maps of total – wet plus dry – atmospheric deposition and estimates of fluxes of atmospheric pollutants on a global scale in a semi-operational manner. This initiative, still in its early stages, is known as the Measurement-Model Fusion for Global Total Atmospheric Deposition (MMF-GTAD). It is worth noting that current MMF maps of atmospheric deposition are the result of efforts undertaken by individual countries or two countries working together and are national or regional in scope.

Currently, many countries lack the capability and knowledge to account for atmospheric deposition in their scientific, policy-making and planning decisions related to the United Nations SDGs. MMF maps of deposition on a global scale, formulated from best-estimates of measurements and models, will serve to inform and support this decision-making processes.

Global high-quality deposition and concentration maps, and their associated data files, will allow government agencies and other stakeholders to assess the impacts of atmospheric deposition of chemicals on population health, land and ocean ecosystems, agricultural land surfaces and climate change. Their decision and actions would be based on the best-available scientific data. GAW already plays a central role in the data collection and quality control of surface measurements of deposition. In the framework of the MMF-GTAD , it will also play a key role in advancing the operational production of MMF maps of atmospheric deposition on a global scale (and, additionally, on regional scales in areas of the world with poor measurement coverage) and in providing authoritative results and knowledge to the UN and its member states. This is reflected in the following Vision Statement for the MMF-GTAD Initiative:

Stakeholders will be able to access high-resolution, high-quality, global-scale maps of total atmospheric deposition to meet societal needs as they relate to the environment and global sustainable development.

Implementation of the MMF-GTAD Initiative

The WMO GAW Implementation Plan for 2016–2023 is built on the concept of "Science-for Services". In this context, the MMF-GTAD Initiative is one of the new GAW services identified by the World Meteorological Congress in June 2019 in Resolution 60 addressing user needs. Based on this vision, the MMF-GTAD Initiative objectives are as follows:

- Create and disseminate high-quality global MMF maps and high-spatial-resolution data products of atmospheric deposition on an semi-operational basis (including associated quality-assured measurement data sets and chemical transport model outputs)

- Provide continuous improvement to the operational products through research innovations in deposition monitoring, chemical transport modelling, data assimilation/fusion techniques and other observation systems (e.g., satellite measurements)

- Continuously engage data users, stakeholders and partners to meet their evolving needs and priorities

- Provide customized procedures, technical advice and tailored products for specific user and stakeholder needs (e.g., ecosystem-specific deposition, derived indicators, long-term deposition trends)

- Build capacity (technical/institutional/personnel) and reach out to relevant science/policy communities and organizations for which information on deposition is unknown, underused or limited

- Work with existing WMO, UN partners, regional and national measurement programmes (e.g., networks, satellites) to encourage the expansion and improvement of deposition observations in under-sampled areas

- Enhance and improve deposition, air quality and climate predictions by providing guidance on incorporating atmospheric deposition into the Earth system modelling approach for land, ice, oceans and the atmosphere

- Enable and collaborate with users and stakeholders to apply current and future knowledge of global deposition from the MMF-GTAD to assess the impact of deposition changes on changes to the Earth's climate, ecosystems, emissions and society through its relationship to the relevant United Nations SDGs

- Establish a formal Implementation Plan to organize and execute the MMF-GTAD Initiative following its stated near-term and mid-term objectives.

The MMF-GTAD Initiative will implement a comprehensive operating system that incorporates the gathering of measurement data and modelling output, the application of MMF techniques, and the development and delivery of products and services. The Initiative will require a highly integrated and coordinated approach to activities that span several different atmospheric science fields. The list includes atmospheric composition and deposition measurements (such as GAW stations, regional and national measurement networks), chemical transport modelling (regional, national and global scales), emission inventories, data assimilation/measurement-model fusion, database management and product dissemination and delivery.

To meet the objectives of the MMF-GTAD Initiative, all services and products provided by the Initiative will be driven by user needs. This will be achieved through consultation and feedback in meetings and workshops aimed at defining their specific needs.

The MMF-GTAD Initiative was launched in February 2019 by an Expert Meeting with members from the fields of observations and modelling of atmospheric deposition, aerosols and reactive gases, MMF techniques to food security and ecosystems – at WMO Headquarters in Geneva. The meeting defined the technical and financial aspects related to the implementation of the initiative and work was started on its implementation plan.

Many of the technical and scientific elements are currently in place. The Initiative is now seeking funds to move forward with the production of global deposition maps. GAW welcomes both in-kind and financial contributions from WMO Members and partners to the MMF-GTAD Initiative. Several scientific, societal and policy-based organizations are awaiting the routine production of global MMF-GTAD maps under this initiative.

Acknowledgement: This article is based on the MMF-GTAD Initiative's Concept Note document, drafted by Wenche Aas, Camilla Andersson, Amanda Cole, Frank Dentener, Joshua Fu, Corinne Galy-Lacaux, Maria Kanakidou, Lorenzo Labrador, Kobus Pienaar, Donna Schwede and Robert Vet.

References

Avnery, S., Mauzerall, D.L, Liu, J. and Horowitz, L.W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. Atmospheric Environment, 45:13, pp. 2284-2296.

Leung, W., Alpfjord Wylde, H. and Andersson, C. (2019). National environmental assessment with the MATCH Sweden system, evaluation of results for the years 2015-2017 (in Swedish 2015-2017. Swedish Meteorological and Hydrological Institute. https://www.smhi.se/polopoly_fs/1.146627!/Slutrapport2015-17_M%C3%96.pdf.

Mills, G., Sharps, K., Simpson, D., Pleijel, H., Broberg, M., Uddling, J., Jaramillo, F., Davies, D., Dentener, F., Van den Berg, M., Agrawal, M., Agrawal., S.B., Ainsworth, E.A., Büker, P., Emberson, L., Feng, Z., Harmens, H., Hayes, F., Kobayashi, K., Paoletti, E., and Van Dingenen, R. (2018). Ozone pollution will compromise efforts to increase global wheat production. (2018). Global Change Biology, 24: 8, pp. 3560-3574. doi.org/10.1111/gcb.14157.

Schwede, D., Cole, A., Vet, R., and Lear, G. (2019). On-going U.S.-Canada collaboration on nitrogen and sulfur deposition. EM: The Magazine for Environmental Managers, June 2019.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (UK) and New York, Cambridge University Press

WMO, 2018: WMO Reactive Gases Bulletin. No 2: Highlights from the Global Atmosphere Watch Programme. Geneva.

WMO Space-based Weather and Climate Extremes Monitoring Demonstration Project for East Asia and Western Pacific

By Yuriy Kuleshov[1], Takuji Kubota[2], Tomoko Tashima[2], Pingping Xie[3], Toshiyuki Kurino[4], Peer Hechler[4] and Lisa V. Alexander[5]

Meteorological observations clearly demonstrate that global climate change has occurred since the beginning of the Industrial Revolution. That change has been particularly pronounced since about 1950, and includes changes in weather and extreme climate events. Changes in weather and climate extremes can significantly increase the impacts on society, leading to a greater number of disaster worldwide. One of the world's most disaster-prone regions is the Asia-Pacific. Since 1970, disasters have killed two million people in the Asia and Pacific region — 59% of the global death toll. The most frequent natural hazards in the region are hydro-meteorological events [1]. There is a pressing need to develop and implement new tools for global monitoring of these increasingly frequent and severe hazardous phenomena, including using modern satellite remote sensing techniques..

Recognizing the importance of this issue, WMO launched a two-year (2018–2019) Demonstration Project on space-based weather and climate extremes monitoring. The project is focused on drought and heavy precipitation over the South-East Asia region and the Pacific Ocean. In June 2019, the Eighteenth World Meteorological Congress (Cg-18) reviewed the outcomes and recommended the expansion of the project to other WMO regions and adopted an implementation plan to transition it into an operational phase. This article highlights the outcomes of the Demonstration Project in two Australian case studies: during the Millennium Drought and extreme precipitation events during the 2010/2011 La Niña event.

Knowledge transfer essential

The Demonstration Project was set up following the recommendations from a February 2017 WMO workshop on Operational Space-based Weather and Climate Extremes Monitoring. The workshop gathered representatives from satellite operators, research and development agencies, WMO Regional Climate Centres (RCCs) and National Meteorological and Hydrological Services (NMHSs) to stimulate a dialog about enhancing utilization of space-based observation data and products for monitoring weather and climate extremes.

The workshop recognized that many developing and least developed countries were not benefiting from the significant progress made in space-based observations in most geophysical domains – several high-resolution satellite products are available on a quasi-real time basis, enabling enhanced use for monitoring weather and climate extremes from space. Participants recommended the strengthening of human and technological capacity through knowledge transfer in order for all countries to benefit fully from the advantages of modern space-based data and derived products. The RCCs could

1 The Australian Bureau of Meteorology, Australia
2 The Earth Observation Research Center, Japan Aerospace Exploration Agency (JAXA), Japan
3 The Climate Prediction Center, National Oceanic and Atmospheric Administration (NOAA), USA
4 WMO Secretariat
5 UNSW Sydney, Australia

enable such a knowledge transfer. Following the workshop's recommendations, WMO established the Demonstration Project to make a case for the use of space-based observations and products for monitoring weather and climate extremes.

Situation in Asia-Pacific region

Most NMHSs in South-East Asian and Pacific countries use conventional surface-based rain gauge observations for extreme precipitation monitoring. Rain gauge observations provide accurate point-based measurements of precipitation; however, data are restricted to the locations of meteorological observation stations. Over Australia, for example, the spatial distribution of rain gauges is not uniform: while the most densely populated regions are well covered, spatial coverage in other regions – like western Tasmania and the interior of the country – is very poor. This issue of non-uniform spatial coverage is typical in the Asia-Pacific region, where the rain gauge density in many areas is inadequate. Therefore, complementary rainfall estimates derived from space-based observations would better address various users' needs for precipitation information.

Current operational climate products for drought monitoring – derived from surface-based observations – focus typically on identifying rainfall deficits over extended periods (months to years) using percentile and/or decile analysis. And heavy precipitation is diagnosed typically on a monthly time scale (although higher resolution time information is available from gauges). Using space-based observations, it is possible to monitor extreme precipitation events over shorter time periods – pentad (5 days), week and longer periods of up to a month, in order to respond to current and future users' requirements. Thus, space-based observations can address users' needs for information about precipitation extremes on short timescales. Both RCCs and NMHSs consider the monitoring of weather and climate extremes on shorter time scales as a valuable extension of their operational products to enhance climate services for users in Asia-Pacific.

The Standardized Precipitation (SPI) is also widely used for meteorological drought detection and monitoring. Positive values of the SPI correspond to precipitation above median and negative values to precipitation below median. Drought conditions are classified when the SPI values are equal to or below -1.0. For example, an SPI of -1.0 or lower is classified as "moderately dry", -1.5 or lower – as "severely dry", and -2.0 or lower as "extremely dry".

Precipitation Products

The Demonstration Project aimed to demonstrate the benefits of using space-based extreme precipitation observations to the operational services of RCCs and NMHSs. It was implemented in WMO Regions II (Asia) and V (South-West Pacific), covering the geographical area of the South-East Asia region and the Pacific Ocean – from 40°N to 45°S; 50°E to 160°W. Two agencies – Japan Aerospace Exploration Agency (JAXA) and the Climate Prediction Center, National Oceanic and Atmospheric Administration (CPC/NOAA) – provide satellite data and products for the region.

The Demonstration Project based its definition of drought and heavy rainfall events on the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 Working Group I definition of extreme events: “An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).”

WMO recommendations and extensive consultations with the satellite data providers and users (RCCs and NMHSs in South-East Asia and the Pacific) determined that the Demonstration Project should aim to satisfy users' requirements for monitoring precipitation extremes on short timescales. Using JAXA and CPC/NOAA satellite-based near-real-time products for monitoring "heavy precipitation" and "drought" events operationally for climate analysis, the Demonstration Project developed pentad (5-day) to weekly and up to monthly climate information services for users.

JAXA precipitation products are based on the Global Satellite Mapping of Precipitation (GSMaP) [3]. For the Demonstration Project's users in Asia-Pacific, JAXA provided mean precipitation estimates derived from GSMaP version 6 for hourly, daily (00-23UTC), pentad (5 days), weekly (Monday – Sunday), 10 days and monthly precipitation with spatial resolution of 0.1° latitude/longitude grid box. In addition, statistics for daily, pentad and weekly extreme precipitation (90th to 99th percentiles) and percentage of rainy (>=1mm/day) days in a month was provided. For drought monitoring, the SPI (1-month, 2-month and 3-month) for grid boxes over land with spatial resolution of 0.25°lat/long grid box was provided. These data are available within a few hours of their observation.

CPC/NOAA provided the Demonstration Project users with a similar set of products based on the Climate Prediction Center's morphing technique (CMORPH) satellite precipitation estimates (see [4] for detail). The climatology of the CMORPH products are defined for a 20-year period from 1998 to the 2017. In addition to the SPI, weekly normalized differential vegetation index (NDVI) and the vegetation health index (VHI) were also made available.

Case study: Drought Monitoring in Australia

The Demonstration Project examined the usefulness of space-based observations for drought monitoring over Australia in 2007, a critical year of the Millennium Drought, using three-month SPI values derived from JAXA GSMaP data.

Australia is the driest inhabited continent on Earth. Some 70% of Australia receives less than 500 millimetres of rain annually, classifying them as arid or semi-arid areas. In Australia, drought monitoring is, therefore, vital for informed decision-making in agriculture, disaster risk management, water management and other sectors. Australia's Bureau of Meteorology (BOM) reports drought when rainfall over a three-month period remains in the lowest decile recorded for that region in the past [5]. BOM operational records go back over a century in Australia, show that on average drought occurs once every 18 years, however, the severity and duration of droughts vary.

One of the severest Australian droughts – the Millennium Drought – occurred in the 2000s and affected vast parts of the country. The Murray-Darling basin, Australia's largest agricultural region, was severely affected as were the supply of water resources of many cities and towns, including Melbourne, Sydney, Brisbane and Adelaide. The drought commenced with a rainfall deficit in 1996/1997 and continued with very dry years through to 2001/2002. During 2006, south-eastern parts of Australia had their second driest year on record. By 2007, the Murray-Darling basin was experiencing its seventh consecutive year of below average rainfall. The dry, hot conditions continued to affect Australia through to early 2010. The 2010/2011 La Niña, one of the strongest on record, brought the Millennium Drought to the end. It resulted in record-breaking rainfall in the Murray-Darling basin and above average rainfall over the south-east of the country. The continuing above average rainfall significantly increased surface water storage and soil moisture, ending the drought.

The examination of three-month SPI for June-July-August 2007 (Figure 1) in the Murray-Darling basin derived from both the JAXA GSMaP and the CPC/NOAA CMORPH indicated SPI values below -1.5 ("severely dry") in areas defined as "very much below average" on rainfall deciles map derived from BOM's rain gauge observations (Figure 2). Space-based and in situ observations were, therefore, in agreement over the Murray-Darling basin in south-eastern Australia where the density of surface-based observations is high. However, there were noticeable discrepancies between SPI values and rainfall decile maps over the central parts of the country where the density of surface-based observations is very low. This demonstrates the value of space-based rainfall estimates for drought detection and monitoring, especially in regions where rain gauge observations are limited or unavailable.

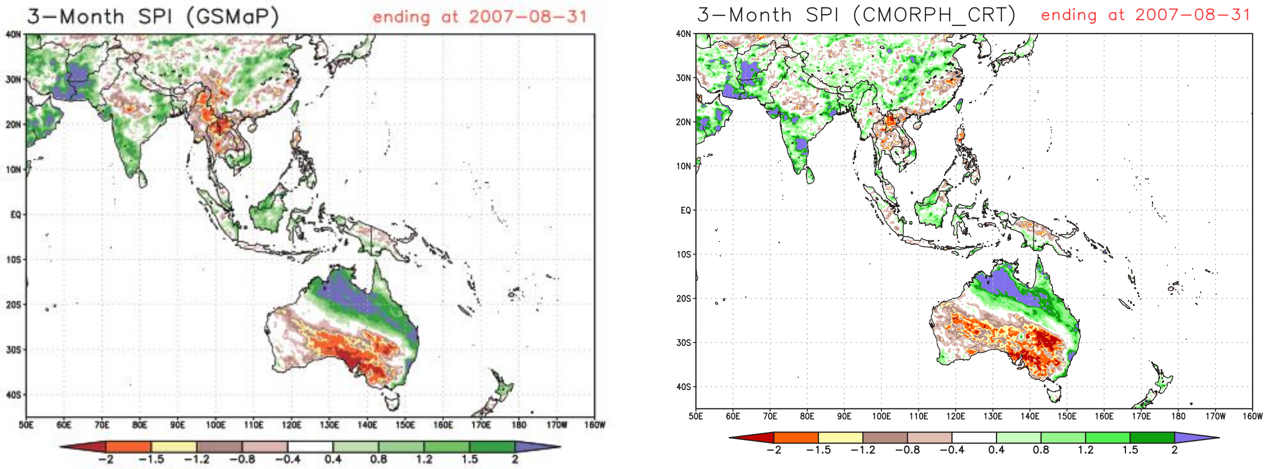


Figure 1. Three-months SPI for June-July-August 2007 derived from the JAXA GSMaP (left) and the CPC/NOAA CMORPH bias-corrected precipitation data (right).

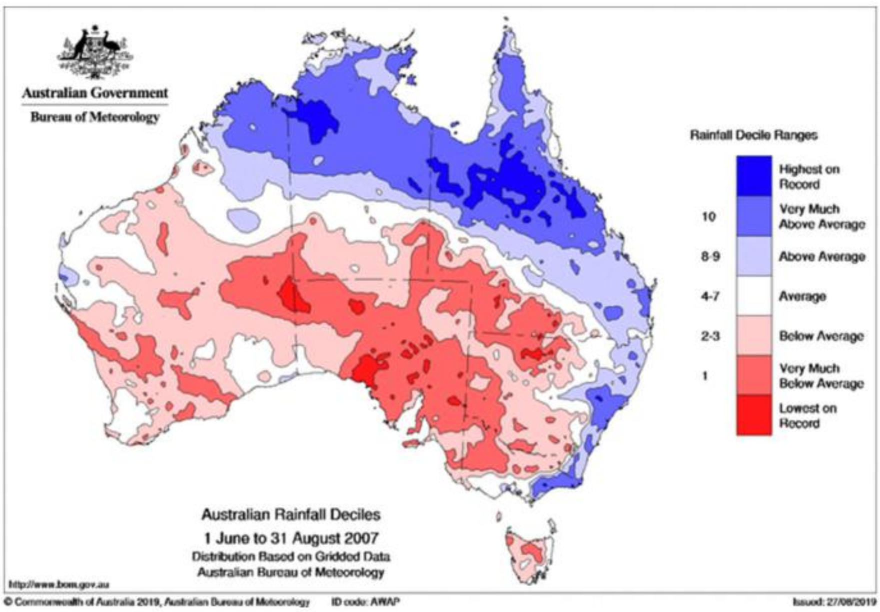


Figure 2. Rainfall deciles for Australia in June-July-August 2007 derived from the Australian Bureau of Meteorology rain gauge observations.

Case study: Heavy rains in Australia

This second case study looks at two heavy precipitation events over Australia in December 2010 and January 2011, which caused widespread flooding.

An "extreme rainfall" event is defined as occurring when mean rainfall for a specified period is higher than a certain percentile threshold, for example in the 90th to 99th percentile. Australia experienced such extreme rainfall during the La Niña event in 2010/2011 – 2011 was the third-wettest year since national rainfall records began in Australia in 1900.

Averaged across Australia, both years experienced rainfall well above average: 690 mm (225 mm above the long-term average of 465 mm) in 2010 and 699 mm (234 mm above the long-term average of 465 mm) in 2011.

The 2010/2011 La Niña event had a significant impact on Australian rainfall. La Niña is typically associated with increased rainfall in northern and eastern Australia. During the 2010/2011 La Niña, most of mainland Australia experienced significantly higher than average rainfall over the nine months from July 2010 to March 2011. A number of new Australian

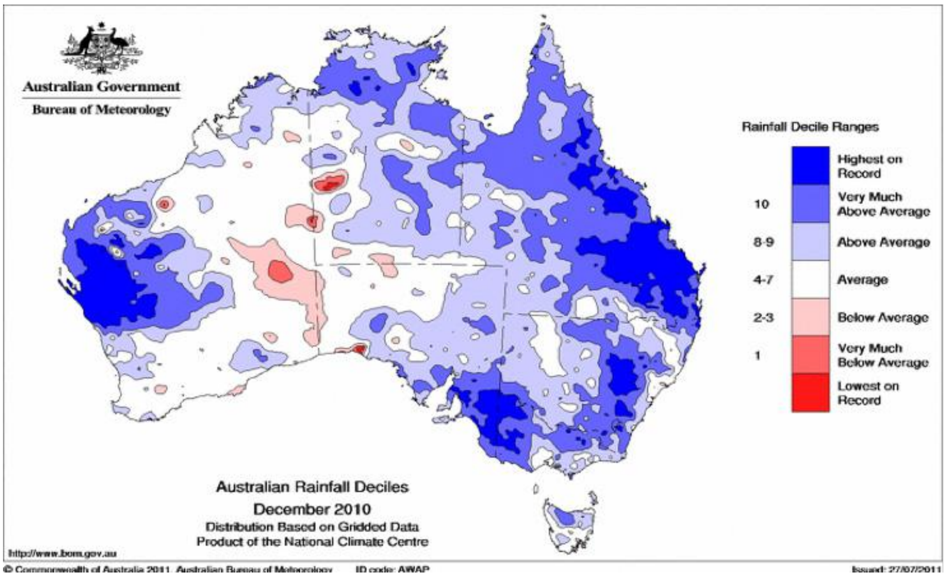


Figure 3. Australian rainfall deciles for December 2010 derived from the Australian Bureau of Meteorology rain gauge observations. The extreme rainfall observed over parts of western and eastern Australia in December 2010 were associated with the 2010-2011 La Niña event.

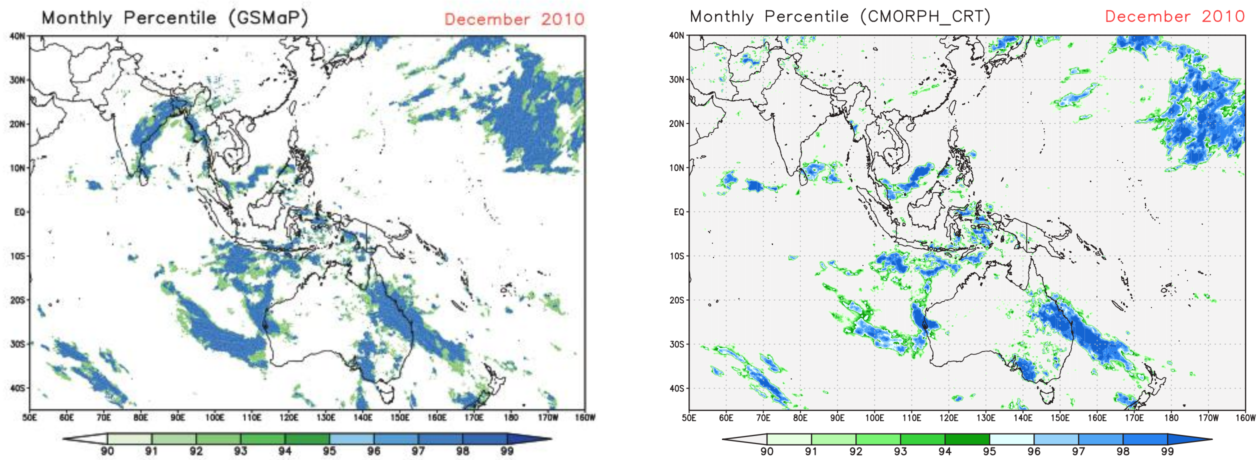


Figure 4. JAXA GSMaP (left) and CPC/NOAA CMORPH (right) monthly rainfall percentiles for December 2010.

rainfall records were set: wettest September, December and March on record and second-wettest October and February. The record-breaking rainfall during the 2010/2011 La Niña led to widespread flooding in many regions between September 2010 and March 2011 including southeast Queensland, large areas of northern and western Victoria, New South Wales, northwestern Western Australia and eastern Tasmania.

JAXA GSMaP and CPC/NOAA CMORPH monthly rainfall percentiles for December 2010 (see figure 4 on page 62) were used to examine the widespread flooding that occurred in the Australian State of Queensland in December 2010. A monsoonal trough crossed the coast from the Coral Sea on 23 December, bringing torrential rainfall to a large area of Queensland from the Gulf of Carpentaria to the Gold Coast. This was followed by intense rainfall on 25 December, due to the landfall of tropical cyclone Tasha. By 28 December, nearly half of Queensland was flooded; economic losses reached A$6 billion. The areas of rainfall above the 95th percentile shown in both the GSMaP and the CMORPH analyses maps corresponded to the "very much above average" rainfall deciles derived from BOM rain gauge observations (Figure 3). Furthermore, the weekly rainfall percentiles for 20–26 December (shown

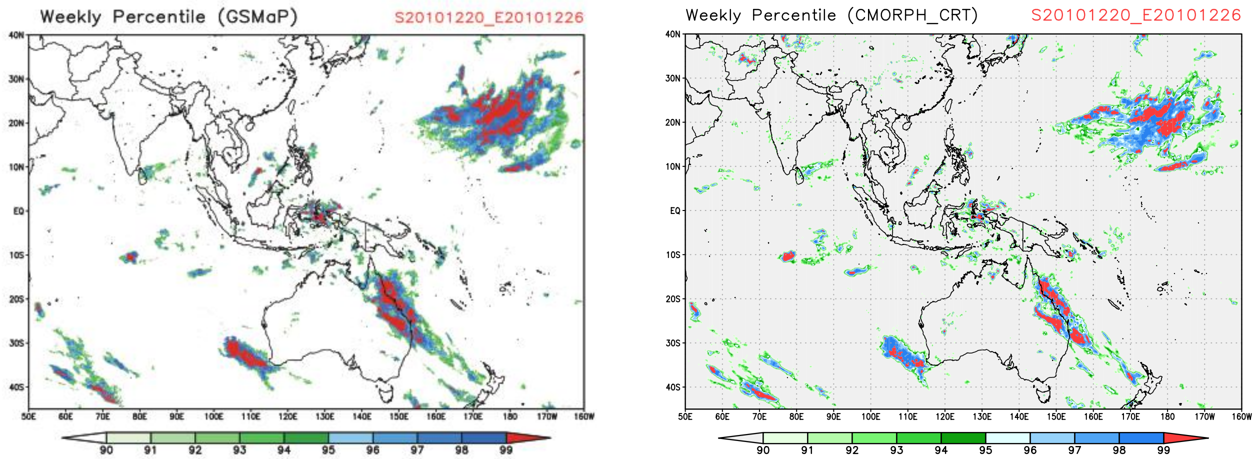


Figure 5. JAXA GSMaP (left) and CPC / NOAA CMORPH (right) weekly rainfall percentiles for 20-26 December 2010.

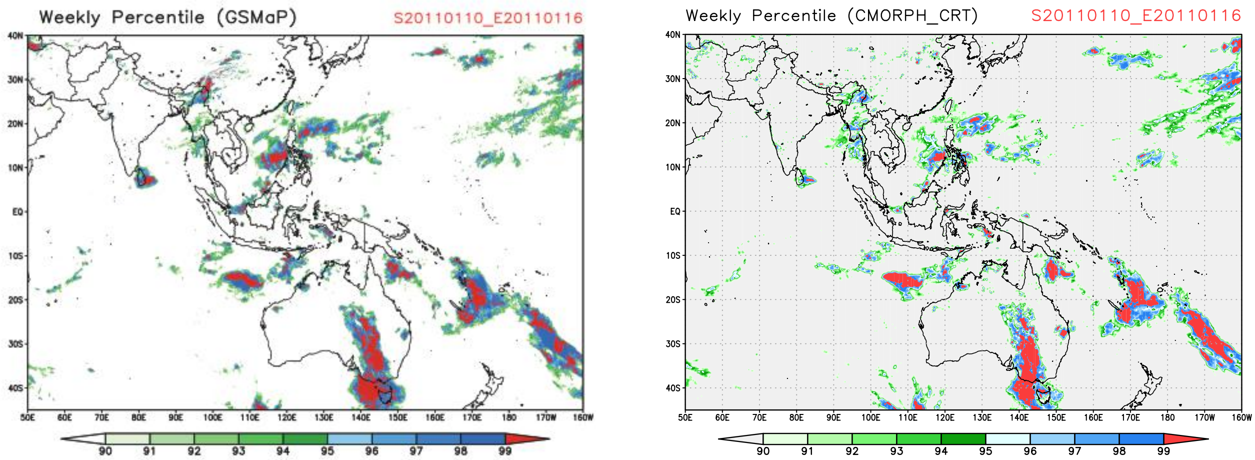


Figure 6. JAXA GSMaP (left) and CPC/NOAA CMORPH (right) weekly rainfall percentiles for 10-16 January 2011.

in Figure 5) demonstrate that the extreme rainfall event in Queensland was well detected using the two satellite precipitation products.

An episode of heavy precipitation over the Australian state of Victoria in January 2011 was the second event examined. High intensity rainfall between 12–14 January caused major flooding across much of the western and central parts of Victoria. The 2011 flood event was described as one of the biggest floods in the state's history, it affected over 50 communities. Over 1 730 properties were flooded and over 17 000 homes lost electricity supply. Total damages amounted to A$ 2 billion.

JAXA GSMaP and CPC/NOAA CMORPH weekly rainfall percentiles for 10–16 January 2011 (Figure 6) show areas of rainfall above the 99th percentile, clearly indicating that parts of Victoria were affected by extreme rainfall. In all of these cases, the GSMaP and CMORPH showed very similar results in indicating the overall spatial patterns and magnitude of the extreme events, although small differences exist due to differences in both the products and the periods defining the base extreme climatology.

These examples demonstrate that space-based observations provide valuable information for monitoring heavy rainfall.

Conclusions

It is of vital importance to sustain in situ rain gauge networks, however, the first results of the Demonstration Project in Asia-Pacific demonstrate that space-based estimates of extreme precipitation are an effective solution to enhance capacity of RCCs and NMHSs for monitoring drought and heavy rainfall. Such capacity would enable service providers to assist Governments and local communities with informed decision making in adaptation to climate variability and change. Recognizing the achievements of Demonstration Project in assisting RCCs and NMHSs in East Asia and the Pacific, the Eighteenth World Meteorological Congress (Cg-18) adopted the Space-based Weather and Climate Extremes Monitoring (SWCEM) Implementation Plan (see [6] for detail). It further endorsed its implementation from 1 January 2020 to mark the transition of the project into an operational phase. The Cg-18 also requested WMO technical commissions and relevant Regional Associations to consider the possibility of implementing similar demonstration projects in Africa and South America.

References

1. Asia-Pacific Disaster Report 2019: The Disaster Riskscape across Asia-Pacific – Passways for Resilience, Inclusion and Empowerment. UNESCAP [Internet]. 2019.

2. IPCC AR5 WG I, Annex III Glossary [Internet]. 2013.

3. Kubota T, Shige S, Hashizume H, Aonashi K, Takahashi N, Seto S, Hirose M, Takayabu YN, Ushio T, Nakagawa K, Iwanami K, Kachi M & Okamoto K. Global Precipitation Map Using Satellite-borne Microwave Radiometers by the GSMaP Project: Production and Validation. IEEE Transactions on Geoscience and Remote Sensing. 2007:45(7, part 2):2259-2275. DOI: 10.1109/TGRS.2007.895337

4. Xie P, Joyce R, Wu S, Yoo S-H, Yarosh Y, Sun F & Lin R. Reprocessed, Bias-Corrected CMORPH Global High-Resolution Precipitation Estimates from 1998. Journal of Hydrometeorology. 2017:18(6):1617-1641. DOI: 10.1175/JHM-D-16-0168.1

5. Drought definition in Australia [Internet]. 2019.

6. The Space-based Weather and Climate Extremes Monitoring (SWCEM) - East Asia and Western Pacific Regional Sub-project in Operation - Implementation Plan [Internet]. 2019.

Women in Science taking the lead in the Pacific Islands

By Sylvie Castonguay, WMO Secretariat

Participants, including Samoa Deputy Prime Minister and High-Chief, the Honorable Fiame Naomi Mata'afa, at the CREWS Pacific Small-Islands Developing States (SIDS) Project leadership training workshop in Samoa.

Climate change and its impacts are affecting all members of society – women, men, girls and boys – but not always in the same way. In the widely-dispersed Pacific islands with their varying geographical conditions, cultures and socials structures, these differences are magnified. Pauline Pogi a hydrologist in the Water Resource Division of the Ministry of Natural Resources and Environment in Samoa stated, "Women, especially women who care for children or the elderly, are among the groups that are most vulnerable to the impacts of climate change. Therefore, their opinions matter in addressing the issues faced within these thematic areas." In line with this, Samoa Deputy Prime Minister and High-Chief, the Honorable Fiame Naomi Mata'afa urged female scientists in the Pacific to be examples for the young girls in school and to take strength from each other by forming a network of Pacific Island women.

The CREWS (Climate Risk and Warning System) Initiative includes a gender dimension in project implementation in recognition of the fact that different genders access and react to warnings in different ways. This allows national early warning systems that WMO supports to be gender-responsive. Culture, social and religious structures, and institutional systems are the main influencers of gender roles in families and the broader community. Gender roles being different, the communication of early warning of risks, as well as the risk themselves, may differ. The CREWS Pacific Small-Islands Developing States (SIDS) Project has offered leadership training to women in the National Meteorological and Hydrological Services to enable and empower them to include gender dimension in their work, to be confident in encouraging girls to choose scientific careers and to build a strong Pacific Island network of women leaders.

To mark International Women's Day, 8 March 2020, WMO has conducted interviews with Pacific Island women who are leading this initiative.

Pauline Pogi
Principal Officer, Water Resource Division, Ministry of Natural Resources and Environment, (MNRE), Samoa

On her career in Hydrology

I have always been interested in water resource management as I believe that water is one of the most important natural resources for sustenance of life on earth. Samoa is blessed to have an abundance of water resources and we are striving to maintain this in light of a growing population. It is very important to ensure there is sufficient water resources available for future generations, but there is a challenge to try to change the mindset of people who see water as "free," to convince them to use it more wisely and sparingly. We aim to educate our communities on the importance of water resource management. This is done through community engagement programmes and ensuring the involvement of the people in the development of water resource management tools as well as creating a sense of ownership amongst our people to look after our water resources. Our approach has been very successful so far – we aim to build on it moving forward.

Women and climate change

Women, especially women who care for children or the elderly, are among the groups that are most vulnerable to the impacts of climate change. Therefore, their opinions matter in addressing the issues faced within these thematic areas.

Women in science

Scientific careers and those in technical fields are often labelled as a "man's job" and this mentality needs to change. The courses which coincide with these scientific careers are also usually seen to be more suited for men. Often times, women self-doubt when it comes to what kind of careers they can excel in and whether or not a scientific career is one of them.

Women need to empower each other and be great role models for younger women. Those who are already in the scientific field need to rise up and be influential to empower young women to push the boundaries and excel in a very male-dominated field.

The qualities that I aspire to have and would also love to see in strong female leaders are confidence, empathy, honesty, motivation, and to be approachable.

Rossylynn Pulehetoa-Mitiepo
Director, Niue Meteorology Service

On her career in climate

In school I opted for science subjects as I enjoy learning the physical dynamics of why things are the way they are. I then applied for a scholarship as an Assistant Forecaster, and from thereon I was able to build a career in weather, which has since expanded into climate, and climate change.

On striving for success

I always recall my dad's story about how life was hard during his younger days, walking a long distance to school and making use of the daylight to do his homework as there was no electricity in his home. When he landed a job and his kids were born, he worked hard to put food on the table for all of us. This pushed me even harder to make use of opportunities that came about in order to become successful.

The challenges

It was a great challenge when I was appointed Acting Director for two years and then officially got the role. I now aim to build my officers into great future leaders. Being in a leadership position for the first time, I realize there is a big responsibility on my shoulders.

Being a strong women leader means being courageous and having a sense of self-worth. Not believing in themselves is something that may hold women back from a scientific career. Once they take a leap of faith and change their belief system, they will be amazed at the outcomes.

We need to establish a regional women's science forum to raise and discuss issues, and implement solutions for a way forward. Women have the ability to lead for the resilience of vulnerable people and communities.

Seluvaia ‘Ilolahia

Senior Forecaster, Tonga Meteorology Service (MEIDECC)

The challenges of balancing family and career

Throughout my years in school, math and science were always my favourite subjects. The biggest challenges I faced while studying were finance and family. I struggled to look after my mother, younger siblings and my 9-year-old son. My greatest achievement is my role in the workforce, leading the climate department, while still pursuing higher education.

What holds back women is in the mind of the individual. Mother’s should raise their children in a positive manner, teaching them the importance of equality from a young age. As young children, they should be taught to understand that you can do anything in school and that everyone has equal opportunity anywhere.

Women in the climate change agenda

Climate change and weather are very prominent topics. Women make for strong role models for all, especially when it comes to taking the lead on initiatives for change.

Qualities required in a strong leader

I believe a strong female leader should be courageous, fearless, and have lots of confidence and trust in God.

We all have a role

Encourage your female colleagues in the workplace. Use school visits to Meteorological offices as a good time to promote the importance of Science to students. Be a role model, be strong, creative, supportive, help each other and most importantly, have lots of faith and confidence.

Elinor Lutu-McMoore

Director, National Weather Service - Pago Pago, U.S. National Oceanic and Atmospheric Administration (NOAA)

On her career at the Weather Service

I started my career in the National Weather Service Office (WSO) in American Samoa in 2005 as a meteorological technician. When I was part of the WSO Pago Pago team, I realized that the best way for me to use my business management degree was to become a meteorologist. In 2008, I decided to pursue a four-year degree in meteorology at the University of Hawaii at Manoa (UH), which I completed in two years. Upon graduating, I started an internship at the U.S National Weather Office in Honolulu, which became a full-time position soon after. In 2012, I completed a Master of Public Administration (MPA) degree, and a year later I moved back to American Samoa as a general forecaster at WSO Pago Pago as it was important for me to provide service to my community. In 2017, I was promoted to the Meteorologist-In-Charge.

I faced many challenges along the journey to become a meteorologist; however, I was taught to always look at them as life's lessons from which I could learn and grow. Having the perspective that challenges are meant to arm me with tools for my journey forward in life has made the individual that I am today. I will continue to pass these lessons down to my children, who are my greatest accomplishments.

It is a great honour and blessing for me to be a Meteorologist-In-Charge. My staff are my family, and as their leader, finding new ways to better serve them is always a humbling experience. Having the ability to support the needs of my staff allows us to provide the services our people deserve. Furthermore, it enables us to provide our local emergency managers and leaders with information they need to make the hard decisions for our communities.

Throughout my journey I have met so many people, some briefly, and some that remain. Every single person has taught me something and contributed to the person I am now, and for that I am thankful. I give all the glory and honor to God, my family for their support and patience, and my Samoan people and culture.

Women in Meteorology

Women have always been nurturers. They have a calm way of relating any impending danger to their families and communities. In a region where women are the treasures within the communities and families, where their patience and skills of teaching are valued, women leaders within the Pacific can join the voices of existing and past Pacific leaders in preparing our island communities for any impending natural disaster so our islands may continue to be resilient.

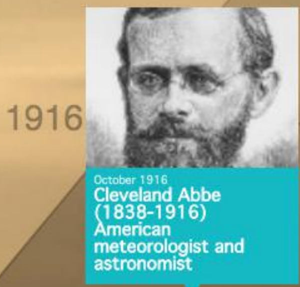
I am blessed to live in a Country with endless opportunities, and more blessed to be employed by the federal government that has policies in place to protect any individual from discrimination. Opportunities are numerous, and may be attainable with hard work and passion. I find scientific careers difficult to pursue, but the difficulties may be overcome by perseverance and the ability to utilize available resources and ask for guidance from those who have already succeeded in these fields.

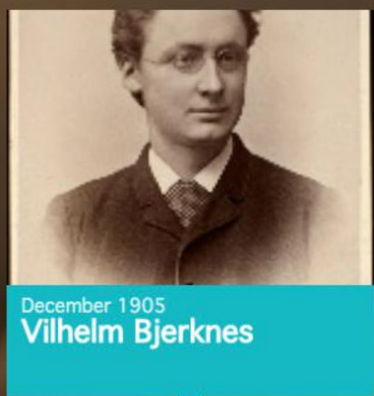
Women Leader

Every woman has her own journey through life. In the Pacific Island culture, we are raised to learn from those who came before us, to ask questions, listen, and serve in order to lead. Women are key in any family, village or community structure. To recognize the strengths they bring to complete any tasks, regardless of how small or big, is to recognize the various leaders that do exist within our communities. In the field of science, there are few women in leadership. It is why the acknowledgement of each and the role they continue to play in the success of their mission and service is important. Furthermore, the idea of a mentorship program that may inspire future women leaders in our region may also pave a path for an increase in women leaders in science.

Strong women leader are inspiring, flexible in the way they teach and encourage others. They recognize the strengths of individuals they lead, and are great listeners. They are humble but are also fearless to stand up for what is right to greatly benefit their community and country. They are selfless and have a heart of service, passionate and hard working.

WMO Chronology of Weather Science





Visit the multimedia WMO Chronology of Weather Science and fly through the history of weather research on the traces of the people and institutions that have supported the progress of Earth System Science!

World Meteorological Organization

7 bis, avenue de la Paix - Case postale 2300 - CH-1211 Geneva 2 - Switzerland
Tel.: +41 (0) 22 730 81 11 - Fax: +41 (0) 22 730 81 81
Email: wmo@wmo.int - Website: www.public.wmo.int

ISSN 0042-9767