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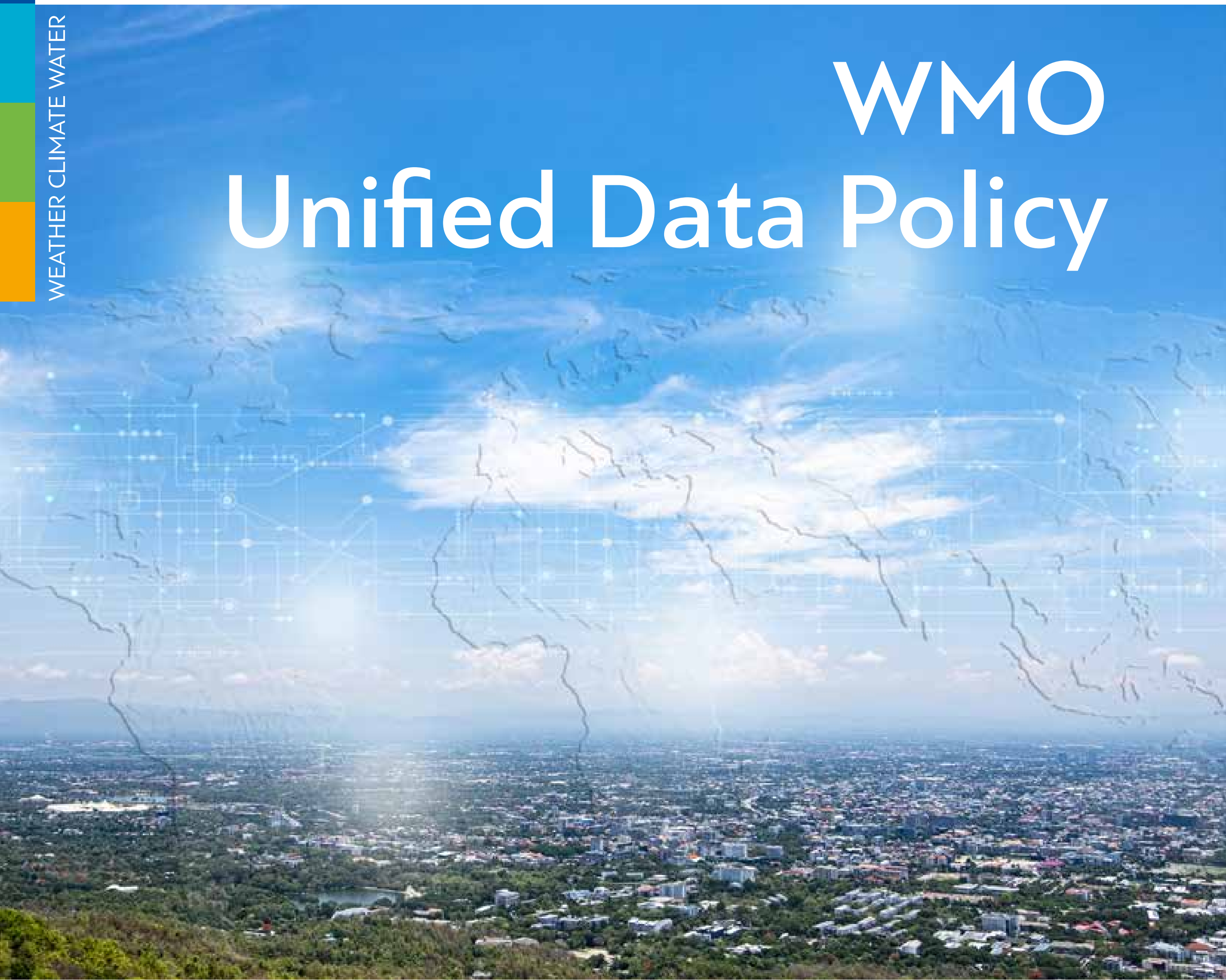

WEATHER CLIMATE WATER

WMO
Unified Data Policy

Modernizing Data Exchange for Earth System Monitoring and Prediction

The Furthest and Most Frigid Parts of the Globe

Space Weather, Extending the Borders Beyond the Earth

WMO Bulletin

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Foreword

Weather and climate are global in nature and all successful attempts to understand, monitor and predict them ultimately rely on international collaboration and the global exchange of observations and other data. Meteorology and some of its sister disciplines (notably oceanography) have traditions of international exchange of data and information extending back more than 200 years. As we continue to extend our prediction range and improve our understanding of the Earth's climate as an integrated system extending well beyond the atmosphere, it is becoming clear that the data exchange must be strengthened in other areas such as hydrology, atmospheric composition, cryosphere and space weather.

WMO data policy has been instrumental to the success of weather prediction and to climate monitoring and prediction. However, Resolution 40 (Congress-XI), arguably the most important of the WMO data policy resolutions, is now more than 25 years old and was drafted in a context far different from today's: the relationship between the research and operational communities is even more critical to both sides, satellite data are far more important than ever before, and the private sector is playing a much more central role in all parts of the meteorological value chain than it did in 1995. Likewise, Resolution 60 (Cg-17) predates the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), and the need for exchange of climate-related data has grown immeasurably in importance since it was adopted.

There is a clear need for WMO to update its data policy statements to ensure that its Members can continue to meet the ever growing demand for weather, climate and related environmental information and services. In keeping with its strategic focus on adopting an integrated Earth system approach to monitoring and prediction, WMO has chosen to update its policy statements under a single umbrella: the WMO Unified Data Policy, which encompasses data from all WMO-relevant Earth system discipline and domain areas. This will help WMO Members to improve their monitoring and prediction capabilities significantly and will help ensure that developing country WMO Members will reap the full benefits of the improved model products that will result from it.

WMO is putting forward three linked, strategic priority areas at the Extraordinary Session of the World Meteorological Congress in October 2021: The new Unified WMO Data Policy, the Global Basic Observing Network (GBON), aimed at securing the exchange of critically needed weather and climate observations, and the Systematic Observations Financing Facility (SOFF), which will provide technical and financial support for GBON where it is most needed.

This issue of the WMO Bulletin is dedicated entirely to international data exchange in Earth system monitoring and prediction and to the role of WMO data policy in establishing and maintaining this exchange. You will read about the history of data exchange, the current status and plans for data exchange in all major domains and discipline areas and about opportunities. The technical, political and financial challenges that some of our Members are facing with their implementation of data exchange are also addressed. The Bulletin includes a two-part article dedicated to the particular issues of data exchange with and from developing country WMO Members. The first presents the views of four Permanent Representatives on the current situation and the expected impact of the three initiatives mentioned above from their developing country perspective. The second presents the experiences, lessons learned and perspectives on the future from a series of development and climate finance partners.

Regarding observational data, most of the articles focus on issues related to the international exchange of surface-based observations. Satellite data, provided by the satellite agencies as members of the Coordination Group for Meteorological Satellites and the Committee on Earth Obsertion Satellites, continue to be vitally important for all WMO activity areas, and in several of them the importance of these data is growing rapidly. However, it would be difficult within the constraints of a single issue of the Bulletin to give fair treatment and proportionate visibility to both surface- and space-based observations. Reflecting the historical importance of the Congress decisions on the WMO Unified Data Policy and GBON, we have chosen to focus this particular issue of the Bulletin primarily on surface-based observations, and I promise that there will be future opportunities to highlight the current and future role of satellite data for WMO activities.

Prof. Petteri Taalas
Secretary-General
World Meteorological Organization

WMO Data Exchange – Background, history and impact

By Lars Peter Riishojgaard, WMO Secretariat, John Zillman (Australia), Former President of WMO (1995–2003), Adrian Simmons, European Centre for Medium-Range Weather Forecasts (ECMWF), and John Eyre, Met Office (UK)

While our everyday experience of weather is dominated by its local impact, weather and climate are truly global phenomena. It is often said that "Weather and Climate know no boundaries", and an observer will quickly realize that weather systems develop and move across the planet regardless of political boundaries. The implications of this basic fact on how we monitor weather, and how we attempt to understand and predict it, are profound.

The science and practice of meteorology are built on the realization that if we can describe the current state of the atmosphere and underlying surface and know the physical laws which govern their behaviour, we can, in principle, predict future weather and climate in ways that can contribute usefully to human safety and well-being. For nearly 200 years, we have been aware that, if we can observe the present state of the atmosphere over our national territory, we can predict our local weather with some skill for a few hours or maybe a day ahead. For nearly 100 years, we have known that, to predict the future weather for longer than a few days in any country, we must have access to atmospheric data from everywhere else on the globe. As the atmosphere has no geographic boundaries, it is only in its entirety that it can be comprehensively understood and, in our modern times, simulated mathematically. Modern weather or climate prediction is therefore undertaken through international coordination and a global infrastructure – without both of which it would be impossible.

As our understanding of meteorology and Earth system science grew through the eighteenth, nineteenth and twentieth centuries, so too did our awareness of the needs for all countries to access global data and reliable systems for the collection of the observations. The collection of that data started with the invention of the thermometer and the barometer in the seventeenth century and has continuously progressed technologically – leading to today's vital space-based solutions. The history of WMO data exchange is a remarkable story of scientific vision, technological development and service provision and, most of all, of a unique system of cooperation between institutions, scientific disciplines and national governments for the good of all.

History of data exchange

The history of international sharing of meteorological data goes back to the early nineteenth century foundations of Humboldtian science (Wulf 2015), the applications-oriented data exchange legacy of the 1853 Brussels Conference (Maury 1855) and the 1873 origins of the International Meteorological Organization (IMO), the predecessor of WMO. IMO built a highly effective international framework for enabling all countries to obtain the observations from other countries and from ships at sea for research and for the provision of weather and climate services to their national communities.

The need to strengthen and expand international data exchange for both research and practical application was central to the replacement of the non-governmental IMO by the intergovernmental WMO. Data exchange was identified as a central purpose of WMO in its 1947 Convention. The new WMO framework was reinforced over its first two decades through the special data collection systems that were put in place for the 1957 International Geophysical Year and then, more ambitiously, through the 1967 launch of the World Weather Watch (Davies, 1990) and the Global Atmospheric Research Programme (GARP).

The 1970s implementation of the World Weather Watch and GARP enabled the National Meteorological Services (NMSs) to greatly strengthen their data collection and exchange, research, modelling and forecasting. This allowed them to support a wide range of public and private meteorological services with extensive national economic and social benefits. However, with the 1980s trend towards the privatization of government services previously provided as a public good, pressures mounted in several countries to commercialize the public meteorological services of NMSs. This led to competition with the private sector, tensions between previously cooperating NMSs and fees for access to data that had been formerly freely exchanged for research.

The commercialization issue erupted across the international meteorological community through the late 1980s and early 1990s. Despite the best efforts of the WMO Executive Council, the 1995 World Meteorological Congress faced the prospect of a complete breakdown of international data exchange and a global meteorological data war (WMO, 2019). Delegations were divided between those who believed that, without free exchange of data, international meteorological cooperation would collapse and those who believed that data commercialization was desirable (or inevitable) and that a new international data regime must be found. After long and difficult negotiations, WMO Members reached consensus that the traditional policy and practice of "free and unrestricted international exchange of meteorological and related data and products" was too globally beneficial and too important to be put at risk. The Congress unanimously adopted Resolution 40, affirming the free exchange of "essential" data as a "fundamental principle" of WMO (Figure 1).

The implementation of Resolution 40 proved challenging for WMO and many individual countries, and it was soon realized that it did not fully cover many aspects of data exchange. This included several categories of the "additional" data needed for national weather forecasting as well as hydrological and oceanographic data and the many types of data needed for climate purposes. In due course, hydrological data exchange was addressed through Resolution 25 of the 1999 Congress, oceanographic data by the 2003 Assembly of the Intergovernmental Oceanographic Commission and climatological data through the subsequent WMO Resolution 60. But, while Resolution 40 restored and reinforced the global commitment to free and unrestricted international exchange of "meteorological and related data", it left the WMO community with a growing awareness of the need for a more robust and unified policy framework for international exchange of all Earth system data. The origins and early history of the WMO system of data exchange and the negotiation and impact of Resolution 40 are summarized in Zillman (2019, 2021) and WMO (2019).

Figure 1. Twelfth World Meteorological Congress, 1995 (from left to right): A.S. Zaitsev, Assistant Secretary-General, J.W. Zillman, First Vice-President, Zou Jingmemg, President, Prof. G.O.P. Obasi, Secretary-General, and M. Jarraud, Deputy Secretary-General (WMO/Bianco)

Emergence and expansion of global numerical weather prediction

The basic principles of Numerical Weather Prediction (NWP) were enunciated by Vilhelm Bjerknes (1904), who identified the need to apply dynamical-physical methods to the fundamental tasks of determining the initial state of the atmosphere and the evolution of the atmosphere from one state to another. His work had considerable influence on a remarkable study by Lewis Fry Richardson (1922), who set out in detail a comprehensive series of governing equations and a numerical process for their solution. Richardson's scheme was "complicated because the atmosphere is complicated", and well beyond practical application at the time.

The advent of electronic computers in the 1940s made it possible for the first time to solve a much simpler equation numerically (Charney et al., 1950) and, in due course to evolve solutions forward in time faster than the actual weather would develop – a prerequisite for the application of NWP in operational forecasting. Initially, the rate of progress was slow. It was not until the 1970s that NWP systems were able to outperform human forecasters consistently and convincingly.

Operational global NWP began on 18 September 1974, in the United States of America (US) (Dey, 1989). It was made possible by the international exchange of data from the ground-based observing systems of the World Weather Watch, and by the availability of data from US satellites: global soundings of temperature from polar orbits and regional winds estimated from tracking clouds viewed from geostationary orbits. It drew on the prior development of global atmospheric modelling and a method of analysing observational data to produce the starting conditions needed by the forecast model. Increased computer power was another enabling factor.

The European Centre for Medium-Range Weather Forecasts (ECMWF) was established in the 1970s in recognition of the potential benefits of a common computational resource and pooled scientific expertise. ECMWF became the second centre providing operational global forecasts on 1 August 1979. The Met Office in the UK and the US Navy followed in 1982. Today, WMO has nine designated Regional Specialized Meteorological Centres(RSMCs) for Global Deterministic NWP as part of its Global Data-Processing and Forecasting System (GDPFS). The GDPFS coordinates the preparation of meteorological analysis and forecast fields and makes them available worldwide. In recent decades, the RSMCs have considerably expanded the number and quality of products made available, enabling all who provide observational data to benefit from the analyses and forecasts that their observations support.

The global forecast products available from multiple sources and for multiple starting times have been important for indicating the uncertainty of forecasts and possible extreme conditions. Extensive probabilistic information from global ensemble forecasting systems have been added to them. These complement the single "deterministic" forecast with a set of generally lower resolution forecasts that are perturbed to account for uncertainties in the forecast model's starting conditions and physical processes. Ensemble forecasting was first introduced operationally in Europe and the US in December 1992. Eight of the nine RSMCs for Global Deterministic NWP are also designated as RSMCs for Global Ensemble NWP.

The limited-area NWP systems operated by many countries also benefit from global data exchange. Although these systems only require observational data over the domains they cover, specified values at domain boundaries are needed for the duration of the forecast. These boundary values are typically provided by global systems.

Evolution of the global observing system

Observing systems have evolved considerably over the past 75 years or so. Upper-air measurements from the radiosonde network, developed in the 1940s and 1950s, were a crucial addition to the established surface observations from land stations and ships. Observations from aircraft became available in significant numbers in the 1970s, and deployment of substantial numbers of drifting ocean buoys began in 1979. Many of these types of observation have subsequently improved in quality due to better instrumentation and are today available in much greater quantity, due largely to increased automation and the willingness and capacity of WMO Members to transmit them globally.

The first satellite images of weather patterns were obtained in the 1960s, but the key developments in satellite observations for NWP came in the 1970s. Operational measurement of temperature- and humidity-sensitive radiances began in late 1972. An enhancement of radiance measurements from polar orbit and wind estimates from geostationary orbit came later in the decade. Better orbital coverage, from an increasing number of operators, better instruments and more types of measurement have followed decade by decade since then. Today, data from around 90 satellite instruments are processed by the atmospheric component of the ECMWF forecasting system.

Moreover, both in situ and space-based measurements are now being used routinely to determine starting conditions for the oceanic models that are being coupled with atmospheric models for prediction across an increasing range of timescales. Greater sophistication of the representations in forecast models of land surfaces, including hydrological aspects, and of atmospheric composition broaden further the needs for observational data and their international exchange, but also provide opportunities for exchange of a broader set of derived data products.

Uses of observations and the improvement of forecasts

Many observations are used and re-used numerous times. Forecasting centres use observations to initialize several types of forecast, to evaluate forecast quality, to calibrate products and to develop and test improvements to forecasting systems. This involves both direct use and the use of analyses or reanalyses based on them.

Figure 2 shows the improvement over time of ECMWF forecasts for three, five and seven days ahead. The upper panel refines and updates a figure first published by Simmons and Hollingsworth (2002). It shows that operational forecasts over the southern hemisphere were substantially poorer on average than those over the northern hemisphere until the early 1980s, that there then followed a period of 20 years during which improvement was greater in the southern hemisphere and that since the 2000s improvement has gone hand-in-hand for the two hemispheres.

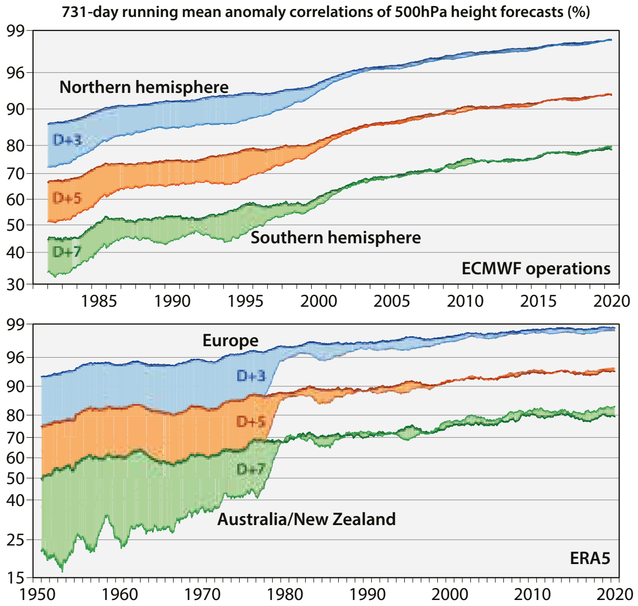

Figure 2. Variation over time of measures of the accuracy of ECMWF forecasts at ranges of three, five and seven days ahead. Upper: 731-day running means of anomaly correlations of 500hPa forecasts for the extratropical northern and southern hemispheres for the operational forecasts made from 1 January 1981 to 30 June 2021. Lower: Corresponding values for regions encompassing Europe and Australia/New Zealand, from forecasts made in hindsight twice daily from the ERA5 reanalyses from 1 January 1950 to 30 June 2021. The ERA5 results are shown for two regions where the availability of radiosonde data makes verifying analyses (also taken from ERA5) more reliable than those for the whole hemispheres in the years before satellite data became available.

The lower panel shows performance from 1950 for forecasts made from ERA5 reanalyses (Hersbach et al., 2020, for more on reanalysis see Article 5). Results are presented for Europe and Australia/New Zealand in this case as the availability of radiosonde data makes the verifying analyses (also taken from ERA5) more reliable for these regions than they are for the hemispheres as a whole, especially in the pre-satellite period. The lower panel shows that the ERA5 forecasts over the two regions were largely similar in quality from 1979 onwards. Nevertheless, there was a fairly steady improvement in the ERA5 forecasts from 1979 onward due to the increased availability and quality of observational data. Better use of observational data and better modelling were the main reasons for the operational improvements of the 1980s and 1990s. There was a little more gain in the southern than the northern hemisphere for a spell around 2000, suggesting greater impact of the new satellite-borne instruments introduced at that time.

The very large improvement in ERA5 forecasts for Australia and New Zealand around 1979 was due to the developments of both space-based and in situ observing systems made for GARP's 1979 Global Weather Experiment, and sustained thereafter. Improvement due to observing system changes in the 1960s and 1970s is also evident for this region. The pre-1979 forecasts for Europe were generally closer in quality to those for later years, but there was improvement in the 1950s, when the expansion of radiosonde coverage included completion of the networks of ocean weather ships, and in the 1970s, when the first operational soundings from space were followed by the observing-system enhancements made as part of GARP.

Forecasting for the tropics poses more difficulties than for the extra-tropics. The approximations used in NWP were developed for mid-latitude weather and some of them are questionable in the tropics. In addition, phenomena that occur on spatial scales smaller than those that can be resolved by the model play a much more significant role in the tropics than they do in temperate latitudes. The observational data coverage, especially for in situ upper air observations, is poor in most areas of the tropics, especially in developing countries. The lack of upper air observations is a serious problem – the relatively few radiosonde observations that are available in the tropics have disproportionally large impacts on NWP skill, indicating that the system is under-nourished with these data. The lack of surface observations severely limits the ability to verify the quality of the actual weather forecast, as distinct from skill of the NWP output.

Nevertheless, there are success stories. Chief among these is the improvement of tropical cyclone forecasts and the efficacy of the resultant actions taken to protect lives and limit material damage. The official forecasts of the US National Hurricane Center, for example, routinely draw on the products made available by five global weather forecasting centres (three of them non-US) and three regional systems. The improvement over the past thirty years in track forecasts for the Atlantic Basin (Figure 3) has been considerable. There have also been distinct, though more modest, improvements over the same period in forecasts of intensity.

Observations for climate analysis and the implementation of GCOS

The observations used for NWP are also used for monitoring, understanding, modelling and predicting climate. In general, climate applications require more comprehensive observations of the Earth system and there is a wide variety of institutional arrangements for making and processing these observations. The

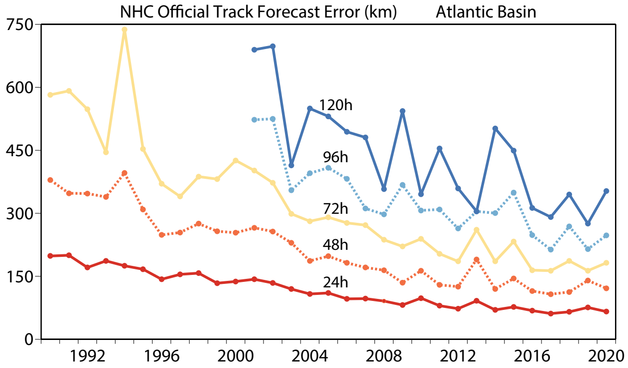

Figure 3. Annual average position error (km) in official US National Hurricane Center forecasts for the Atlantic Basin, from 1990 to 2020 (Adapted from Cangialosi, 2021).

integrated Global Climate Observing System (GCOS) was formally established in 1992 as an international, interagency, interdisciplinary framework with the goal of ensuring the availability of comprehensive information on the entire climate system (Houghton et al., 2012). GCOS has identified a set of Essential Climate Variables (ECVs; Bojinski et al., 2014) that are needed for the characterization of the climate system and its changes and whose observation is technically feasible and affordable, mainly relying on coordinated observing systems using proven technology. Thus, they can take advantage where possible of historical datasets. GCOS has also regularly assessed the status of global climate observations and the needs for implementation, reporting to WMO and its other sponsors[1], and to the Parties to the United Nations Framework Convention on Climate Change.

International exchange of data for climate applications is needed both for historical and current observations. Various factors may mean that some of the latest observational data and products are available only with a delay. Such is the case for the monthly climatological data reports (CLIMATs) from observing stations that are important for extending the record of temperature change since the nineteenth century. Nevertheless, the timely meteorological and related data for weather forecasting are also used within a few days at most in the extensions of multi-purpose reanalyses. These reanalyses provide, for example, prompt updates of the temperature data record built from monthly station data (and observations of sea temperatures) for earlier decades (Figure 4). In addition to providing a much more comprehensive set of monthly records of variability and change, the reanalyses complement daily station data in identifying and characterizing the extreme events for which there is a strong and urgent demand for public information, not least concerning the role of climate change. The exchange of data products from reanalysis (see Article 5) has become more open over the years since the activity began in the 1990s, providing further benefit to those who provide the observational data on which the products are based.

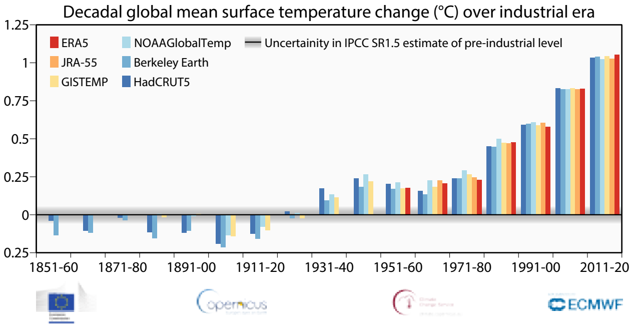

Figure 4. Decadal-averages of global-mean surface temperature estimates from six datasets, expressed as a change over the industrial era. Two datasets (ERA5 and JRA-55) use analysis of synoptic surface air temperature data; the other four use analysis of monthly average station data. See https://climate.copernicus.eu/copernicus-2020-warmest-year-record-europe-globally-2020-ties-2016-warmest-year-recorded *for details.*

Design of observing networks

Starting in 1995, WMO established the process for Rolling Review of Requirements (RRR) for observations:

- Requirements for observations are assessed for each of (currently) 14 application areas spanning the full spectrum of WMO activities.
- The capabilities of present and planned surface-based and spaced-based observing systems are also assessed.
- Requirements and capabilities are compared, and current or projected gaps in capabilities are identified.
- Based on this gap analysis, a vision for the future observing system is developed, together with a plan of actions to implement the vision.

The RRR process draws heavily on the experience of both applications experts and technology experts.

From the outset, the RRR process has sought to engage all the application areas covered by WMO programmes, but progress has been more rapid in some areas than in others. Close links to GCOS ensured that the requirements of climate monitoring has always been well represented. However, the main

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[1] The Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme and the International Science Council

application area driving the RRR process from the beginning has been global NWP. The NWP community was already well coordinated, and its requirements for observations were fairly well understood. Since the 1990s this community has been effective in articulating its requirements for a rapidly expanding range of satellite data, initially through coordination between the NWP centres of Europe and North America, and the respective space agencies. This evolved into a coordination between all the major global NWP centres and space agencies, under the umbrella of the Global Observation Data Exchange (GODEX) forum with the involvement of the WMO Secretariat.

Coordination on the exchange of surface-based observations has proven to be more difficult. This is partly due to the large number of entities involved – 193 WMO Members, as opposed to a small number of space agencies – and partly due to the absence of a strong and well-organized lobby behind these observing systems. In many parts of the world, especially in developing countries, the observational data coverage has decreased over the last 20 years, even though the requirements for these data remain very strongly supported. In large part triggered by the RRR, the WMO is now taking action through its implementation of the Global Basic Observing network (GBON), in which the surface-based observing network needed to support global NWP and climate reanalysis is designed and defined at the global level. The GBON regulations will include quantitative targets for variables measured and for minimum temporal and spatial resolution, and international exchange will be mandatory.

Much of the drive for improvements in the observing networks and data exchange has come from the global NWP community. However, this has not necessarily meant that the other application areas have been overlooked or poorly served with observations. The output from global NWP systems is directly used to drive many of the other application areas, which thus inherit some of their observational data requirements from NWP.

Historically, separate observing networks were developed to serve different communities and applications, using different standards, formats and communications mechanisms, even though many of the geophysical variables being measured were the same. In principle it was possible to use the observations made by one community to serve another, but in practice this was often difficult, time-consuming and expensive. In order to eliminate the perceived redundancy between such networks and facilitate a joint use of the assets, WMO developed the concept for a WMO Integrated Global Observing System (WIGOS), which was launched in 2011 and declared operational in 2019. The draft data policy resolution submitted to the Extraordinary Congress in 2021 is in large part driven by the need to facilitate the further development of WIGOS and thus support a truly integrated Earth system approach to monitoring and predicting the environment (see Article 2).

Conclusions

Nearly 60 years of data exchange through the WMO World Weather Watch have shown the immense power and benefits of global collaboration in understanding, predicting and responding to the diverse phenomena of weather and climate. Over this time, weather forecasting has progressed from being a niche area of value mainly to mariners, aviators, farmers and outdoor enthusiasts to becoming accepted as a community necessity and right for nearly all sectors of the economy, used in the everyday lives of nearly all people on the planet. Many of the practices originating in meteorology have found their way into adjacent discipline areas, and many of these are working closely together with the meteorological community. WMO is updating its data policy to respond to these developments, and the driving forces behind the update and its expected impact will be further illustrated in the remainder of this issue.

References online

WMO Data Policy for the 21st Century

By Gerhard Adrian, President of WMO, Michel Jean, President, WMO Commission for Observation, Infrastructure and Information Systems (INFCOM) and Associate Emeritus, Meteorological Service of Canada, Environment and Climate Change Canada, Sue Barrell, Chair, INFCOM Study Group on Data Issues and Policies, and Lars Peter Riishojgaard, WMO Secretariat

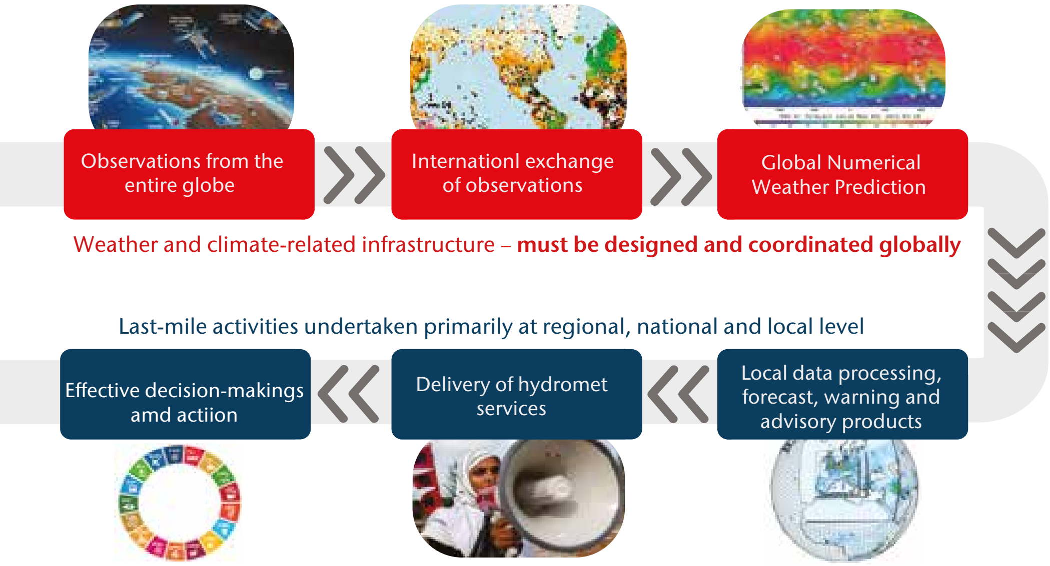

Figure 1. The weather and climate services value chain. All links in the chain must operate effectively to yield success.

The meteorological value chain and the roles of WMO and its Members

The ultimate goal of the activities coordinated through WMO is to enable the citizens and economies of all WMO Members to benefit from weather, climate and related environmental services. This is accomplished via the meteorological value chain[1] (see Figure 1), which starts with observations, our basic source of knowledge about the atmosphere and the climate system, and ends with effective decision-making based on the services they enable. The value chain can be schematically described as follows:

- Weather and climate observations are routinely made all over the globe.
- Those observations are exchanged internationally, including with global Numerical Weather Prediction (NWP) Centres.
- Global NWP output, monitoring and prediction data for weather and climate are generated and shared with all WMO Members (193 States and Territories).
- Global NWP output is used by National Meteorological and Hydrological Services (NMHSs) and other entities as a basis for weather and climate information.
- Weather and climate information services are delivered to users, including national and local authorities, businesses, media, academia and the general public.
- Effective decisions in response to weather and climate information are made by authorities, agents in all economic sectors and individuals.

The first three links in the value chain (shown in red) constitute the meteorological infrastructure, which must be implemented and coordinated globally as explained in the first article in this issue. The last three links (in blue) are typically implemented nationally, and in some cases with significant regional elements or partly locally in large countries. Government

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[1] The meteorological value chain covers weather, climate, atmospheric composition and several related disciplines, which depend on global exchange of data.

entities typically play significant roles in all links in the chain.

It is a commonly held view that the most important role of a national government is to protect its people. Hence, within WMO's sphere of activity, the aim of governments and their NMHSs is to maximize the societal benefits of meteorological, hydrological and climatological information, in particular its use to help save lives, protect property and foster economic prosperity.

As discussed in the first article, the global nature of weather and climate makes international data exchange an essential prerequisite to any attempt to monitor, understand and predict their manifestations. This has been recognized for over 200 years, and meteorology therefore has a history of international collaboration on exchange of observations and other types of information that goes back to the invention of the telegraph in the first half of the nineteenth century.

The establishment of the International Meteorological Organization (IMO) and later of WMO was grounded on this recognition. The preamble of the WMO Convention reaffirms the point: "the vital importance of the mission of the National Meteorological, Hydrometeorological and Hydrological Services in observing and understanding weather and climate and in providing meteorological, hydrological and related services in support of relevant national needs which should include the following areas: (a) Protection of life and property, (b) Safeguarding the environment, (c) Contributing to sustainable development…."

The WMO Convention thus acknowledges that for most disasters that result from meteorological and associated hydrological phenomena, impacts can be mitigated by increasing the capability of Members to prepare for and respond to such events, and there is a need for international collaboration in order to do so.

WMO data policy and the current drivers of change

One of the primary roles of WMO is to facilitate and coordinate the international data exchange needed to support service delivery. The role of its data policy is to articulate the principles of this exchange and the practices that support its implementation: which types of data will be exchanged, by whom and with whom will they be exchanged, for which purposes, and under which conditions?

While the need for international data exchange is clear and nearly universally understood by the WMO Members, it is not necessarily easy to formulate a policy that is both useable by and acceptable to all Members. Within the common aim of national governments to provide weather and climate services to their citizens, there is a broad spectrum of different national implementations, with different assignments of responsibilities to the various actors. There is, for instance, no universal, common understanding of the role of public versus private sectors. There is no universal agreement on which services must be provided by government institutions free-of-charge, versus the role of fee-based services, which may be provided either by private entities or by governmental institutions acting as private entities. An effective data policy must provide enough clarity to allow Members to generate products and deliver services to their constituencies. At the same time, it must remain sufficiently broad and non-prescriptive to accommodate these different national policies and national implementations of the meteorological value chain.

Over the years, the WMO data policy has had to evolve to accommodate new requirements, new application areas, new technologies and shifting political and economic realities. The data policy continues to evolve in the twenty-first century, with a major update being put forth for deliberation by the Extraordinary Session of the World Meteorological Congress in October 2021. There are several major drivers behind this new development, and some of the most important will be listed in the following paragraphs.

First, the phenomenal progress and successful application of weather and climate monitoring and prediction outlined in the first article has led to an explosive growth in demand for weather, climate and related Earth system information from all sectors of society. This has led to an increased recognition of the economic value of all types of Earth system data, which in turn has led to an increasingly diverse group of stakeholders active in the generation and use of these data. Furthermore, in spite of our steadily advancing technological capability, it can be argued that our vulnerability to the adverse impacts of weather is increasing in many areas. More people than ever before in history live in high-risk zones such as low-lying, exposed coastal areas and flood plains. Megacities have their own vulnerability to high-impact weather related to the importance of maintaining critical infrastructures operating in all situations and the difficulties related to potential evacuations. Additionally, ongoing climate change is already now modifying the frequency of high-impact weather phenomena. Improved monitoring and prediction capabilities are needed not just to manage the impact of current weather events, but also to help society understand and adapt to the weather we may expect to see in the future.

Second, the ever-increasing demand for Earth system data and the steady advance of technology, spanning observations, telecommunication and data processing, has led to an enormous increase in the volume of available Earth system data. Developments in ground and space-based remote sensing technology and in the processing speed and memory size of the computers used for meteorological modelling necessitate the adoption of new approaches to data distribution and data access. Older solutions, such as the Global Telecommunication System (GTS), can no longer adequately support the data exchange and must be replaced with internet- and cloud technologies. The WMO Information System (WIS) provides required standards for data formats and meta data (see Article 4).

Third, in recent years many countries, especially the developed, have been moving toward making all publicly funded data generally available as "open data". Data providers, such as NMHSs, are faced with increasing demand for open access to any data they generate. The European Union spear-headed such an approach with its directive "on open data and the re-use of public sector information" (directive 2019/1024), which its member states are obliged to implement in their national laws. The socioeconomic rationale behind this directive is laid out clearly in its preamble (par. 9 and 16): "Documents produced by public sector bodies of the executive, legislature or judiciary constitute a vast, diverse and valuable pool of resources that can benefit society. Providing that information, which includes dynamic data, in a commonly used electronic format allows citizens and legal entities to find new ways to use them and create new, innovative products and services..."

Fourth, there has been a steady expansion of meteorological observing and modelling practices into adjacent application areas such as environmental monitoring, and the quest for extending both the accuracy and the predicted range of various weather, climate and hydrological phenomena. This has made it clear that an integrated Earth system approach is needed. In order to succeed, this approach must encompass observing network design, making and exchanging observations, integrated Earth system modelling and the subsequent exchange of the resulting model data.

After a thorough analysis of these drivers and their implications, WMO has decided that adopting a single overarching policy statement that lays out the scope of the data exchange required for the twenty-first century clearly and unambiguously would be the best way to respond and to help the world of meteorology to further progress.

Societal context and external developments – As stated earlier, in recent years a diverse group of stakeholders have been joining the NMHSs as active or potential participants in the data exchange. These include non-NMHS government agencies, non-profit organizations and various entities from the private sector and academia. This diversity is highly desirable and, if managed properly, will help achieve the breadth of data exchange that is needed for the implementation of the Earth system approach just described. In order to harness the value that such a broad and diverse participation will provide, a WMO data policy must be able to accommodate this diversity in its formulation and implementation.

In acknowledgement of these opportunities, the 18th session of the World Meteorological Congress adopted the Geneva Declaration

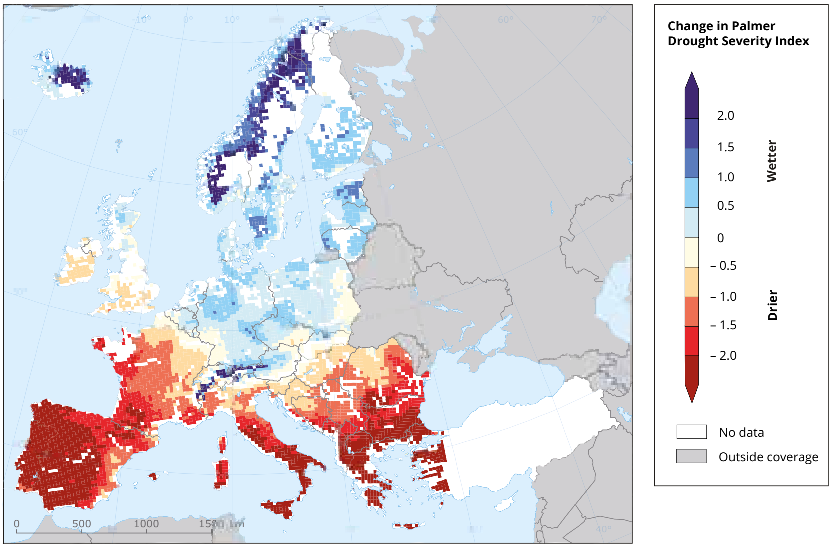

Figure 2. Projected changes in summer soil moisture. Changes are presented as mean multi-model change between 1961–1990 and 2021–2050 using 12 Regional Climate Models (RCMs); with red indicating drier and blue indicating wetter conditions. (Source: European Environmental Agency (CC BY 2.5 DK))

2019: Building Community for Weather, Climate and Water Actions, and agreed to convene a High-Level Open Consultative Dialogue on Partnership and Innovation for the Next Generation of Weather and Climate Intelligence.

The new WMO Unified Data Policy has been developed against the backdrop provided by the Geneva Declaration. Representatives from public, private and academic sectors have participated actively in its drafting. The policy aims to provide win-win opportunities by facilitating broad participation in the free and unrestricted exchange of meteorological and related Earth system data. Through specific language on the practice of the policy and its use of precise definitions, it provides clarity for all parties regarding the expectations placed on them and the benefits they can reap. Broad consultation, involving all participants in the data exchange, will remain a key element of the regular reviews of the policy and practice, with the intention to ensure that the policy stays current and responds to the evolving context.

Key strategic initiatives taken around the world, both in the private and government domains, already illustrate some of the trends mentioned above. A common thread is the involvement of multi-player consortia where all parties benefit from substantial investments in collaborative infrastructures. Some examples of such initiatives, that have either helped inform the development of the new WMO data policy and/or will benefit from its implementation by the WMO Members, are highlighted below.

Copernicus – Via its Copernicus programme, the European Commission (EC) on behalf of its member states is investing in consolidating data integration and modelling platforms to better leverage and maximize the use of existing capabilities and to build on its critical mass of expertise. The Copernicus programme's mission is to exploit Earth observations and numerical predictions to generate value added information covering all components of the environment for the benefit of policymakers, researchers, commercial and private users as well as the global scientific community. Copernicus covers six main service areas, of which one is focused on climate change and its cumulative impacts (see Article 5). The programme is implemented in partnership with European Union member states, the European Space Agency (ESA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF) and various other EU Agencies as well as Mercator Ocean.

Microsoft Earth – In December 2017, Microsoft announced a US$ 50 million investment in their "AI for Earth program" to develop artificial intelligence technology to better understand and address the environmental issues facing the planet. As they put it: "Fundamentally, AI can accelerate our ability to observe environmental systems and how they are changing at a global scale, convert the data into useful information and apply that information to take concrete steps to better manage our natural resources." AI for Earth aims to provide better access to computing and AI tools. It lowers the barriers for entry for smaller organizations that cannot afford the IT infrastructure investment and creates a community of contributors that will advance AI solutions that are innovative and scalable.

In parallel, Microsoft and other cloud providers are connecting government databases to their proprietary cloud infrastructure to increase the data offering that they make available to their clients.

IBM Environmental Intelligence Suite: Geospatial Analytics – The IBM Environmental Intelligence Suite: Geospatial Analytics is a platform specifically designed for massive geospatial-temporal data (maps, satellite, weather, drone, Internet of Things), query and analytics services from a continually updated geospatial-temporal information database that includes satellite weather and climate information. It makes various transformations to make both historical and real-time datasets easier to use, then enables rapid data discovery. Simultaneously, the Geospatial Analytics is a computational platform for running physical and statistical models on the curated datasets. It aims to support the development of applications including AI and other types of data analytics.

WMO Unified Data Policy on the International Exchange of Earth System Data and its expected impact – Compared to the three existing WMO data policy resolutions it is intended to replace, the new WMO Unified Data Policy will provide a more comprehensive, more flexible and more easily implementable approach to data exchange.

The current (September 2021) WMO data policy is laid out in three separate Congress resolutions, each covering a specific domain: Resolution 40 (Cg-XII, weather), Resolution 25 (Cg-XIII, water) and Resolution 60 (Cg-17 climate). In contrast, the WMO Unified Data Policy resolution covers seven disciplines and domains – together encompassing all WMO Earth system data – in a single policy resolution. Additionally, the new policy expands – from addressing only the exchange between

NMHSs – to encompass Members as a whole, and thereby all entities participating in the exchange, including the private sector and academia.

Similar to Resolution 40[2], the new resolution distinguishes between "core data", for which data exchange is considered mandatory, and "recommended data", for which the exchange is strongly recommended. However, in contrast to Resolution 40, the new resolution takes a modular approach to the specification of what, exactly, will be included in these two categories. Specific details on what is considered "core data" and "recommended data" are – or in some cases will be – provided in the WMO technical regulations. New developments can thus be accommodated via amendments there, rather than requiring an update of the policy resolution itself. This makes the implementation far easier to maintain and update than is currently the case.

In terms of its expected impact, the proposed data policy update will stimulate and strengthen the international exchange of observations from all parts of the globe. Increasing the number of observations that are shared internationally for use in global and regional NWP models will help significantly improve the quality of the resulting output. This improvement will be felt everywhere on the globe, but it will be especially pronounced in areas where the current observational data coverage is poor, which is the case in many developing countries. In return, the data policy will help provide free and unrestricted access to a much broader range of Earth system model data products for all Members, which will help them improve and broaden the range of the services provided to their constituencies.

Access to additional data, beyond the traditional realm of meteorological observations, will be critical to the continued development and implementation of the coupled modelling systems used in the integrated Earth system approach. Over the coming decades, these systems, spanning time scales from short-range weather prediction to long-term climate prediction and projection, will need to resolve features at higher and higher resolutions and to incorporate detailed land-surface characteristics that capture the level of location-specific detail required by users. The Earth system, as defined by WMO's activities, is likely to further expand beyond its current scope. We may thus see the arrival of coupled bio-geo-chemical systems in support of primary production, bloom prediction, carbon intake, management of fisheries, etc. The following paragraphs list examples of recent or emerging application areas that are built on various levels of integrated Earth system approaches. These are areas that will benefit from the Unified Data Policy and further influence its future development via regularly recurring reviews.

Marine: State-of-the-art marine navigation safety system: Various countries are working toward getting better navigational information into the hands of mariners. These countries are committed to developing robust operationalization using dynamic ocean model solutions to provide planned E-navigational and hydrographic solutions for mariners and navigators. Such joint national endeavours between meteorological, oceanographic and hydrographic services are aimed at delivering operational solutions through seamless modelling capabilities. This approach will enable safe and efficient operations of commercial shipping and marine transportation sectors by promoting an ecosystem approach to management of human activities.

Security and Emergency: In the area of Nuclear Event Characterization, there is a need to improve real-time data exchange, computational capacity, machine-learning and artificial intelligence related to ensemble analysis of weather data as well as other data types. This will require further improvements in the accuracy of weather prediction and atmospheric transport modelling, and in the characterization of associated uncertainties. Additional work is also needed to further develop and integrate atmospheric chemistry modelling into atmospheric transport modelling. These upgrades will improve global capacity for nuclear event identification, source term reconstruction and predictive modelling of radiological or other man-made release health outcomes.

Climate Change: Bringing science innovations to address health implications of air pollution and climate change. Research has shown that multiple data sources can be incorporated into air quality models to improve their detail and accuracy. The explosion of data capture and analytical methods can expand the range of model inputs. At the same time, deep learning and other methodologies have the potential to improve the understanding of underlying relationships and to improve predictive capacity, both for daily forecasting and for long-term predictions. Expanded modelling capacity will be used to strengthen the science that underpins regulatory decision-making and to track the health benefits from market-based instruments such as

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[2] The term "core data" replaces "essential data" used in Resolution 40, and likewise "recommended data" replaces the Resolution 40 term "additional data".

carbon pricing. Tools will be developed to support local public health officials to anticipate and address environmental challenges.

Land and Resource Development: Supporting sustainable land and resource development with analysis ready data. Markets depend on sustainable land and resource development. There is a continuing need to monitor and assess dynamic changes on local, regional and global terrestrial landscape. The ecosystem approach to environmental management focuses on maintaining the capacity of a whole system to produce ecological goods and services. This starts with monitoring and management of, for example, water resources, air and water quality and genetic resources, which maintain the global economy, security, health and well-being. A strong foundation of data and computing infrastructure is required to take an ecosystem approach to enabling advances in assessing the status and trends of Earth's changing landscape. This emerging capability will facilitate cumulative impacts analysis which will provide specific services as well as intelligence for environmental regulations and policy development.

Agriculture: Timely information on weather and climate to monitor drought and manage agroclimate risk. Some countries have implemented drought watch programmes that use a variety of Earth observations and other data to provide timely information and maps on weather and climate parameters that are particularly relevant to their national agricultural sectors. Resource and environmental agriculture require various meteorological and hydrometeorological services depending on the specific crop, its growth phase or the type and current state of the soil. Tillage, irrigation, seed, harvest or efficient application of fertilizers and pesticides with the constraint of ground water protection depend very much on weather. Soil moisture maps are one example of a product created using geophysical data. Such products allow farmers to see where conditions are wetter or drier than normal, enabling resilience in the face of a changing climate.

Health: Earth observation sciences and emerging and re-emerging infectious diseases. Infectious diseases emerge and re-emerge under the influence of key drivers such as the environment, climate, demographics, and socio-economic and human behavioural changes. These are a challenge public health locally and globally. By broadening the exchange of environmental observations and understanding how these drivers affect disease occurrence, officials can predict when, how and where disease will emerge as well as identify the populations at risk and those most vulnerable. Climate change is expected to exacerbate risks from vector-borne disease (VBD) by permitting the spread of animal hosts, pathogens, vectors and VBDs, the establishment of exotic vectors and the diseases they transmit (dengue, Zika, chikungunya, yellow fever) beyond their historical domains. Climate change is also expected to increase the re-emergence (i.e. outbreaks) of VBDs already endemic in countries or sub-continental regions.

The continuous improvements in weather, climate and related Earth System monitoring and prediction services that the world has witnessed over the past 70 years are linked to better science, better technologies and to the real-time exchange of more varied sources of observations. We live in a time of increasingly sophisticated technologies, and the pace of innovation is accelerating. We are flooded with Earth observations. Social media is providing access to contextual information and unprecedented dissemination mechanisms. High-performance computing platforms are allowing us to tackle previously unsolvable problems.

It is only a matter of time before the fusion of weather, water and climate data, big data technologies and business applications go mainstream. This will change the way people and businesses view weather and water data – and experience its force-multiplying effects on improving life and weather sensitive business decisions. These developments are likely to lead many WMO Members to reevaluate their data policies and their partnership strategies at the national level, and they will have a profound impact on the global meteorological enterprise. The new WMO Unified Data Policy is intended to help Members to adapt to these changes and to continue to provide their constituencies with the best possible services in all WMO's disciplines and domain areas also in the future.

WMO Data Initiative and the Broader [UN] Data Agenda

By Michel Jean, President, WMO Commission for Observation, Infrastructure and Information Systems (INFCOM) and Associate Emeritus, Meteorological Service of Canada, Environment and Climate Change Canada, Sue Barrell, Chair, INFCOM Study Group on Data Issues and Policies and Anthony Rea, WMO Secretariat

WMO has been a leader in the facilitation of global data exchange and exploitation since its inception. Data exchange is at the heart of the WMO Convention, defining the core mission and purpose of the organization. The free and open exchange of meteorological observations dates back to 1873 with the creation the International Meteorological Organization, the predecessor to WMO (see Article 1). But in today's fast-changing world, WMO's head start on data exchange is at risk of being lost and a shift in its approach is urgently needed to ensure its Members are not left behind.

In the last few decades, the rest of the world has realized the value of data, creating a groundswell of enthusiasm across all sectors of endeavor for the gathering, analysis and, often, monetization of data. WMO meanwhile has continued to work with its Members to facilitate and grow the amount of data available to the international community – but not, it must be said, at the same pace as the rest of the world.

Data issues have also arisen among Members. Some NMHSs – facing financial difficulties or recognizing the value placed on meteorological and climate data – have joined the move to monetize their data and outputs, selling derived products and in some cases the observations themselves. This can be a source of tensions among Members in an Organization that is built on the free and unrestricted exchange of data. The authors would argue that the real value of Members data is the downstream economic value that is created through analysis and prediction products, and impact-based services to assist decision-makers. Making data available, from the perspective of a government, increases the downstream societal and economic value generated. A good example is the opening of the Landsat archive by the US Government which in 2011 generated an estimated US $1.7 billion in economic benefit for US users alone[1].

Today, the global focus on data provides a number of opportunities to WMO and its Members. The data landscape has opened up through rapid technological development and the societal and economic benefits of open data arrangements have been recognized. This article explores this change in terms of the WMO relationship with global technology players and the potential implications for WMO Members. It also looks at the new WMO Unified Data Policy in the context of the global data agenda and the UN Secretary-General's Data Strategy.

WMO Data Policy and UN Secretary-General's Data Strategy

As a specialized agency, WMO is part of the United Nations (UN) family, which also deals with the global data agenda. The UN Secretary-General is leading the way at the highest level in setting a strategy framework for better use of data, following approaches that are fully grounded in UN values such as human rights. The UN Secretary-General's Data Strategy 2020–2022[2] is a "*strategy for data action by everyone, everywhere in the UN family – for insight, impact and integrity*." It is the UN's agenda for a data-driven transformation, focused on building the data, digital, technology and innovation capabilities that the UN needs to succeed in the 21st century. Data permeates all aspects of work undertaken within the UN system. The power of data, harnessed responsibly, is critical to the global agendas it serves. The UN Data Strategy seeks to capitalize on the UN family's footprint, expertise and connectedness to create unique opportunities to advance global "data action" with insight, impact and integrity.

Starting with a vision of the data-driven organization, the strategy is built on three core pillars:

1. *Setting strategic foundations* – In building a whole-of-UN data ecosystem that maximizes

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[1] Zhe Zhu et al, Benefits of the free and open Landsat data policy, Remote Sensing of Environment, Volume 224, 2019, Pages 382-385, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2019.02.016.

[2] UN Secretary-General's Data Strategy 2020-22

the value of data, the UN is striving to unlock its full potential. It seeks to make better decisions and deliver stronger support to people and the planet – in the moments that matter most.

2. *Create value with data and focus on priorities* – This pillar is based on delivering use cases that demonstrate the value added for stakeholders in accordance with UN priorities, which include the Sustainable Development Goals (SDGs), Climate Action and Gender Equality – all of relevance to WMO.
3. *Foster enablers, nurture capabilities and iterate* – This involves adopting a learning-by-doing approach to foster stronger enablers (people and culture, data governance and strategy oversight, partnerships, technology environments) and to build new capabilities in an iterative and agile fashion. There will be special focus on analytics (what happened, why it happened, what may happen next, and how to respond) and data management (to ensure everyone can discover, access, integrate and share the data needed to fulfill our responsibilities to the organization, people and planet).

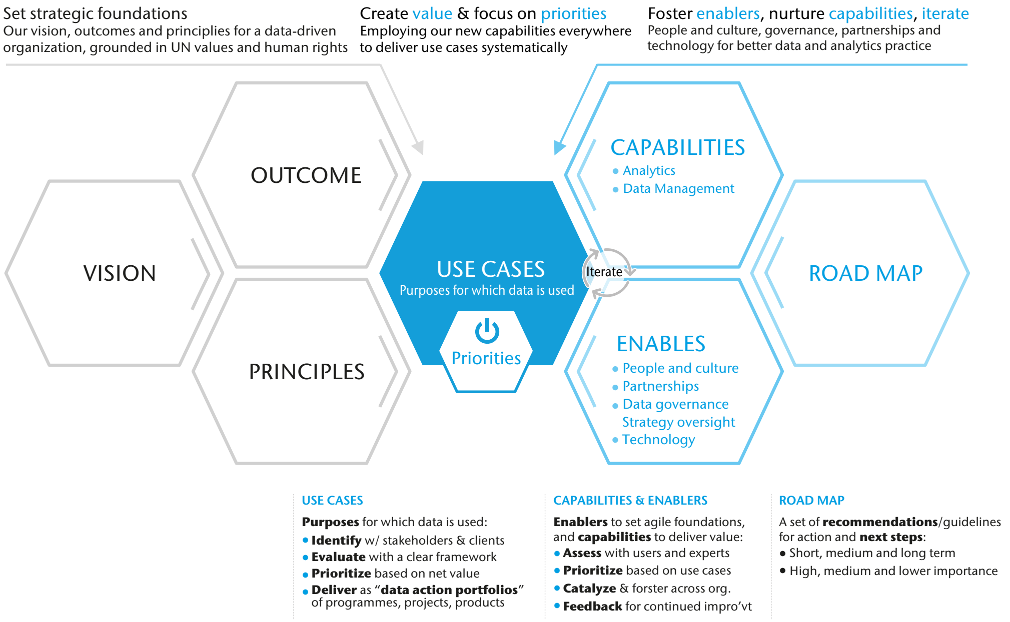
The strategy recognizes the need to build partnerships which connect better with global data ecosystems. There is a strong synergy with the WMO Data Policy of free and unrestricted exchange.

The UN's data strategy acknowledges that the organization is at the start of a long journey, and that it will take some time before its data-related capabilities are truly transformed across the UN family. Having already established a foundation of open data sharing, the WMO is on the same journey but at a different point. Nevertheless, it faces some of the same challenges. For WMO, greater collaboration and partnership on data offer opportunities for the Organization and its Members to play a larger role in addressing the global challenges and to provide better impact-based services at home.

The *WMO Strategic Plan 2020–2023* focuses on an integrated and comprehensive Earth systems approach, with data at its heart. This core goal is supported by the advanced and advancing capabilities of WMO Integrated Global Observing System (WIGOS), WMO Information System (WIS) 2.0 and the seamless Global Data-processing and Forecasting System (GDPFS). WMO has also come to appreciate the need to broaden its collaboration and partnership opportunities.

Within the UN system, WMO has strong collaborative relationships with many organizations, specialized agencies and programmes. The International Oceanographic Commission (IOC) of UNESCO is a key collaborator and partner that is aligning its own data policies with those of WMO. WMO is also building a strong collaboration on research and services with the World Health Organization (WHO), with potential under the WMO Unified Data Policy to further develop data exchange between the two organizations as new service requirements are identified and prioritized.

WMO is working with its partners to integrate meteorological, climatological, hydrological and environmental data with demographic, health and



USE CASES

Purposes for which data is used:
- **Identify** w/ stakeholders & clients
- **Evaluate** with a clear framework
- **Prioritize** based on net value
- **Deliver** as "**data action portfolios**" of programmes, projects, products

CAPABILITIES & ENABLERS

Enablers to set agile foundations, and **capabilities** to deliver value:
- **Assess** with users and experts
- **Prioritize** based on use cases
- **Catalyze** & forster across org.
- **Feedback** for continued impro'vt

ROAD MAP

A set of **recommendations**/guidelines for action and **next steps**:
- Short, medium and long term
- High, medium and lower importance

Figure 1. UN Secretary-General's Data Strategy Model (Source: https://www.un.org/en/desa/products/publications)

other data from UN partner agencies. This will provide improved guidance to decision-makers and address the strategic priorities of the broader data agenda within the UN.

The move to broaden, reframe and reassert its data policy via the Unified Data Policy is motivated to deliver what WMO needs to serve global challenges and the mandates of its Members. These goals align with the ambitions of the UN SG's data strategy.

The Unified Data Policy reflects that international data exchange within WMO and with its partners supports multiple global agendas. Weather, climate, water and related environmental data and services are essential to the implementation of the SDGs, the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) and the Sendai Declaration and Framework for Disaster Risk Reduction 2015–2030.

WMO Data Policy and the global data agenda

It is often stated that we live in a data-driven world. Algorithms built on data feed our news cycle, suggest movies for us to watch, curate our social media and select the advertisements we see. Whilst WMO has historically been a leader on the free and open exchange of data, it is fair to say that the global discussion on data has progressed quickly, creating new technologies, terminologies and tools in the process, overtaking WMO. Whilst WMO continues to work with its Members to facilitate and grow the amount of data available to the international community, it is no longer in advance or moving at the same pace as the rest of the world.

On the other hand, the machinery of WMO needs to be stable and reliable for three reasons. Firstly, it is essential to closely manage and track the impacts of any changes in observing technology and practices to monitor long-term trends in the climate. To that end, there is a tendency to conservatism that has influenced many aspects of data acquisition, management and sharing. Secondly, WMO technical regulations and resolutions are made and implemented by consensus and WMO can be limited to some extent by the capabilities and capacity for change of its Members. Thirdly, to enable prompt and effective life-saving decisions, such as issuing targeted warnings to prepare communities when severe weather events threaten them, it is critical to have trusted data available to underpin models and services.

The global data landscape and the technology giants

Data policy and the exchange of data between Members is enabled by technology, and the rise of data as a commodity has driven, in a synergistic way, enormous advances, from cloud computing to artificial intelligence. Data handling systems are commoditized to the extent that these capabilities are available to almost anyone with an Internet connection. And with this technological innovation has come a level of disruption to traditional markets, the emergence of new commercial opportunities and many new enterprises, both big and small. Amongst these, there are clear market leaders who dominate the industry and provide the bulk of the "as a service" segment.

Amazon is the market leader for cloud-based solutions, followed by Microsoft and then Alibaba and Google (Alphabet) (Table 1). Apple and Facebook dominate their own segments, but are not currently significant players in cloud-based computing services. IBM also holds a strong market position but more as a supplier of hardware and services such as those delivered by the Weather Company, its subsidiary.

Social media and Internet search engines play an important role in the provision and dissemination of weather information. The latest data shows that there were 4.48 billion social media users around the world in July 2021, some 57% of the total population. Nearly 93% of all web traffic transits through search engines and more than four in five Internet users access news through social media.

This trend is only going up. In 2020, Facebook provided a regular source of news for about a third of Americans. According to one study, nearly 65% of Google searches ended without a click to another website – up from 50% in June 2019. Google's vision statement is "to provide access to the world's information in one click", and the results are frequently provided as a predictive search, that is, giving information before users launch a search query. For example, if one clicks "weather" after typing "w," Google provides a large amount of weather data for the user's location at the top of the results: current conditions (temperature, precipitation and wind). Many users undoubtedly find what they need without having to click through to where the data is sourced – weather.com or the website of the local NMHS which may be located further down the list of results.

Table 1. Worldwide IaaS Public Cloud Services Market Share, 2019–2020 (millions of US$)

Company	*2020 Revenue*	*2020 % Market share*	*2019 Revenue*	*2019 % Market share*	*2019–2020 % Growth*
Amazon	26 201	40.8	20 365	44.6	28.7
Microsoft	12 658	19.7	7 950	17.4	59.2
Alibaba	6 117	9.5	4 004	8.8	52.8
Google	3 932	6.1	2 367	5.2	66.1
Huawei	2 672	4.2	882	1.9	202.8
Others	12 706	19.8	10 115	22.1	25.6
Total	**64 286**	**100.0**	**45 684**	**100.0**	**40.7**

Source: Gartner (June 2021)

According to a report from the International Data Corporation (IDC), there is an important strategic shift among leading public cloud Infrastructure as a Service (IaaS) providers towards development of a range of dedicated and hybrid cloud deployment options to meet enterprise demand for high performance and distributed edge use cases. The public cloud IaaS market experienced tremendous growth during 2020, expanding 34% to US$ 65.5 billion.

With such large players dominating the market and providing economies of scale, it is not economic for NMHSs to try to "go it alone" on cloud computing, for example. Whilst there are plans for a "European Weather Cloud" supported by ECMWF, EUMETSAT and the NMHSs of their Member States, this is out of reach for the majority of WMO Members. Similarly, for distribution of information, it is impossible to compete with the big players in terms of reach and market power.

The great data challenge

The global weather machine[3] produces enormous volumes of data each day. With each increase in computing power comes heightened spatial and vertical model resolution, driving improved performance and massive increases in data volume. For example, ECMWF produces 120 Terabytes (TBs) of raw weather data daily and 30 TBs of user-defined products, the equivalent of a 144 TB portable hard disk or a Petabyte (PB) per week[4].

In terms of delivery to users, the average data transmission volume handled by the ECMWF Production Data Store (ECPDS) is approaching one PB per month. ECMWF forecast products are disseminated to 547 places in 78 countries, and observational data are retrieved from 557 places in 34 countries.

The large volume of data creates a problem. It is not practical to shift entire datasets around using Internet connections. For many WMO Members, the problem is exacerbated by limitations in their own storage and processing systems, and in many cases slow and possibly unreliable Internet connections. The increased capacity of computing systems and the desire of many NMHSs for higher resolution products will further aggravate this problem.

The global nature of both weather and the technology sector brings another issue. Developers of technology – such as mobile telephony and smart watches – may wish to incorporate weather information into their products. A simple example would be an "active" smart watch that tracks exercise, provides weather information to its user and integrates weather information to compute the user's level of exertion or other derived data. In such a case, a separate weather interface would not be developed for each country or territory, instead the developer would look for a globally consistent source of data that they can be accessed in a standard way. The simplest delivery method would be an Application Program Interface (API) that delivers the data required to meet the needs of the user through a simple query. For example, the API would provide current conditions or a weather forecast for a specific location.

There is no existing global platform providing real-time and forecast information from individual NMHSs. It would also be impractical for developers to cobble together inputs from the individual websites of NMHSs that have no consistency in

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[3] The Weather Machine: A journey inside the forecast, A Blum – 2019 – HarperCollins

[4] https://meetingorganizer.copernicus.org/EGU2020/EGU2020-15048.html

format or delivery. The simple solution for developers is to go to a single global source of information such as The Weather Company. Developers seeking more detailed information may source data from, for example, National Oceanic and Atmospheric Administration's (NOAA) freely available products. However, this may come at the expense of ease of use as files are in scientific formats and some are very large.

This creates a problem for NMHSs. Though they often hold the most locally accurate products and data relating to their territory, they are simply too small for the app developers, who may also be too small to deal with NMHSs individually, particularly when markets are global. How then can the individual NMHS get its information to users without creating its own app?

Bringing it together

The evolution of the global data phenomenon and the rise of the tech giants creates opportunities for WMO and its Members. Too big to ignore and with technical capabilities that can benefit WMO Members, the large companies can be part of the solution.

What has become clear is that WMO and its Members can be direct beneficiaries of the opportunities available. One example would be in recognizing the important role of the tech giants in providing the underpinning technology for data exchange and for enabling the efficient distribution of information and services for sound decision-making.

The opportunities are perhaps even more compelling at the global level in the pursuit of efficiency and effectiveness, while building on the stability, reliability and trust that are so important to meeting Members' service commitments at a national level. For example, NMHSs could be consumers of cloud services for computing and storage; but there is also a further opportunity here to create collaborative spaces where NMHSs can work together on large datasets. What is clear is that strong engagement with the sector is required and, whilst there will be a need for engagement by individual NMHSs, this will be enhanced and the full benefits realized only through coordination at the global level.

Similarly, the growing role of data in international policy means the time is ripe for WMO to benefit from greater collaboration and partnership within the UN. The broader data strategy within the UN is aligned with, and supports, the free and unrestricted exchange of data under WMO Data Policy. The increased availability of ancillary data – such as impacts of disasters, health information and other data held by UN agencies – will enhance the ability of WMO Members to provide impact-based services by combining meteorological, climatological, water and environmental data with these datasets. At the same time, WMO has an important role to play in providing data to support larger UN agendas – from disaster risk reduction and climate change to sustainable ocean management and global public health.

Modernizing Data Exchange for Earth System Monitoring and Prediction

By Rémy Giraud, Météo-France, Jeremy Tandy and John Eyre, Met Office (UK), Tobias Spears, Fisheries and Oceans Canada, Tom Kralidis, Meteorological Service of Canada, Robert A. Varley (UK) and Enrico Fucile, WMO Secretariat

National Meteorological and Hydrological Services (NMHS) have a critical role to play as humanity faces growing risks from weather and climate extremes (IPCC 2021[1]). Climate and weather information and early warning systems enable timely and effective decision-making to protect lives and livelihoods, supporting global efforts to reduce poverty and promote shared prosperity (WMO et al 2015[2]).

The work of every NMHS relies on observations and other data products, shared freely, in real time, in accordance with the principles of the World Weather Watch (WMO 1995[3]). Former WMO President John Zillman described the World Weather Watch as *"the most successful fully international system yet devised for sustained global cooperation for the common good in science or in any other field"* (Zillman 2018[4]).

However, many countries experience a significant gap between current network performance and the requirements of the global forecasting systems upon which almost all weather and climate services depend (Alliance for Hydromet Development, 2021[5]).

The first article in this Bulletin sets out the history of the collaboration between WMO Members in making and exchanging observations in support of weather forecasting and climate monitoring. This article examines the infrastructure and technology supporting the WMO global data exchange – from its origins more than 50 years ago to the present day. It then looks ahead to how Internet-based technologies can bridge the capacity gap and new opportunities to make global data more reliable, more accessible and more exploitable in support of building global resilience.

Data exchange in support of Earth system monitoring and prediction

Weather forecasting applications cover a wide range of timescales: from nowcasting and very short-range forecasting, to short- and medium-range forecasting, to monthly, seasonal and longer-range predictions. As the prediction systems supporting these applications become ever more sophisticated, they rely increasingly on observations of all Earth system components to which the atmosphere is linked: the ocean, the cryosphere and the land surface. Moreover, observations are required of a growing number of geophysical variables at ever greater spatial and temporal resolutions.

In recent years, the space agencies around the world have been making key contributions in support of these activities. More and better performing instruments are being deployed on a growing number of satellites, providing information on additional geophysical variables. However, NMHSs are not always able to access the full set of observational data that they could use from these space-based systems; compromises have to be made to reduce the volume of data transmitted to them.

For surface-based observations, many issues need to be tackled in the establishment and maintenance of the observing systems themselves. But even when these issues are resolved, additional problems may arise when attempting to communicate the observations to users in a

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[1] IPCC (2021). Sixth Assessment Report, Working Group 1 – the Physical Science Basis.

[2] WMO, World Bank, GFDRR and USAID (2015). Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services. WMO, World Bank, Global Facility for Disaster Reduction and Recovery, United States Agency for International Development, WMO-No. 1153, Geneva, Switzerland.

[3] WMO (1995). WMO Policy and Practice for the Exchange of Meteorological and Related Data and Products Including Guidelines on Relationships in Commercial Meteorological Activities. Resolution 40, World Meteorological Congress XII.

[4] Zillman, J.W. (2018). "International Cooperation in Meteorology, Part 2: The Golden Years and their Legacy". Weather, 73 (11), 341-347.

[5] Alliance for Hydromet Development (2021). Hydromet Gap Report.

timely and effective manner. These may relate to a number of issues:

- Data policy (see Article 2)
- National and international telecommunications infrastructure
- Metadata – the information that accompanies the observations to allow the users to interpret them
- Specific enhancements to support evolving user requirements, such as the transition to radiosonde data at high veritical resolution
- Exploding data volumes, particularly associated with surface-based remote sensing, for example, weather radars.

Additionally, while the data exchange in the early days of WMO (see Article 1) mainly focused on the exchange of observations, there has developed over the years an increasing need to exchange other types of meteorological data and products. These additional data types are now driving some of the requirements for improved communications technology. In terms of data volumes, the main challenges arise from the requirement to exchange the output of Numerical Weather Prediction (NWP) or, more generally, Earth system models, and the increasing resolution of these models and thus the data volumes generated by them.

In the remainder of this article, we describe (i) the development of the existing WMO data exchange networks, (ii) what is happening already to address the outstanding problems of data exchange, (iii) what is planned, and (iv) how the whole WMO community will be involved in improving the exchange of the data on which all rely.

A brief history of the GTS, the WIS and their shortcomings

In 1971 the Sixth World Meteorological Congress approved the Manual on the Global Telecommunication System (GTS), thereby starting the operational life of the system. The Manual described the GTS as "The coordinated global system of telecommunication facilities and arrangements for the rapid collection, exchange and distribution of observations and processed information within the framework of the World Weather Watch" (WMO-No. 49).

During the past fifty years, the GTS has maintained a continuous real-time exchange of essential data, providing observations to the Global Data Processing and Forecasting System Centres and disseminating processed information to NMHSs. Despite some evolution of the technologies used for data exchange, the GTS has kept its basic technical foundations unchanged. The emergence of increasingly rapid, high bandwidth global connectivity through the Internet now offers new opportunities for the future evolution of the GTS.

One example of the GTS' architecture is the so-called "store and forward" mechanism: a message received

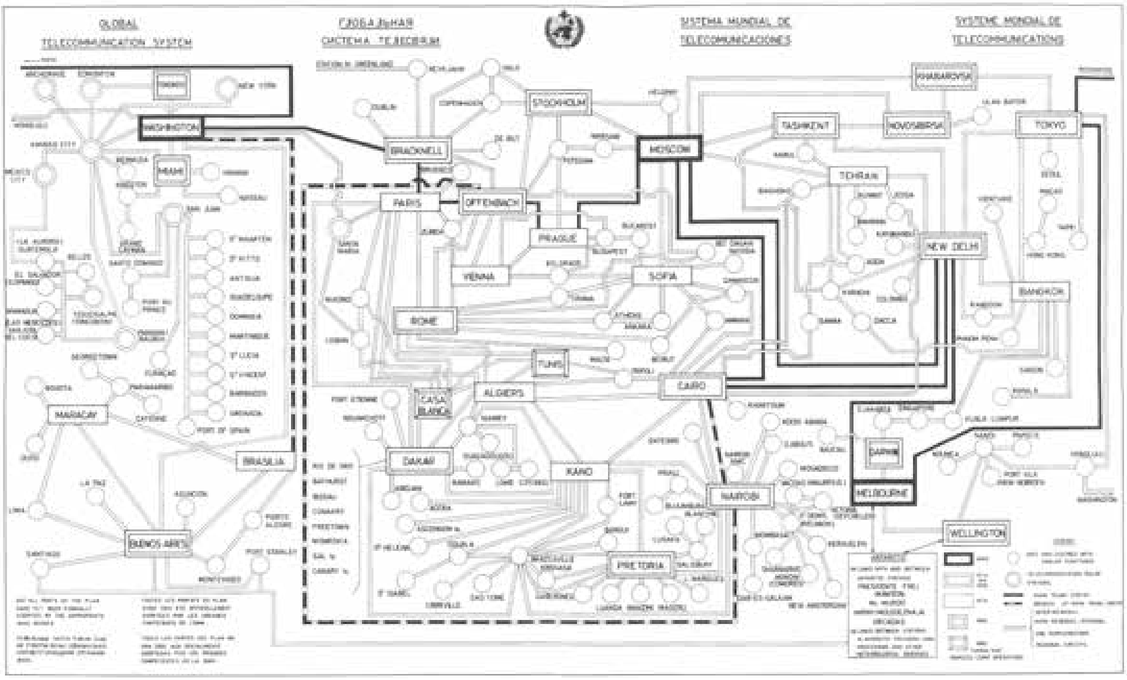

Figure 1. The GTS as defined by WMO in 1969, and "almost current" even today.

by a Centre is stored and forwarded to the "next" Centre in the complex topology shown in Figure 1. This mechanism, which predates the Internet, is based on the use of private networks to ensure high availability of the connections between NMHSs. Today, however, migrating to the Internet could provide a similar level of resilience at lower costs.

Another example is the use of identifiers, called "GTS headings" to route data through the complex network depicted in Figure 1. These headings, based on groups of six letters, are statically assigned to bulletins, and "routing tables" are maintained in each transmission centre to direct the messages along the planned route through the network. Whilst this mechanism has worked successfully for the past fifty years, the static nature of routing tables and the relatively simple syntax of the GTS identifiers are not scalable to the current explosion in both volume and variety of data. Now, with a growing need for diversified data, the routing mechanism is one of the most severe structural limitations of the GTS. A fundamental system redesign is needed to overcome this.

A further limitation of the GTS is in the complexity of the topology, which requires a level of coordination between WMO Members that is sometimes difficult to reach, for a variety of technical and political reasons. The possibility of a drastic simplification of the data exchange topology could not have been anticipated in the earlier years of the GTS. Today, with the Web as a backbone of global data and information exchange, there is a clear way forward that may help WMO resolve many of the fundamental issues with the architecture of the GTS.

A significant move to improve the system and address these issues was initiated by the Fifteenth World Meteorological Congress in 2007, driven by the need to provide data access to entities not directly connected to the GTS. This led to the development of the WMO Information System (WIS), which was intended to complement the GTS. WIS provides a searchable catalogue and global cache to enable additional discovery, access and retrieval services through Web portals, maintained by 15 designated Global Information System Centres (GISCs), each of them operated by a WMO Member.

WIS also defined new roles for WMO Centres worldwide, recognizing the need to improve the coordination between Members and to facilitate data exchange beyond the World Weather Watch. However, WIS still uses the GTS as its underlying operational service for data exchange with only minor improvements, thereby inheriting most of its intrinsic limitations.

Finding and accessing data through WIS and GTS

Teams of technicians specialized in GTS operations ensure that data are continuously acquired and delivered to support the operational activities of the NMHSs. However, finding and accessing data from the GTS requires specialized knowledge available only within a limited community of GTS experts from mostly well-resourced NMHSs. This means that the NMHSs of less developed WMO Members are often not well-equipped to access and use this valuable stream of real-time data, and that other institutions and the general public are entirely excluded.

The implementation of WIS, commencing in 2007, meant that users worldwide could now, in principle, search and access data freely or request permission from the data owners. However, despite enabling the publication of many datasets from GTS and other sources, WIS has never totally fulfilled its original purpose of providing easy access to WMO data. WIS users have encountered various problems:

- The complex portal interface does not provide a seamless experience to users
- Searches return too many results
- Searches return varied data types and products, making it difficult for users to perform more granular searches
- Broken links make the data inaccessible
- Specialized WMO data formats, with few available processing tools, make the use of the retrieved data problematic.

The 15 GISCs provide a variety of web interfaces. However, the GISC portals are less valuable than originally intended because they present too many barriers to non-expert users. The WIS catalogue currently consists of over 100 000 records published by several hundred entities, not all following consistent description standards. The complexity of the information for each record presents difficulties in maintaining a consistent and effective catalogue with meaningful, high-quality metadata. This often makes searches ineffective: finding data without the help of GTS experts can be an impossible task using the current WIS catalogue model. Thus, ultimately the WIS catalogue is targeting the wrong audience – the original intent of exposing the GTS to non-experts through search portals has not succeeded. Additionally, the translation from GTS language and WMO-specific data structures and formats is currently missing. Without this translation, the data will not reach the intended wider audience.

The growing variety and volume of data used by NMHSs make the current WIS data discovery and access methodologies an unsuitable solution for Earth system monitoring and prediction. A clean break with the past and a significant leap forward in technologies and architecture is therefore urgently needed for the future evolution of WIS. A new approach is essential to make the data accessible to all NMHSs, especially those of less developed countries, to the external organizations fostering research and supporting the evolution of WMO programmes, and to the growing community of other potential users worldwide.

WIS 2.0

WIS 2.0 is now being designed and implemented to address the issues of the current WIS and GTS implementations discussed above: to meet the demand for data volume, variety, and velocity. By doing so, WIS 2.0 will make authoritative weather, water and climate data more relevant than ever before for everyone.

WIS 2.0 will provide low-barrier infrastructure, data and services, resulting in easy and approachable data sharing for all of the WMO community and beyond. However, getting there will not happen by accident; WIS 2.0 is grounded by three foundational pillars:

- Simpler data exchange
- Open standards
- Cloud-based infrastructure.

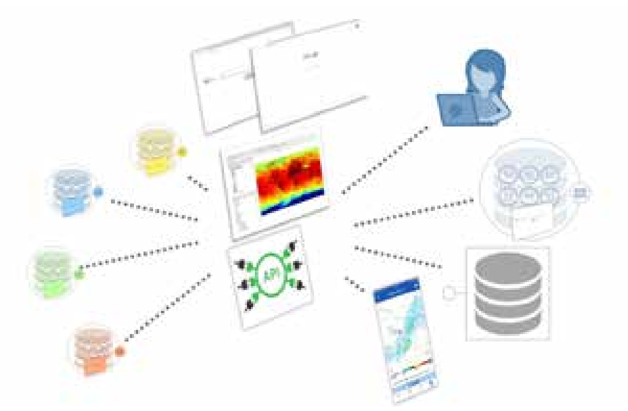

Figure 2. Conceptual view of WIS 2.0.

Simpler data exchange

WIS 2.0 prioritizes public telecommunication networks, in contrast to the use of private networks for GTS links. The use of the Internet will enable the best choice for a local connection, using technology that is commonly available and well understood.

WIS 2.0 will thus both rely on and actively support the implementation of United Nations Sustainable Development Goal (SDG) 9, which includes the target to provide affordable, universal Internet access to Least Developed Countries (LDCs).

The backbone to modern and ubiquitous information sharing is the World Wide Web. Adopting Web technologies as the core of WIS 2.0 will lay the foundation for improved discovery, access and use of weather, climate and water data. The Web also provides a truly collaborative platform for a more participatory approach, where users are no longer just observers.

Data exchange using the Web also facilitates easy access mechanisms. NMHSs can publish their data as directories of flat files, as well as via Web Service APIs[6], in order to allow for dynamic discovery, access and visualization, enabling users to download exactly what they are looking for. Browsers and search engines allow Web users to discover data without the need for specialized software. The Web also allows additional platforms to access data, for example, desktop Geographic Information Systems (GIS), mobile applications, forecaster workstations, etc.

Providing data on the Web does not automatically mean that all data are freely available to all without restrictions on use. Access controls and security developed for applications such as online banking and e-Commerce may be implemented to limit access to data and services where needed. Web technologies also allow for authentication and authorization where necessary, practices which allow the provider to retain control of who can access published resources, and to request users to accept a license specifying the terms and conditions for use of the data as a condition for providing access to them.

WIS 2.0 will not push data around the network like GTS is doing today. Real-time data exchange will be implemented with "publish-subscribe"

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[6] Application Programming Interfaces, or software intermediaries that allow two applications to talk to each other.

Figure 3. Open standard message protocols in WIS 2.0.

open standards using a simple group messaging system, analogous to a "WhatsApp for weather". Data providers will be able to publish their data via Web services, and users can ask to subscribe to those data streams they are interested in. As new data become available, the subscribed users will receive them immediately, the same way that users receive a message from a WhatsApp group they belong to.

Leveraging open standards

WIS 2.0 will leverage existing industry standards, which are open and publicly available. In today's standards development ecosystem, standards bodies work closely together to minimize overlap and build on one another's areas of expertise. The World Wide Web Consortium provides the framework of Web standards, which are leveraged by the Open Geospatial Consortium and other key standards bodies. WMO's use of open standards allows for a "build by exception" philosophy. It will leverage open standards that have industry adoption and wider, stable and robust implementations, thus extending the reach of WMO data sharing and lowering the barrier to access by Members.

Open standards also provide organizations with access to a wide range of off-the-shelf software (open source and proprietary). This lowers the cost of software development and maintenance, and it helps lower the barriers to implementation and use. Organizations will be able to choose from existing tools that enable them to access and use their selected data quickly and efficiently.

Cloud-based infrastructure

Satellites, radars and numerical models are generating more data than ever before. Storage, management and processing of this data requires expensive infrastructure. Moreover, the data volumes are becoming so large that it is increasingly impractical to download all the data for local processing by the user. A better approach is to move the processing closer to the data using cloud technology. Cloud platforms' provisioning of infrastructure and software-as-a-service enables processing adjacent to the data in environments that can be easily replicated and re-used.

While WIS 2.0 will not enforce the use of the cloud, it will encourage WIS centres to adopt cloud technologies where appropriate to meet their users' needs. So whilst the use of cloud services will not be mandated by WMO technical regulations, WIS 2.0 will encourage a gradual adoption of cloud technologies where they provide the most effective solution.

Cloud-based infrastructure provides a turn-key solution to hosting data and services in a flexible manner. This means that a system implemented by a specific country can be packaged and deployed easily in other countries with similar needs. The use of cloud technologies will allow WIS 2.0 to deploy infrastructure and systems efficiently with minimum effort for the NMHSs by shipping ready-made services and allowing the implementation of consistent data processing and exchange techniques.

It should be made clear that hosting data and/or services on the cloud does not affect data ownership. Even in a cloud environment, organizations still retain ownership of their data, software, configuration and change management, exactly as if they were hosting their own infrastructure. As a result, data authority and provenance stay with the organization, and the cloud is simply a technical means to publish the data.

Cloud services are highly effective tools to deliver infrastructure and software. However, the need to fund these services on an ongoing basis poses a challenge for some Members and does not align well with typical business models used by the international development agencies. However, there are opportunities to obtain seed funding and technical support and training from cloud service companies. Indeed, one such opportunity is being explored through the WIS 2.0 demonstration project

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[7] The Systematic Observations Financing Facility is proposed by the Alliance for Hydromet Development as a means of providing technical and financial assistance the enable developing countries to generate and exchange basic observational data critical for improved weather forecasts and climate services.

"Malawi Automatic Weather Stations Data Exchange". The cloud services provided without charge to WMO by Amazon will allow the development of a WIS 2.0 data exchange system that would potentially be deployable in other countries. The continuous funding needs may be covered by the Systematic Observations Financing Facility (SOFF) initiative[7]. This represents an opportunity to make the exchange of observational data constant and reliable in regions where the lack of data is a long-standing issue affecting NWP quality and the performance of early warning systems.

A new approach for implementing WIS 2.0

WIS 2.0 will use the lessons learned in the development and implementation of WIS, including its limited success in meeting the needs of the wider WMO community. A more collaborative implementation approach is planned, helping to lower barriers and increase system participation by WMO Members and partner organizations. As with many modern data initiatives, WIS 2.0 embraces a co-development approach, working with organizations to participate in WIS while iteratively evolving the core system. There will be a particular focus on the needs of LDCs and on ensuring that nobody is left behind.

The WIS 2.0 Principles[8] are central to its success. They comprise a set of technical and working practices intended to modernize access to promote discoverability and accessibility of data and information resources while improving the efficiency of physical data exchange.

Two critical elements of co-development include the core WIS 2.0 engagement function and the WIS 2.0 portfolio of demonstration projects. WIS engagement is undertaken with WMO Regional Associations, with various WMO Programmes and with external partners such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the private sector. This permits advance and ongoing identification of user and contributor needs and opportunities, barriers to participation, and any factors that need to be considered by the teams developing the WIS 2.0 architecture and technical components. Meanwhile, the WIS 2.0 demonstration projects will explore, demonstrate and evolve elements of WIS 2.0 through focused initiatives that adhere to the WIS 2.0 Principles.

Co-developing WIS 2.0 through demonstration projects

Demonstration projects have been selected based on their alignment with the WIS 2.0 Principles, their role in evolving and validating WIS 2.0 concepts, solutions and implementation approach, their demonstration of benefits that WIS 2.0 will bring to the WMO community, and the cooperation by several WMO Members participating in the project. These projects encompass several elements, including:

- Data discovery – activities include investigations into lightweight data description (metadata), cataloguing and search, and implementation of a modernized catalogue – covering the GISC Beijing area of responsibility – which can be indexed and searched by commercial search engines.
- Data exchange – activities include investigations into lightweight data exchange protocols as a modern web-based alternative to GTS data exchange, and the establishment of data exchange arrangements using industry formats including NetCDF (Network Common Data Form).
- Earth system domains – activities include data exchange between specific applications related to Earth system domains, and demonstrations of light-weight approaches to lower barriers for participating centres.
- Supporting LDCs and small-island developing states (SIDS) and territories – activities include modernization of the Malawi Automatic Weather Stations data exchange to support forecasting requirements, and implementation of interconnections between GISC Casablanca and centres in its area of responsibility and leveraging the Internet for data exchange.

WIS 2.0 and support for LDCs

Although the network of WIS Centres is well established and fully operational, it is recognized that there are regions where data availability is still very sparse. Therefore, WIS 2.0 will place a specific focus on improving data availability by supporting LDCs in the challenge of exchanging and making use of data. A combination of lightweight standards and protocols, cloud technologies and the public Internet will enable LDCs to leverage existing capabilities where they exist, and to manage complexity by lowering technological barriers and optimizing data exchange to account for infrastructure limitations.

Again, the Malawi Automatic Weather Stations Data Exchange demonstration project provides an

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[8] See WMO INFCOM-1-INF04-1-3(1).

example of this work. This project seeks to modernize the regional data exchange to address long-standing gaps in the observational data coverage. The work entails a mix of cellular infrastructure upgrades, process optimization and IT systems upgrades to leverage the cloud for reliability and sustainability, and to enable the flow of data via WIS 2.0.

Supporting Members through the transition to WIS 2.0

As described above, the fundamental component of WIS is the GTS, the private dedicated network and the technology stack used for real-time global data exchange. It is recognized that, although a modernized architecture and lighter-weight standards and protocols will facilitate easier participation in WIS 2.0, the shift away from the GTS, as envisioned for the project, will require dedicated support to ensure that Members are able to migrate smoothly. Members will be supported in the transition to WIS 2.0 through a combination of training, outreach and development of communities of practice to enable them to focus on challenges in specific aspects of the transition. A change management strategy will be implemented for the project, with the migration away from the GTS managed prior to its eventual shutdown. It will be critical for Members to fully participate in this work to enable to complete the migration as efficiently as possible, and the WIS 2.0 team is available to help on request.

WIS 2.0 enabling the unified data policy implementation

WIS 2.0 represents the next step in data exchange infrastructure for WMO. It will provide the technological means to implement the new WMO Unified Data Policy. It will allow the data owner better control over how the data is shared and used by allowing either open or restricted access, as required. WIS 2.0 presents a critical opportunity to overcome long-standing challenges with the GTS, enabling NMHSs, the wider WMO community and many other users worldwide to access weather, climate and related Earth system data more easily than ever before. The needs are urgent, the vision is clear and compelling, and migration work is now underway. WIS 2.0 will play a vital role in bridging the capacity gap and building global resilience in the face of increasing weather and climate risks.

The Critical Role of Observations in Informing Climate Science, Assessment and Policy

By Dick Dee, Planet-A Consulting, Estonia, Peter Thorne and Simon Noone, National University of Ireland Maynooth and Omar Baddour and Caterina Tassone, WMO Secretariat.

Scientific evidence of climate change is unequivocal. Human-induced climate change is already affecting every region of the Earth, with many experiencing more frequent weather and climate extremes. This conclusion was reached by the Intergovernmental Panel on Climate Change (IPCC), Working Group I (WGI) in its Sixth Assessment report (AR6, IPCC, 2021) by drawing upon a variety of datasets and reanalysis derived from climate observations (Figure 1).

Observations are our primary source of information about climate change. The available historical observations undertaken by National Meteorological and Hydrological Services (NMHSs), although known to be incomplete, underpin our understanding of key climate processes and climate change. Long-term records from land and ship-based meteorological stations (Figure 2), radiosondes, satellites and other observational instruments provide the necessary long-term data to understand our rapidly changing climate. These data have been analysed using a variety of techniques to provide the robust scientific basis upon which to undertake scientific assessments and monitoring activities.

Without historical observations, it would be impossible to draw any firm conclusion on climate

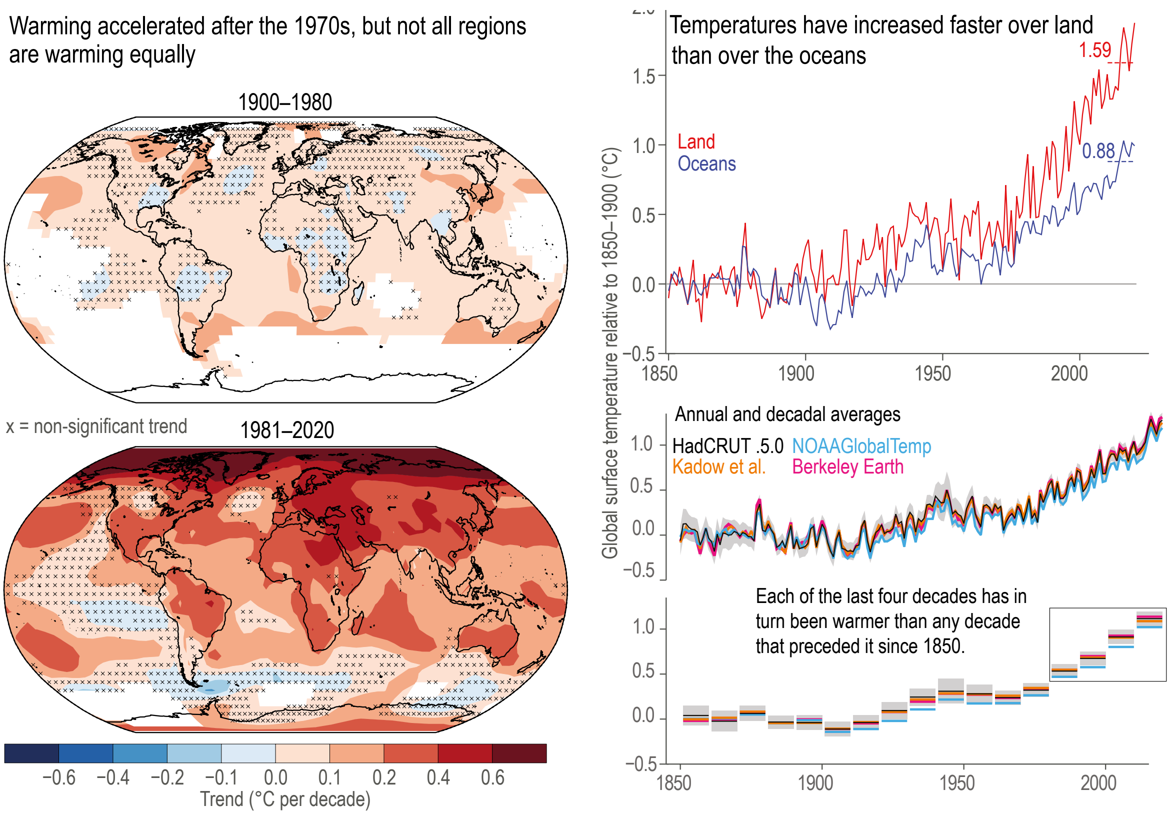

Figure 1. Subset of Figure 2.11 from IPCC AR6 WG1 showing trends and timeseries for global mean surface temperature reconstructed from land and marine meteorological observations. The HadCRUTv5 product includes substantial interpolation over data void regions (Source: IPCC AR6 Figure 2.11)

Figure 2. Centennial station – Sonnblick (Austria). Old photo from 1886, new photo from 2001

change. However, in many parts of the world, the available historical and present-day observations are insufficient to adequately monitor and predict the climate at regional and local levels.This is especially true for climate extremes, which tend to be more localized and short term. The available datasets under ClimDEX, using the climate change indices developed by WMO, have large gaps over many critical areas of the globe. In those areas, monitoring requires a much denser network of observations at daily or synoptic report resolution.

An assessment of climate extremes in several IPCC regions was not possible in AR6 owing, in many cases, to the lack of data available to the scientific research community. This means there is no observational basis for verifying future projections of changes in impacts in those regions and hence no means to effectively plan the necessary adaptation measures. While oftentimes this may be due to a scaricity of historical observations, it is undoubtedly the case that the existing historical data record is not made available to the scientific community.

The Global Climate Observing System (GCOS) defines a set of Essential ClimateVariables (ECV) that cover atmospheric, ocean and terrestrial components of the climate system, including meteorology, hydrology and the cryosphere. Observations of ECVs have many uses:

- For monitoring the climate, detecting trends and providing information about the occurrence of weather extremes
- To enable reanalysis to provide long time series of consistent climate data for the past
- To improve our scientific understanding of the climate and develop climate model projections
- To deliver the information products needed for adaptation.

The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), approved in 2015, aims to limit the impact of climate change by asking all Parties to the Convention for voluntary commitments to reduce their emissions of greenhouse gases (mitigation) and to improve resilience to the effects of climate change (adaptation). NMHSs can support those goals by providing climate observations and projections as needed for adaptation and other climate services. To do so, NMHSs must depend on and contribute to a system of free and open data exchange.

Many parts of the Paris Agreement require access to both historical and ongoing meteorological observations:

- The goal of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" requires observations to monitor its achievement and the impacts of mitigation measures.
- The adaptation goal of "increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development" requires observation-based predictions of a changing climate. The IPCC has identified a lack of access to data as a significant issue for adaptation in some parts of the world, particularly in the African continent.
- Determining greenhouse gas fluxes from observations (based on measurements of atmospheric composition) can guide Parties in their assessments of progress, and support reporting under the transparency framework.
- Observations of land cover and above ground biomass are fundamental to supporting efforts to conserve and enhance sinks and reservoirs, including forests.
- Parties should enhance understanding, action and support of the loss and damage associated with the adverse effects of climate change. Observations are necessary to identify, attribute and predict extreme weather and slow onset events and are an essential part of emergency warning systems.
- Informing the public of the state and future of the climate system.
- Supporting the Global Stocktake, by reporting on collective progress towards aims and goals of the Paris Agreement.

A long record of climate observations is needed with sufficiently high levels of quality and consistency to allow the detection of long-term changes embedded in diurnal, seasonal and multi-annual variations. The fundamental climate data records of "original" observations must be preserved indefinitely, even if they are not often used directly without further processing. Global estimates derived from observations such as reanalyses and other high-level data products are more commonly used to monitor climate change, to support policy development and implementation and to inform the public. Those global datasets are often downscaled to higher resolution in order to support local climate services. The entire value chain from observation to climate services, however, crucially depends on global availability and free and unrestricted exchange of observational data as well as model output and reanalysis data. New and improved climate datasets, including reanalyses and other innovative information products, will come and go – each benefiting in succession from new insights and capabilities – but they cannot be produced without sustained access to the original observations.

It is of fundamental importance that we share and preserve historical observations, manage them robustly and effectively, and make them available to all. The current and future generations of researchers must be able use and exploit these data to provide the products and services required for effective climate decision-making.

Reanalysis

Reanalysis has benefits for Numerical Weather Prediction (NWP) as well as climate studies. It has an important role in providing high quality and detailed data on the climate of the past and present which are required to support decisions for adaptation. It accurately represents low-frequency variability in several ECVs that have been reasonably well observed globally since the 1980s (Simmons et al. 2017). These include surface-air temperature, tropospheric and lower-stratospheric temperatures, surface-air humidity and precipitation. Reanalysis data also provide useful information about several ECVs that are not well observed, such as tropospheric winds, soil moisture, river discharge, and runoff (Dunn et al., 2020). Reanalysis is critically dependent on the availability of global high-quality observations.

Global reanalysis using NWP infrastructure

The evolution of the global observing system, including the necessary infrastructure and protocols to enable data exchange in near-real time, has made it possible to implement increasingly skillful NWP systems that use observations to initialize global forecast models. Forecast skill strongly depends on the availability of both ground and space-based observations sensitive to key meteorological variables such as surface pressure, air temperature and humidity, and wind speed and direction. As the models evolve to more accurately represent various physical and chemical processes, many other types of observations – related, for example, to atmospheric composition, ocean biochemistry and land-surface processes – become important. Forecast products are updated several times per day as new observations become available, and are disseminated to users within hours. A critical step in this process is the initiation of a new model forecast based on adjustments made as a result of new information extracted from the most recent observations. The technical term for this continuous process of blending observations with model output is "data assimilation".

Over time, a global NWP system will generate a long time series of meteorological fields for several geophysical parameters, based on observations and consistent with the laws of physics, covering the entire globe from the Earth surface to the stratosphere. When NWP systems became operational in the 1970s it was soon realized that such a digital representation of the atmospheric circulation, containing a history of weather events around the world, would be invaluable for research and development in atmospheric science. However, creating a consistent data record spanning multiple decades requires reprocessing, or "reanalysis", of archived and quality-controlled observations using a fixed configuration of an NWP model and data assimilation system. Such a reanalysis needs to be repeated occasionally when forecast models, input observations and data assimilation methodology have improved substantially, and new computing capabilities enable higher spatial and temporal resolution of the data.

Reanalysis provides the academic research community with access to the vast amount of information generated by the global observing system, synthesized using state-of-the-art forecast models, in a form that is convenient to use.

The NWP Centres are major users of reanalysis data, for example as a benchmark for evaluation of medium-range forecast performance. High-quality reanalysis data are indispensable for the development of seasonal climate prediction systems, which depend on the availability of a large database of hindcasts (i.e. re-forecasts of representative historic conditions) to enable statistical correction of the systematic errors that tend to develop in long-range forecasts. Reanalysis data are used to estimate global climatologies and probability density functions for various meteorological parameters that underpin a growing suite of probabilistic forecast products that can be used for risk assessment, emergency warning systems, planning and decision-making. These include, for example, maps that indicate locations where extreme weather is likely to develop in the near-to-medium range (Figure 3).

Climate reanalysis

The use of global reanalysis data for climate applications has grown rapidly, despite the well-known effect of biases in models and observations on the representation of climate variability and change (Bengtsson et al., 2007). A reanalysis is a multi-decadal model simulation constrained by observations; any significant change in the observational constraint potentially interferes with the estimated climate signals. Modern reanalyses are better able to correct biases due to increased availability of high-quality controlled observations, better forecast models and advances in data assimilation. As a result, and reflecting the growing role of reanalysis in climate services, it is now commonplace to refer to "climate reanalysis."

Together with other climatological datasets derived from observations alone, data from climate reanalysis are now routinely used in annual State of the Climate reports published by WMO, the American Meteorological Society, and the Copernicus Climate Change Service. The use of NWP infrastructure for climate reanalysis has several important advantages: (1) data on climate change can be updated within days of observation; (2) ECV estimates cover the entire globe, including tropical and high-latitude regions; (3) the estimates are informed by quality-controlled observations from all available sources; (4) estimates for multiple ECVs are physically consistent with one another, (5) meteorological observations are effectively reused for climate increasing the benefits of exchanging them.

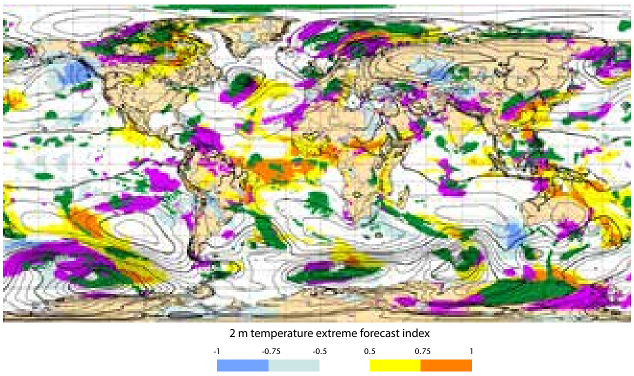

Figure 3. Extreme Forecast Index (EFI) map for 5 October 2021, showing where anomalous weather is likely to occur within the next seven days. The colours mark areas with likely high winds (magenta), heavy rainfall (green), high temperatures (yellow/orange) and low temperatures (light blue/blue). The EFI relies on climatologies and anomaly probabilities derived from reanalysis data. (Source: ECMWF)

The increasing awareness of climate change and its considerable impact on lives and livelihoods has led to a growing demand for science-based services for various industrial sectors. Climate reanalysis has a key role to play in their development. The re-insurance industry relies on reanalysis data to develop statistics and trends on windstorms, coastal flooding and other weather-related events to estimate future vulnerabilities and losses. Similarly, adaptation to climate change in the transport and infrastructure sectors requires information about trends and variability in temperature and precipitation, as well as other key variables affected by climate change such as soil moisture, sea level and sea ice. The energy sector critically depends on reanalysis data to provide the parameters needed to estimate the potential value of different renewable energy sources around the world, including wind, solar and hydro. In agriculture and forestry, reanalysis data are routinely used to map the movement of climate zones affecting crop planning and water supply.

The current status of global historical meteorological data archives

As noted above, archival climate data and free and unrestricted access to climate data is of fundamental importance. Although there have been substantive recent improvements in the archival of climate data (Noone et al., 2020, Durre et al., 2018), many obstacles still exist:

- Data may not be freely shared. In some cases, observations may not be internationally exchanged, or only against payment.
- Data may be freely available, but a lack of resources may hinder the process of sharing the data.
- Data may be exchanged, but on a restricted basis, for example only for certain purposes or with certain groups.

- Poor data stewardship can lead to data not being discoverable and thus not used, even if nominally available.
- Climate data can be lost: paper records degrade, electronic formats becoming unreadable, lack of backup and proper archiving can all contribute.

Historically, data preservation has fallen on a handful of institutions, and submissions of historical data have been piecemeal in nature. Collections are more complete since the advent of data sharing over the Global Telecommunication System (GTS), which has allowed these data to be captured and archived.

Marine observations have led the way. For several decades data have been collected and collated via International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Freeman et al., 2017). Data are held in a multivariate archive and all original sources are retained. Undoubtedly, there remain national archives which could be further integrated improving coverage. The ICOADS effort is mature and the process well documented with good levels of community buy-in.

The World Data Centre for Meteorology is maintained by the US National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information (NCEI) in Asheville. In collaboration with international and national organizations, NCEI acquires, catalogues and archives global meteorological data which is freely and openly made available to the scientific community and the public via data portals and web-based services.

NOAA's Integrated Global Radiosonde Archive (IGRA) consists of radiosonde and pilot balloon observations from more than 2 800 globally distributed stations, retained as multivariate records. Data collection is principally based on data exchanged across the GTS, supplemented by dedicated data rescue efforts. IGRA is owned solely by NCEI in its role as the World Data Centre for Meteorology and has far lower visibility and buy-in than ICOADS.

Land meteorological data holdings are in a far less advanced state and are generally shared at a mixture of synoptic, daily and monthly aggregations. Data management has often been structured per variable or per timestep and been project-based rather than sustained in nature, which means that data have been disaggregated (Thorne et al, 2017). Piecing the data back together again is difficult, since different data archives use distinct data formats and metadata. Figure 4 provides an indication both of the spatial distribution of presently acquired holdings and how the availability of data subject to various levels of temporal aggregation has changed over time. Further details of current status are given in Noone et al. (2020).

The Global Land and Marine Observations Database (GLAMOD) is part of the Copernicus Climate Change Service (C3S). GLAMOD will be hugely important for reanalysis and producing climate services.

Filling the gaps and enriching our knowledge

Climate Data Rescue

Hundreds of millions of weather observations made from the eighteenth through the early twentieth century are still available in hard-copy or image form

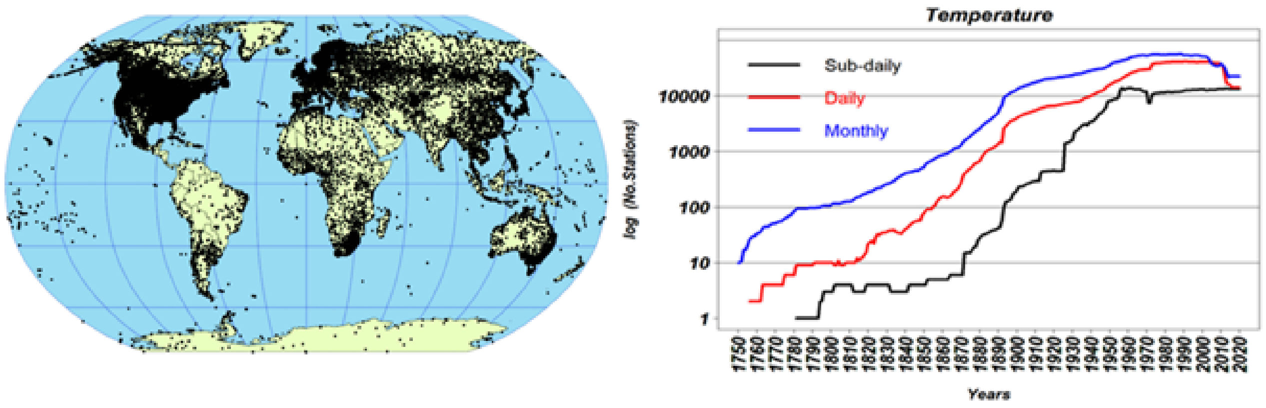

Figure 4. Location of land-based stations with temperature observations. Plot shows number of land-based stations operational for temperature from 1750–2020 at each timescale using a logarithmic scale. (Source: Noone et al., 2020)

only and are at risk of being lost forever (Brönnimann et al., 2019). Many additional holdings of various libraries, records offices and archives that pre-date the establishment of NMHSs lie undiscovered and uncatalogued. If digitized and made discoverable and accessible, these observations would complement the temporal and spatial coverage of existing records for data-sparse regions and times where climate change impact studies are crucial. This would provide long climate data records to support high-quality centennial-scale reanalysis products (Slivinski et al., 2019). Despite huge efforts in data rescue, there are still considerable volumes waiting to be processed (Figure 5). Known data rescue projects and a catalogue of data available for rescue is maintained by WMO, hosted by the Royal Netherlands Meteorological Institute (KNMI), at https://www.idare-portal.org/ and best-practice guidance are available from both WMO and C3S (https://datarescue.climate.copernicus.eu/).

Data management

Access to high quality, well-managed climate data are the cornerstone of climate services. However, standards and recommended practices for sourcing, storing indefinitely, managing, assessing and cataloguing climate data are required, and the infrastructure for their free and unrestricted exchange. Consistently assessing how well the data are managed is one way to establish or demonstrate the trustworthiness of the data. The High-quality Global Data Management Framework for Climate (HQ-GDMFC, WMO, 2019b)) is a WMO collaborative initiative that provides such an assessment at the global, regional and national levels. The scope of international collaboration within HQ-GDMFC is based on a set of principles:

1. Promoting adherence to WMO data policies
2. Registering datasets to be shared internationally for use in climate studies, monitoring and applications
3. Facilitating easy access to metadata and documentation underpinning the datasets
4. Promoting preservation and sound, standards-based management of all data that are used, or may potentially be useful for, climate-change monitoring, including backing up in duplicate repositories for the duration of their specified retention periods
5. Assessing and improving the maturity and quality of stewardship practices underpinning the datasets, cataloguing them for easy search, discovery and access, and promoting their use in informing policy-relevant frameworks
6. Promoting acquisition of user feedback on the quality, fitness for purpose and usability of shared datasets.

Figure 5. The hard-copy historical meteorological observations storage facility at NCEI, Asheville, USA. (Source: S. Noone, 2017)

As part of data centre management, (e.g. WMO technical regulations (WMO, 2019)), operators are responsible for ensuring that a business continuity plan is developed and maintained to mitigate risks associated with disruption of operations to their databases. Such a plan should incorporate provision for routine backup, and procedures for timely restoration of the database and associated infrastructure. WMO Members engage to ensure that climate data is stored indefinitely.

Among the numerous challenges to the implementation of quality climate services at both the global and national level is that much of the existing guidance on climate data management struggles to keep pace with the rapid advances in technologies, community best practices and user requirements. The WMO has developed and baselined the Stewardship Maturity Matrix for Climate Data (SMM-CD) (Peng et al., 2019), to allow data stewards (e.g. in NHMSs) to assess their data management practices in an internationally standardized framework, identifying gaps and other elements of their processes that would benefit most from improvement.

Effective data stewardship requires a combination of sustained stewardship efforts at national, regional and global levels, working synergistically. NMHS either directly manage or otherwise have stewardship over national observations and have the local knowledge to most effectively manage observations made under their auspices. However, due to the global nature of weather and climate, data need to be shared with regional and global repositories to ensure that new products and services derived from these aggregated holdings have the highest possible utility at the national level.

Data in service to society

In recent years, major international programmes, such as the WMO Global Framework for Climate Services (GFCS) and the European Union's Copernicus Climate Change Service (C3S), have been established to coordinate and organize climate data and tools for use by governments, public authorities and private entities around the world. Their common goal is to create a set of operational services and shared practices that put the best available science and tools in the hands of those facing the immediate challenges of adaptation and mitigation in the communities where they live. They operate on the principle that free and unrestricted access to quality-assured data and information about the past, present and future climate is essential to enable climate-resilient and climate-smart societies.

The implementation of C3S by ECMWF represents a turning point in improving access to observations and to the tools needed to use them effectively in climate services. C3S offers user-driven operational services, including reliable data services and user support via a dedicated Climate Data Store (CDS). The CDS catalogue includes numerous datasets derived from observations addressing the majority of GCOS ECVs, as well as high-quality climate reanalyses generated using ECMWF's NWP infrastructure. C3S coordinates and supports a wide range of activities to ensure continuous availability and improvement of those datasets, including data rescue, data collection, data management, quality control, data re-processing and reanalysis production.

Way forward

Observations constitute our primary source of information about how our climate is changing. They provide direct and convincing evidence on the impacts of climate change, are indispensable for the development of seasonal climate predictions, and are needed to validate and improve the models used to simulate future climates under different emission scenarios. None of this is possible without shared access to high-quality observations – global, regional, local; past, present and on a sustained basis into the future.

The proposed WMO Unified Data Policy resolution, which calls for free and unrestricted exchange of historical observations, is a potential game-changer for climate services. It would lead to wider availability and greater quality of the science-based information needed for better decision-making in the face of a changing climate.

Climate observations include not only meteorological observations provided by the NMHSs but also ocean and terrestrial observations, covering cryosphere, hydrology and biosphere. Most terrestrial observations are performed and resourced at a national level. Many observations are exchanged freely at the global level. Hydrological observations are the exception, only a few are exchanged globally(see article 6). The new WMO data policy covers the exchange of all publicly funded Earth system data. "Non-weather" observations, such as the terrestrial and oceanic observations, are for now considered to be recommended data under the policy, but may eventually become core data if and when the requirements to exchange them becomes substantiated and broadly agreed.

References online

Hydrological Data Exchange

By Robert Argent, Bureau of Meteorology, Australia, Jan Daňhelka, Czech Hydrometeorological Institute, Marcelo Medeiros, Brazilian National Water Agency (ANA), and Dominique Berod, WMO Secretariat

Floods and droughts immediately come to mind when considering water challenges. Yet, water impacts our daily lives directly or indirectly through its use for domestic and drinking purposes, agriculture, industry, hydropower, navigation, recreation, ecosystem management and much more. Poor governance or management of water can lead to socio-economic and environmental crises. There are many conflicting or competing uses for water between individuals, among countries sharing river basins or across generations – typically for groundwater with slow recharge process.

Water is identified as one of the highest global risks to humanity in terms of impact by the World Economic Forum. It is the 6th of the 17 Sustainable Development Goals (SDGs)and impacts on 15 SDGs. There is a growing demand for water due to population and economic growth. Climate change is making water supply less predictable and more episodic in many regions. Water quality is under threat from untreated wastewater, more intensive agricultural practices, exacerbated pressure from industry and salinity intrusion. The challenges are too many to list.

SDG6, the Sendai Framework for Disaster Reduction 2015-2030 and the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) urge identification and implementation of sustainable solutions to water challenges. The dramatic flooding events around the world in the summer of 2021 are a cruel reminder that nobody is safe. The current situation has various origins, one is that many critical water processes are unknown and difficult to predict.

Irrawaddy Delta Myanmar (Credit: contains modified Copernicus Sentinel data (2017), processed by ESA, CC BY-SA 3.0 IGO)

Water complexity

The study of hydrology encompasses the entire hydrological cycle: evaporation, precipitation, surface and sub-surface runoff, soil moisture, groundwater fluxes and water quality. The complex interactions between these hydrological processes are not fully understood at all time and space scale. In 2017, the International Association for Hydrological Sciences launched a "Call to Arms[1]" urging all hydrologists of the world to identify and tackle the 23 unsolved problems in Hydrology.[2] WMO Research Board is currently preparing a strategy for applied research in operational hydrology.

The complexity of hydrology is further amplified by climate change and by human activities. Dams, water intakes, urbanization and other human impacts transform the hydrological regime, making it necessary, but difficult, to adapt water management practices and water sharing agreements. Furthermore, water stakeholder groups tend to be very diverse and the providers of hydrological services and related product are often fragmented and uncoordinated, hindering efficiency of service delivery.

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[1] Blöschl et al, 2019. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. Hydrological Sciences Journal 64, issue 10

[2] Inspired by David Hilbert's 23 problems in the discipline of mathematics, published in 1900

Water level measurements at Mucum station. (Source: Agência Nacional de Águas e Saneamento Básico (ANA))

Need for a holistic Earth system approach

The entire Earth system is involved in the hydrological cycle. Ocean and land provide evaporated water, the atmosphere and cryosphere produce inputs to the terrestrial systems, and the latter, together with cryosphere again, shape the time-space repartition of water in surface and subsurface runoff and storage, groundwater dynamic, until water returns to the ocean, minutes or centuries after leaving it. It is impossible to capture the dynamics of one component without understanding the others and their interactions.

This is particularly true for systems such as estuaries, coastal and polar regions, and high mountain areas. Combined processes in such systems can generate devastating events such as coastal inundations, salinity in groundwater, erosion, glacier lakes outbursts, sea ice dynamic, mangrove destruction, or blue-green algae growth. Consequently, climate analysis and numerical weather prediction (NWP) must be connected to hydrological monitoring and modelling in order to improve prediction capacity. Measured and computed hydrological data also allow validation and verification of atmospheric models. This is the core of WMO Earth system approach.

Shared hydrological data: a global opportunity with local impact

Data sharing has long been a challenge in hydrology from both the technological and policy perspective. The technology challenges include bespoke monitoring and data management systems with unique or idiosyncratic data formats, multiple incomplete or incompatible standards for data storage and exchange, and the inability to publish and maintain data in a publicly accessible way. While the policy challenges at regional, national and international levels include disagreements over priorities, competing or disconnected institutions, policy vacuums and the concept that data is power so sharing it can diminish one's power base. In addition, some governments expect their National Hydrological Services (NHSs) to cover part of their budget by selling data or value-added services to customers, potentially hampering access to citizens who may benefit more from open access.

Nonetheless, there are many hydrological data sharing success stories. There is, for example, the international exchange of runoff data within the academic community and through international centres such as the Global Runoff Data Centre. At

Table 1. (from Bureau of Meteorology, 2017) Societal interests supported by effective hydrological data sharing.

Societal interest	*Effective use of shared data*
Reducing flood risk	• Operating early warning systems • Designing effective flood control structures
Providing reliable potable water supply	• Identifying sustainable water sources • Estimating supply and demand fluctuations
Providing effective sanitation services	• Designing effective drainage systems • Selecting appropriate water treatment trains
Designing drainage and water supply infrastructure (including dams)	• Estimating rainfall Intensity, Frequency, Duration (IFD) relationships • Estimating the Probable Maximum Flood (PMF)
Providing water security for agriculture	• Designing efficient irrigation systems • Setting sustainable limits on water allocation
Providing water security for aquatic ecosystems	• Identifying high value water-dependent ecosystems • Defining environmental flow regimes to sustain ecosystem function
Providing water security for power generation	• Identifying catchments with high reliability water supplies • Dimensioning water storages to operate through protracted drought sequences

regional and national levels, engineers and scientists have for decades recognized the immense value to be gained from data sharing and have supported manual and bespoke approaches to data sharing that contribute to the safety, security and prosperity of people.

The last decade has seen a maturing of technologies and policies in the area of open data that enhances the opportunities for sharing hydrological data. In 2017, the WMO and the Australian Bureau of Meteorology (BoM) published a set of Good Practice Guidelines for Water Data Management Policy (BoM, 2017) that recognized these advances and the opportunities they offer for practical and effective advances in sharing hydrological data.

The Guidelines outline the value that can be gained from effective hydrological data sharing and identify seven inter-related good practices that cover both technology and policy:

1. Identify the priority water management objectives
2. Strengthen water data institutions
3. Establish sustainable water data monitoring systems
4. Adopting water data standards
5. Embrace an open data approach to water data access and licensing
6. Implement effective water data information systems
7. Employ water data quality management processes.

Effective hydrological data sharing has the potential to benefit many areas of society across a range of interests that span time scales from minutes to decades. Examples include the forecasting of groundwater yields, support for navigation and recreation uses, tourism and many more, some of which are listed in the table below. Water security is also a major challenge for many countries, requiring good information on water availability and efficacy in managing demand options.

The pilot implementations of the WMO Hydrological Observing System (WHOS) in La Plata basin and in the Arctic offer good examples of successful multi-national efforts in hydrological data exchange that are achieving benefits for the greater good of society. These systems operate as common platforms bringing together data produced by national meteorological and hydrological data providers. Through the common platform, operational and historical data are made accessible to support better-informed water-related decisions at national and international level, for example, for flood or drought management.

Needs and contribution from stakeholders

At the national level, WMO Members enable effective hydrological data exchange through their policies and investment in the value chain for gathering, managing, holding, publishing and sharing data. Members set the policy framework for effective operation of the many national and local institutions that are involved in water-related work. On the ground, Members also directly support, or provide investment frameworks to support, sustained, high-quality monitoring and data management systems. Members can legislate for the adoption of data standards and sharing policies that maximize returns on investment in monitoring, data management and information sharing systems. They also drive the adoption and implementation of quality management and assurance processes to ensure that data is reliable and can be trusted when applied to supporting the safety, security and prosperity of the nation’s people.

National Hydrological Services (NHSs), including those that also operate by National Meteorological Services, can play a significant leadership role in local, national and global sharing of hydrological data. NHSs can take the lead and influence awareness and adoption of standards and guidelines, such as WMO *Technical Regulations* (WMO-No. 49), Volume III , in countries where hydrological data is spread across many entities. Where control of hydrological data is centralized in the NHS, it is the responsibility of the NHS to ensure that investments is well directed, and that benefits are maximized through good policies, systems and relationships, including with neighbouring countries.

Around the globe, 145 countries share 263 transboundary basins, covering half of the Earth’s land surface. When rivers or groundwater systems run along or across national borders, national interests in effective data sharing become regional or multi-national. A regional international organization is usually established to facilitate common activities in most transboundary basins and data sharing is an important element of the agreed activities. Effective and timely sharing of data between neighbouring countries can bring many societal benefits, both in terms of long-term planning and management as well as during crises, such as floods and droughts. At its very simplest, sharing of rainfall and river flow data by an upstream country supports more accurate and timely forecasts, warnings and water management by countries downstream.

From the global perspective, the impetus for hydrological data sharing is similar to the reasoning behind the sharing of other Earth system data, which can be summarized as "global sharing for local good". All nations can benefit from global water data sharing. At the very least, they gain access to larger data sets to verify and improve hydrological and atmospheric forecasting systems. The sharing of data from extreme events improve national statistics in other catchments with similar features. Other benefits include tracking and understanding climate dynamics, satellite calibration and validation, and monitoring progress toward SDG6 goals. Additionally, in the global marketplace, substantial volumes of virtual water are transferred from one part of the world to the other through the exchange of goods – the so-called water footprint. Global data sharing can help quantify such water transfers.

A broad number of UN-related services and initiatives support and/or can benefit from hydrological data sharing. We can only list a few:

- The Food and Agriculture Organization's (FAO) Aquastat system for sharing water resources data
- The United Nations Economic Commission for Europe's (UNECE) work in the framework of the The Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention)
- The United Nations Environment Programme's (UNEP) role in both the Global Environment Monitoring System for freshwater (GEMS/Water) and World Water Quality Alliance
- The United Nations Office for Disaster Risk Reduction (UNDRR), UNFCCC and United Nations Educational, Scientific and Cultural Organization (UNESCO) led World Water Assessment Programme.

Types of data

Hydrology has been practiced as a quantitative science since the seventeenth century. Today, the term water data encompasses a large number of physical, chemical, biological, social, economic and administrative variables related to water and water management. In the WMO context, hydrological data are those describing the hydrological cycle. They are required for hydrological services delivery and for research. They include measurements from in situ and satellite platforms as well as outputs from hydrological models. They can be (near) real-time data and historical time series, point values as well as aggregated data.

A full list of variables can be found in the WMO Technical Regulation III and in the BoM guidelines. High value variables are grouped in Table 2.

Some data take time to collect and analyse and will need to undergo lengthy post-processing and validation procedures so cannot be shared in a real-time mode or, if so, only as preliminary, unvalidated data, subject to correction before final versions are released.

WMO *Technical Regulations* (WMO-No. 49), Volume III and the WMO Integrated Global Observing System (WIGOS) manual identify certain sets of hydrological data that shall be shared, but a new framework and a more unified approach are required. Experts will be charged with drafting amendments of WMO Technical Regulation to incorporate these new principles, and suggest a list of data considered as core (essential for protection of life, property and the environment) and recommended (important for system understanding and supporting water management), similarly to the other areas.

Core and recommended data

Core hydrological data are required to ensure that operational hydrology can inform flood, drought and water resources management in an effective way, and can help to improve global knowledge of the hydrological cycle. Some of these core data, like river discharge or groundwater level, may be subject to restrictions regarding their exchange. In order to overcome such constraints, the establishment of global reference stations is envisioned. Countries will nominate these stations on a voluntary basis with a commitment to exchange their data. A network of such hydrological stations could be formalized through WMO, similar to what has been or is being done with the long-term – centennial – stations.

Recommended data are those that are needed to improve our understanding of the hydrological cycle, to help determine water balances at different temporal and spatial scales and to allow hydrological service provision. Such data is essential to support scientific research and quantification of water indicators for SDGs. However, they are not essential data for the protection of life, property and the environment. Examples would be the water level of wetlands, sediment transport or water temperature.

A full, consultative process will be established for identifying core and recommended data once the

Table 2. Main hydrological variables

Hydrological cycle component	*Physical entity*	*Example of variables*
Land surface	Rivers	Water level (stage) of rivers, discharge (streamflow), flow velocity, backwater; flood inundation area and depth; characteristics and extent of ice and snow cover, including snow water equivalent.
		Sediment transport and/or deposition (suspended and bed load); water quality (physical and biologic) parameters.
	Lakes and reservoirs	Water storage bathymetry and level, accessible storage volume, storage inflows, outflows and offtakes, water extent
		Temperature (different layers), suspended sediment transportation and deposition, water quality (physical and biologic) parameters.
	Wetland and springs	Water level and velocity, temperature, pH, oxygen, biological parameters.
	Estuaries and coastal regions	Water level of delta and estuaries, backwater curves and tidal dynamics, algae, biological parameters.
		Salinization, algae
Soil and groundwater	Upper layer of soil	Permeability and storage capacity, subsurface flow, soil moisture
	Groundwater	Water level (stage) and pressure; aquifer thickness, flow velocity and direction; recharge of surface water and groundwater
		Temperature, chemical and biological properties of groundwater
Atmosphere		Rainfall, wind speed, humidity, temperature, radiation, evapotranspiration

WMO Unified Data Policy is adopted, and the relevant technical regulation will be adapted within the next two years.

Solutions for data sharing

The Action Plan on Hydrology that will be submitted to the World Meteorological Congress in October 2021 will strengthen and streamline WMO's support for Members in hydrology. The Action Plan contains technical and policy developments and aims to ensure that both are contributing to the Earth system approach.

Policy is a key element in overcoming data sharing challenges. The policy opportunities cover four main areas:

- Better institutions
- Fit-for-purpose monitoring
- Trusted data
- Shared data

WMO assists countries with the framing of effective policies, procedures and guidelines across these areas. The previously cited Good Practice Guidelines for Water Data Management Policy provides guidance for the development and implementation of effective policies. In strengthening water data institutions it is suggested that effective policies include national coordination to build synergies, so that hydrological data can flow naturally to where they it will yield the highest value.

WMO *Technical Regulations* (WMO-No. 49), Volume III provides practical guidance on hydrological monitoring networks. However, such networks operate more effectively under policy conditions that ensure support for sustained operations and asset replacement and that remain fit for (multiple) purpose as conditions and priorities evolve.

Quality management procedures for hydrological data require a policy that values investment in the quality of data used in decisions that affect people, safety, security and prosperity. Policies that support good quality management processes deliver both customer trust and efficiencies in data management workflow, and can save costs.

Finally, the highest quality and best managed data are of little value if inaccessible – either nationally or globally. Many benefits are expected to flow from policies for sharing data within governments, including:[3]

- Improving the efficiency of public services
- Improving data quality
- Developing innovative services
- Creating new business models
- Improving transparency and accountability
- Enhancing citizen participation.

Recognizing that the key to success is a combined effort of technology, policy and advocacy, WMO is leading the World Water Data Initiative (WWDI), together with the Government of Australia, the World Bank and UN Water. WWDI will support NHSs and other relevant players to improve and maintain water observing and data management systems.

Technology

Sharing data requires a range of technical systems and solutions to make sure data are effectively collected, managed, quality controlled, stored and rescued. The solutions should also ensure data are visible and accessible, shared and used without too much burden either on data providers or data users.

In addition to WWDI, WMO is modernizing its approach on three major hydrological monitoring initiatives as part of its paradigm shift to an WMO Earth system strategy:

1. WMO HydroHub/World Hydrological Cycle Observing System (WHYCOS) for innovative monitoring systems and data collection
2. WMO Hydrological Observing System (WHOS) data sharing solution, as the hydrological component of the WMO Information System (WIS) 2.0.
3. WMO Global Hydrological Status and Outlook System (HydroSOS) which assesses the current and near-future status of surface and groundwater systems.

These systems inter-connect with other WMO activities such as the the Flash Flood Guidance System, the Associated programme on flood Management (APFM), Climate Risk and Early Warning Systems (CREWS) initiative and the Integrated Drought Monitoring Programme (IDMP), and are embedded within the general framework of the WIGOS, WIS and the Global Data-processing and Forecasting System (GDPFS).

Advocacy

There is an abundance of data and studies that can be marshalled to make the case for collecting, curating and sharing high quality hydrological data. However, governments have many other, conflicting, investment priorities to consider. Hence, in advocating for change it is important to present strong arguments, supported by initiatives such as the WMO Unified Data Policy, and to be prepared to pursue activities at times when it is most likely to be effective.

Advocacy for data acquisition and sharing must cover various considerations (BoM, 2017):

- Which institutions are involved in water data management and how?
- What are the relevant laws, policies and business imperatives governing their participation?
- What costs are borne by each participant in the water data sector?
- What are the deficiencies in water data collection and dissemination?
- What are the missing technical competencies and technology gaps that need to be redressed?
- How are the current water data management arrangements failing to support priority water management objectives?
- What are the opportunity costs of failing to reform the current policy settings?

Answers to these questions should be assembled into a business case to inform government of the current flaws in the policy and institutional settings and to convince them that the proposed changes will benefit their constituents as well as regional and global agendas. Such a strategy, erects a pragmatic, defensible and supportable way forward that can also align with government commitments to WMO, the SDGs, the Sendai Framework and other initiatives.

The business case must advocate for change in a way that balances government concerns and enable support across differing factions. Ideally, these

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[3] https://www.europeandataportal.eu/en/using-data/benefits-of-open-data

factions would have been engaged and convinced of the merits of change through prior consultations in the case development stage.

Data sharing has many benefits that can be highlighted, including:

- Governments and societies will improve their knowledge of water availability and demands as a basis for managing national water security
- NHS operations will be more effective thanks to multiple use of data, contributing to national and regional economies
- Having multiple users, NHSs will attract greater visibility and will be viewed as trustworthy, effective partners, influencing decisions on national budget allocation, and candidates for major donors who are more eager to engage with countries that share their data
- NHSs can improve their data rescue system, for example, by having a backup database in one of the WMO data centres
- The overall data quality will be higher due to greater use by more organizations, and cross-comparison along international waterways and groundwater systems
- NHSs will be an integral part of the bigger picture of the Earth system, contributing hydrological data to global and local challenges such as climate assessments, coastal inundations, glacier lakes outbursts and many other areas requiring a multidisciplinary approach.

Those benefits must be weighed against existing risks and barriers of sharing data. Commonly quoted risks are related to use of data outside their validity scope, poor use or implementation of the data value chain and derived products by unknown users, data corruption or uncontrolled modifications. Standard risk assessment and management procedures must be used all along the value chain to ensure the ongoing effectiveness and efficiency of investment and that government, other investors and beneficiaries are not exposed to unmanaged risk that may erode or destroy confidence and support.

Conclusions, opportunities and benefits

Actionable information is the main goal of data sharing. Increasingly devastating water-related disasters require effective, modern and sustainable information systems. Inaction is not an option. WMO is contributing to the implementation of a new paradigm for hydrological data. As a guiding principle, hydrological data must be considered as global public goods: water challenges are global, hydrological data must be global as well. Water being a key component of the Earth system, hydrological data must be shared with multiple users to help to resolve water challenges in a holistic way.

Hydrological monitoring is expensive but modern network design will allow higher efficiency, and incorporating all possible data sources will provide high returns on investment. NHSs might wish to collaborate and share data with other data providers in academia, the private sector or citizen associations, to obtain better information, better water and Earth system understanding, and better weather, hydrological and climate predictions.

The potential benefits of data sharing are huge, and related risks can be mitigated. The WMO Unified Data Policy is a critical step in the modernization of hydrological services. A consultation over the next two years will define core and recommended hydrological data, reference stations, and adapt regulatory materials.

Such efforts are cost-effective, and the new WMO data policy provides an excellent opportunity for the hydrological community. It contributes to support NHSs in installation, operation and maintenance of sustainable, efficient observing system, serving the broader WMO community as part of the Earth system approach, and gaining credibility and trust.

References online

Benefits of Atmospheric Composition Monitoring and International Data Exchange

By Jörg Klausen (MeteoSwiss, Chair of WMO/GAW Expert Team on Atmospheric Composition Data Management) and Claudia Volosciuk, Oksana Tarasova and Stoyka Netcheva, WMO Secretariat

Atmospheric composition, and changes therein, have multiple impacts on our lives and the environment. For instance, rising greenhouse gas concentrations cause global warming that intensifies weather extremes and drives ocean acidification. Increasing levels of air pollution are a threat to human health, ecosystems and agricultural production. To understand the state of the air we breathe, changes therein, the resulting impacts and the responsible drivers, observations of atmospheric composition are indispensable and so is the open exchange of that data across all sectors. The new WMO Unified Data Policy is expected to help further strengthen and broaden this exchange. The Policy text includes, for the first time, atmospheric composition data as an essential discipline area for WMO activities and establishes an organizational policy for their exchange. It also clearly recognizes the symbiotic nature of research and operations and the mutually beneficial data exchange between the two communities.

The WMO Global Atmosphere Watch (GAW) assists Member States and Territories in observing atmospheric composition and sharing observational data. However, atmospheric composition data is produced by various agencies within and outside National Meteorological and Hydrological Services (NMHSs), including national and sub-national environmental protection agencies, academia and the private sector. Hence atmospheric composition data sharing occurs far beyond the WMO Community, thus the new WMO data policy is of great interest and relevance to GAW.

To reach the goal of the Paris Agreement to limit global warming to well below 2 °C, many countries have pledged to move towards net-zero greenhouse gas emissions. Without access to and exchange of atmospheric observational data, we would not know about the increasing greenhouse gas concentrations since industrialization and we would not be able to track future progress or identify emission hotspots to take action.

Important applications for atmospheric composition data

Long-term atmospheric measurements are important to inform and support policy – and to demonstrate ultimately the success of any measures taken. For example, long-term atmospheric composition data attest to the beginning of a recovery of the ozone layer – an environmental success story. Stratospheric ozone depletion was among the environmental problems that led to signing in 1987 of the Montreal Protocol to phase out ozone depleting substances. The success of the treaty can be seen through the measured recovery of the ozone layer at a rate of 1–3% per decade since 2000 in upper stratosphere regions outside the poles (WMO, 2018a). Observations of ozone depleting substances, stratospheric ozone and UltraViolet (UV) radiation provide observational evidence to support the Protocol. Observations are made using diverse techniques and instruments from the ground and from the space. Vertical ozone profile are measured using ozonesonde. An example of ozonesonde in preparation for launch is shown in Figure 1. Analysis of the chlorofluorocarbon CFC-11 long-term and quality-controlled observations indicated a slowdown in the decline of the atmospheric concentration after 2012, connecting it to an increase in global emissions from eastern Asia (Montzka et al., 2018; WMO, 2018b).

Greenhouse gas concentrations are also well-documented through long-term measurements around the globe. Global analysis of these observations, presented in the annual WMO Greenhouse Gas Bulletin (see Figure 2), shows that carbon dioxide (CO_2) passed the 400 parts per million (ppm) level throughout GAW stations in the northern hemisphere in 2014. The Bulletin reported in 2016 when remote locations in the southern hemisphere, such as the Cape Grim GAW Global station in Tasmania, also breached that mark. In 1989, when GAW was initiated, the global mean CO_2 concentration was 353 ppm.

Figure 1. Ozone observation at Ushuaia, Argentina. Ozonesondes measure ozone and meteorological variables at different altitudes as the sonde ascends, until the balloon bursts. (Source: Lino Condori)

Atmospheric pollutants (aerosols and reactive gases) are responsible for poor air quality, which causes an estimated seven million premature deaths globally every year (World Health Organization (WHO), 2016). Data on aerosols and reactive gases are important to determine acute health threats and are used in the estimates of the Global Burden of Disease (Shaddick et al., 2021). Observations are also used to monitor compliance with air quality regulations and to track changes in the abundance of pollutants in response to policy (UNECE, 2016). Delivering such data in near real time is crucial for improved forecast accuracy for early warning systems and to guide mitigation measures.

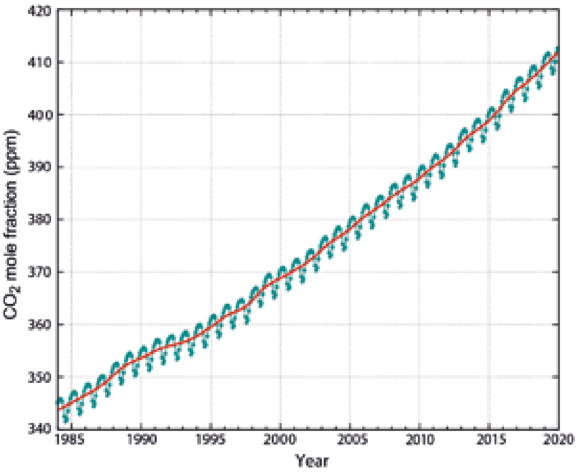


Figure 2. Globally averaged CO_2 mole fraction. The red line is the monthly mean with the seasonal variation removed; the blue dots and blue line depict the monthly averages. Observations from 133 stations were used for this analysis. The data is available, and the analysis is carried out by the World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency (JMA). (Source: WMO Greenhouse Gas Bulletin 16, 2020)

In addition to its health implications, air pollution has a substantial impact on agriculture due to excessive deposition of nitrogen and sulfur constituents and ozone. Surface ozone is one of the main air pollutants affecting crop yields, with global losses for staple crops (wheat, rice, maize and soybean) estimated to be in the 3–16% range, or US$ 14–26 billion annually (Avnery et al., 2011; Mills et al., 2018). The mechanisms whereby ozone affects plants and crops are qualitatively well understood but poorly quantified. Figure 3 illustrates crop damage due to ozone.

A number of short-lived pollutants also have climate impacts, for example, ozone and aerosol. Among the different effects, they contribute to radiative forcing. For example, wildfire smoke aerosols impact on radiation and, thereby, the weather forecast (demonstrated in the WMO Aerosol Bulletin (WMO, 2021b)). To increase our understanding of the different effects they have on the climate system, observations of short-lived pollutants are also of utmost importance.

Atmospheric composition data sources and requirements

As stated earlier, atmospheric composition data are produced within and outside NMHSs. Normally observations of regulated pollutants are made by environmental protection agencies. High-quality observations for research purposes, including time-limited measurement campaigns, are made by research institutions and universities. Ground-based in situ measurements are complemented by aircraft-based in situ measurements (e.g. IAGOS), as well as by remote sensing, both ground-based and from satellite. Recently, new data sources related to citizen science have emerged, and those data are increasingly generated using low-cost sensor devices (WMO, 2021a).

Figure 3. Ozone damage to crops. Damage increases when ozone exposure continues: initially, the level of damage is small (left), then symptoms get worse (centre and right) (Source: K Sharps, ICP Vegetation)

Observational data must be collected in a way that ensures that the data from different sources are comparable in order to produce globally consistent products and to understand spatial and temporal variations in atmospheric composition. To this end, GAW provides measurement guidelines and quality assurance/quality control tools. The data summary of the World Data Centre for Greenhouse Gases provides an example of information that can be derived from such consistent products. Figure 4 illustrates the temporal evolution and geographical distribution of CO_2. Besides the clearly visible increase in CO_2 over time, it shows lower CO_2 concentrations in the southern hemisphere as well as a less pronounced seasonal cycle than in the northern hemisphere, due to the lower fraction of land area, hence less vegetation.

Although the GAW network of observations is growing, important gaps remain (Laj et al., 2019). In large parts of the world there is no observational infrastructure. For political, commercial and institutional reasons as well as because of a lack of capacity, it also happens that some observations are not shared with the international community. Figure 5 showcases the limited availability of measurement through a comparison between reanalysis and GAW measurements of ozone. A large effort has been made in the framework of the Tropospheric Ozone Assessment Report to collect all available data to perform a global assessment of various metrics that address different user communities (Lewis, 2017). This is an important first step towards increasing the availability of data, even if the raw data is not made available, and it hints at large amounts of existing data that is not being fully used.

Data availability represents one challenge, the quality of the observational data is another. Some observations arrive without any associated quality information, which prevents their full utilization. Observational requirements are driven by the quality of the final products and the services that build on them, and they apply not only to the quality of the observations themselves but also to the timeliness with which they are made available. Requirements for atmospheric composition data are defined through three targeted application areas within the broader WMO Rolling Review of Requirement process and are included in a number of other applications. For instance, Monitoring of Atmospheric Composition covers applications related to evaluating distributions of and analyzing changes in atmospheric composition, temporally and spatially, on regional to global scales. Such applications require very small levels of uncertainty and good global or regional data coverage, whereas the timeliness requirement for the data exchanged may be rather relaxed to ensure high quality of the observations.

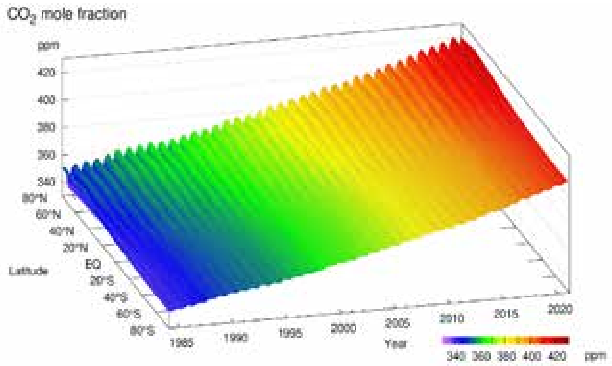


Figure 4. Variation of zonally averaged monthly mean CO_2 mole fractions. The zonally averaged mole fractions were calculated for each 20° zone. (Source: World Data Centre for Greenhouse Gases (JMA, 2020))

In contrast, Forecasting Atmospheric Composition Change and their induced environmental impacts covers applications from global to regional scales, with horizontal resolutions similar to global Numerical Weather Prediction (approx. 10 km and coarser) and stringent (near-real time) timeliness requirements. The uncertainty of observations exchanged for this purpose may be higher than for monitoring. This type of applications supports, for example, sand and dust storm warnings, haze-fog prediction and chemical weather forecasts. An example of near-real-time forecast validation is shown in Figure 6. A very specific set of requirements in terms of uncertainty, timeliness, spatial representation

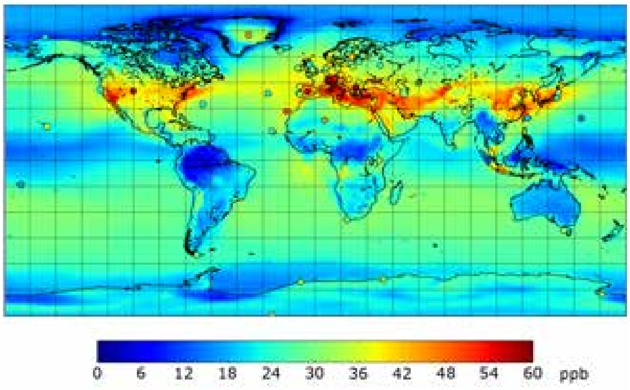


Figure 5. Global distribution of near-surface ozone concentrations measured by the GAW network stations (2000–2009) superimposed on model simulated ozone concentrations from the Monitoring Atmospheric Composition and Climate reanalysis (2003–2010). Monthly mean for July. (Source: GAW Report 209 (WMO, 2013))

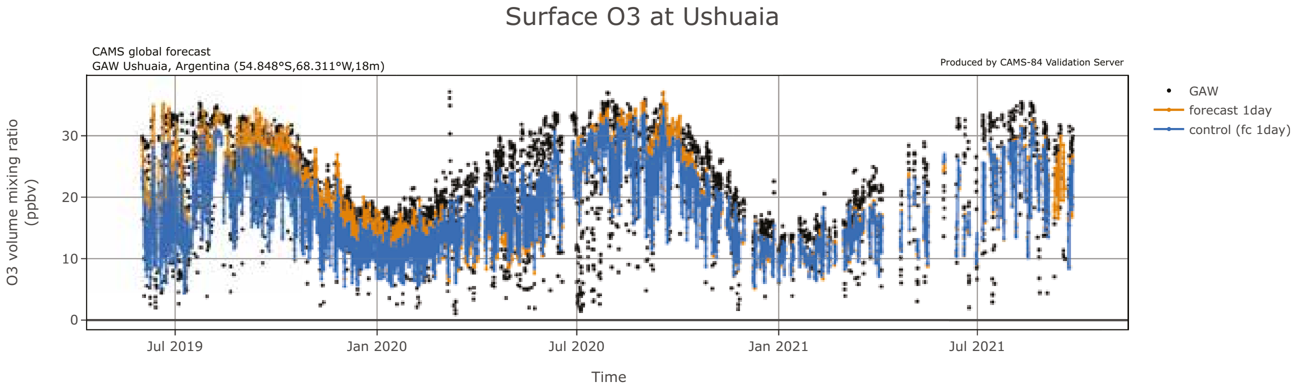


Figure 6. Near-real-time validation of the Copernicus Atmospheric Monitoring (CAMS) surface ozone forecast with data from the GAW station Ushuaia, Argentina. CAMS uses ozone data from 15 GAW stations for near-real-time validation (Eskes et al., 2021). (Source: ECMWF/CAMS *evaluation of global forecasts)*

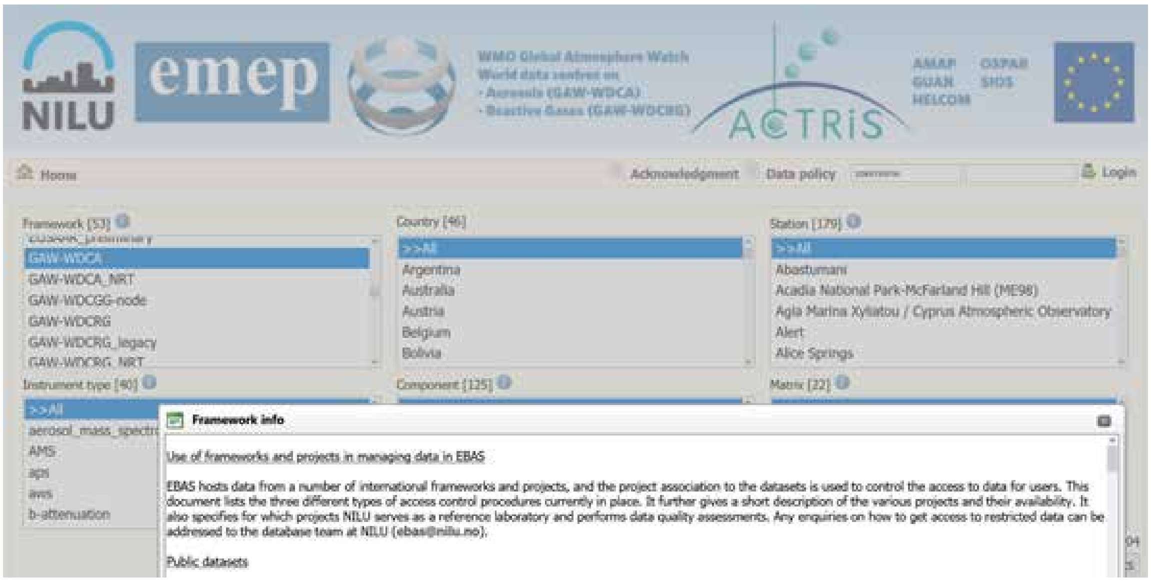
and density is applied to urban applications that target megacities and large urban complexes. These applications need horizontal resolutions of a few kilmetres or finer and, in some cases, they have stringent timeliness requirements for data availability. A distinguishing feature of this category of applications is their emphasis on research in support of operational services, such as air quality forecasting, which use approaches such as pilot projects and feasibility demonstrations. In addition to the areas mentioned here, many other applications benefit indirectly from atmospheric composition data. For instance, atmospheric composition data improves the estimation of radiative forcing in numerical weather prediction and climate projections (see WMO, 2021b).

Management and exchange of atmospheric composition data

The approach to data sharing for atmospheric composition largely depends on two factors: The agency that produced the data and national data-sharing policies. Observations made by government institutions using public funding are often subject to open data policies, where data are made freely available through government portals. This includes pollution data for compliance with national and international air quality regulations with reporting obligations.

For the research community, data represents intellectual property and they are often made available only after relevant articles have been published, which may happen long after the measurements were taken. These data by universities, research institutes and others are usually collected over a limited time period. Overall, these data contribute significantly to the operational WMO community, although in many cases this is not the primary aim behind the data collection. The atmospheric composition community has in general adopted the so-called F.A.I.R. principles (Findable, Accessible, Interoperable, Reusable) for data sharing. However, the F.A.I.R. principles do not explicitly promote open and unrestricted access, and if this is needed, such provisions must be explicitly formulated: Data need to be both technically open (i.e., available in a machine-readable standard format to be processed by a computer application) and legally open (explicitly licensed to allow commercial and non-commercial use and re-use without restrictions).

Research data are typically stored in dedicated data repositories or cloud-based archives. Due to the affiliation of the same research infrastructure to multiple projects, initiatives and programmes, duplicative data holdings across multiple repositories represents a serious issue which is currently discussed by the community. Metadata repositories that allow multiple project/network data affiliations are considered among possible solutions to avoid multiple submissions (see Figure 7). The maintenance of these repositories also presents a challenge in terms of funding and managing rapidly increasing amounts of data. There is also broad implementation of Digital Object Identifiers (DOIs) that facilitate transparency, traceability and attribution, especially between operational, research and applications communities. Further technological developments related to the implementation of data licensing that would allow for the origin and data ownership to be recognized will support researchers to share data as freely as possible. It is recognized that customized licenses and restrictions may lead to complicated license “stacking”.



Use of frameworks and projects in managing data in EBAS

EBAS hosts data from a number of international frameworks and projects, and the project association to the datasets is used to control the access to data for users. This document lists the three different types of access control procedures currently in place. It further gives a short description of the various projects and their availability. It also specifies for which projects NILU serves as a reference laboratory and performs data quality assessments. Any enquiries on how to get access to restricted data can be addressed to the database team at NILU (ebas@nilu.no).

Public datasets

Figure 7. Multiple associations with observing programmes/networks are considered by the WMO-sponsored metadata portals OSCAR/Surface and GAWSIS. A similar concept is implemented by the Norwegian Institute of Air Research (NILU). Among multiple frameworks NILU hosts the GAW World Data Centres for Aerosols and Reactive Gases. Data can be affiliated with multiple frameworks to avoid multiple submissions. (Source: NILU)

Access to citizen science and commercial data is much less structured and may even be restricted by subscription. Citizen science projects usually have dedicated websites. However, there is often a distinction between sharing raw data and processed data (products, plots), the latter being generally much more openly shared than the raw data. This may effectively limit the potential for evaluation of the quality of the underlying raw data.

Data from GAW observing stations are collected, quality-controlled and published by dedicated topical World Data Centres. There are also a number of Contributing Data Centres that provide the data of contributing networks. The metadata is available in the GAW Station Information System (GAWSIS) a part of OSCAR/Surface. These Data Centres have been working on the harmonization of data submission and data access procedures and will continue these efforts with the joint vision of a GAW federated data management system that will allow fully interoperable access to all GAW data. An example of information on available data in the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) is illustrated in Figure 8. GAW will continue to liaise with other relevant actors (contributing and research networks, space agencies, environmental agencies and others) to harmonize metadata and data formats and thus facilitate the use of GAW and other data in various applications (WMO, 2017).

Figure 8. Information on available data in the Data Search/Download website of the World Ozone and Ultraviolet Radiation Data Centre (Source: WOUDC)

Registration and attribution are conditions that do not restrict access and reuse, but that may be critical to motivating the research community to share their data. Without citations or documented evidence of use, it is difficult for the research community to demonstrate the value of the data they create to their funding agencies. Intellectual property rights can be ensured through data licensing, which determines rights of use and provides legal security for users. This allows users from academia and the private sector to build viable use cases and business models based on concrete rights of use.

Benefits of the WMO Unified Data Policy

Broad implementation of the WMO Unified Data Policy is critical for the successful delivery of multiple services related to atmospheric composition. Similarly to other cases are described in Article 2 and Article 9, improved timely forecasting of extreme events, as well as support to environmental policy, require open international data exchange. Implementation of the Unified Data Policy can facilitate advances for multiple applications, ranging from improvement of the air quality forecasts to support of transparency mechanisms under the United Nations Framework Convention on Climate Change (UNFCCC). To effectively use the data for specific applications, the quality of the data needs to be known. Thorough evaluation of the uncertainty of the data provides valuable additional information about data usability for particular services. Near-real time availability of the data is important for applications such as forecasts and warnings that need to be issued in a timely manner. For other application areas, for example, reanalysis and trend analysis, timeliness of data exchange is less important.

Adoption of this policy by multiple agencies within Members, beyond NMHSs, will ensure that advances in environmental services and policy are implemented in a comprehensive and cost-efficient way.

It is necessary to improve data exchange between the operational WMO community and the research community. Research projects often require access to external environmental data and services, including forecast information and observational data records, so there is an inherent inter-dependency between research and operations. The research community may not have access to or influence on the operational data (observations and model output) or data formats, which hinders data interoperability, interpretation and scientific progress. It will be desirable to harmonize data sharing protocols. WMO can offer the research community guidelines on data sharing protocols (WIGOS metadata standard and WIS infrastructure) to optimize the value of research data, though the clear benefits of this proposition have to be outlined to the research community. In return, WMO should facilitate the access of operational data to a wider community, emphasizing the mutual benefit of data sharing for both, academia and the operational communities to advance the common understanding and knowledge of the Earth system.

Current WMO policy is well-recognized in the research community, but that community requests clear guidance on licenses as well as clear definitions of the terms "core" and "recommended" data. Licensing is a likely to be a critical success factor to facilitate the sharing of data amongst WMO Members beyond the traditional NMHS community. Standardizing licenses for WMO data could help significantly with the uptake of the WMO Unified Data Policy. Alignment of the WMO data policy with existing licenses (such as the Creative Commons widely used in the research community) would help ensure acceptance in academia and the private sector and prevent practical obstacles for users.

No matter how timely or precise the data requirements are for a given application, a commonly shared requirement is that the data are made available at all. WMO is well positioned to build on the experience gained over its long history of operational data exchange and to extend this also to atmospheric composition data.

References online

The Global Ocean Observing System: Oceans of Data for Earth System Predictions

By Sid Thurston, NOAA Global Ocean Monitoring and Observing Program, USA, Emma Heslop, Intergovernmental Oceanographic Commission (IOC) of UNESCO, Toste Tanhua, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, R. Venkatesan, National Institute of Ocean Technology, India, and Mathieu Belbéoch, Victor Turpin, Martin Kramp and Long Jiang, all OceanOPS, France

"If you like your 7-day weather forecast, thank an oceanographer." – Craig McLean, Acting Chief Scientist, United States National Oceanic and Atmospheric Administration (NOAA), House Committee on Science, Space, and Technology Subcommittee on Environment, June, 2021.

The ocean affects us all. It covers over two-thirds of the Earth's surface. It impacts our daily lives and a broad range of economic sectors – from agriculture and marine and coastal activities to tourism, construction and insurance. As a key component of the climate system, it has a direct influence on weather patterns all over the globe, also for areas thousands of kilometers from the nearest coastline.Those are just a few of the reasons that the Global Ocean Observing System (GOOS) is critical to improving WMO products and services.

Ocean observations are needed to fulfill the WMO mandate to support the delivery and use of high-quality, authoritative weather, climate, hydrological and related environmental information and services by its Members for the improvement of the well-being of all nations. In particular, as society faces the impacts of climate change, more ocean data will be needed to better adapt and forecast extreme weather and climate events such as drought, flooding, wildfires, heatwaves and tropical cyclones.

The importance of ocean data was underlined in the findings of the recent Assessment Report from the Intergovernmental Panel on Climate Change (IPCC AR6[1], August 2021). Observed changes in several ocean parameters that impact phenomena such as heatwaves, hurricane frequency and inundation figure prominently in the report. Since 1980, sea surface temperature has risen 0.6 °Celsius (C), contributing to an excess of ocean heat content, to a roughly doubled frequency in marine heat waves which have also become more intense, and to sea level rise, while Arctic ice decreases. Before 2050, the Arctic Ocean is likely to be practically ice-free during the seasonal sea-ice minimum. Ocean acidification is increasing as a result of the uptake of carbon dioxide emissions and spreading deeper into the ocean, driving changes in saltwater chemistry.

In the current context, it is difficult to overstate the importance of GOOS as the global system for sustained observations of the ocean. Co-sponsored by WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the UN Environment Programme (UNEP) and the International Science Council (ISC), this program leads, support and coordinates long-term, sustained ocean observing for climate, operational services and ocean health. For three decades, GOOS has been coordinating in situ observations via a broad range of global, national and regional ocean observing initiatives, projects and systems.

Today, evolving and innovating the GOOS system in line with an Earth system approach, and in line with the WMO strategic plan, is critical to improving the weather, climate and water services and products of WMO Members. To support GOOS efforts to evolve and innovate, this article provides five recommendations. These recommendations, if implemented, will not only help GOOS adopt an Earth system approach, but will also accelerate the

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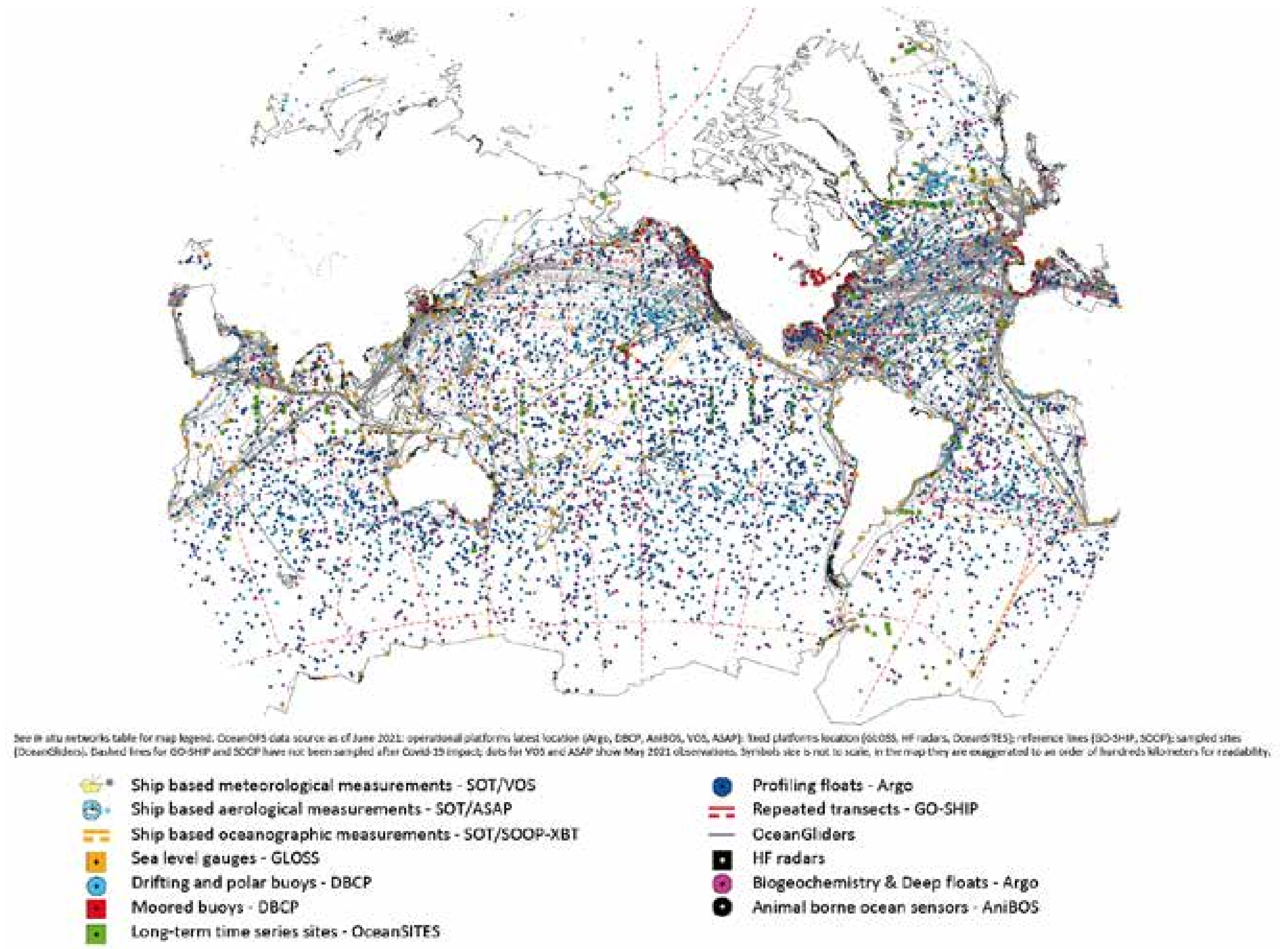
[1] Working Group I Sixth Assessment Report



See in situ networks table for map legend. OceanOPS data source as of June 2021: operational platforms latest location (Argo, DBCP, AniBOS, VOS, ASAP); fixed platforms location (GLOSS, HF radars, OceanSITES); reference lines (GO-SHIP, SOOP); sampled sites (OceanGliders). Dashed lines for GO-SHIP and SOOP have not been sampled after Covid-19 impact; dots for VOS and ASAP show May 2021 observations. Symbols size is not to scale, in the map they are exaggerated to an order of hundreds kilometers for readability.

application of ocean observations and data delivery into WMO operations for improving weather and climate forecasts, especially for extreme events.

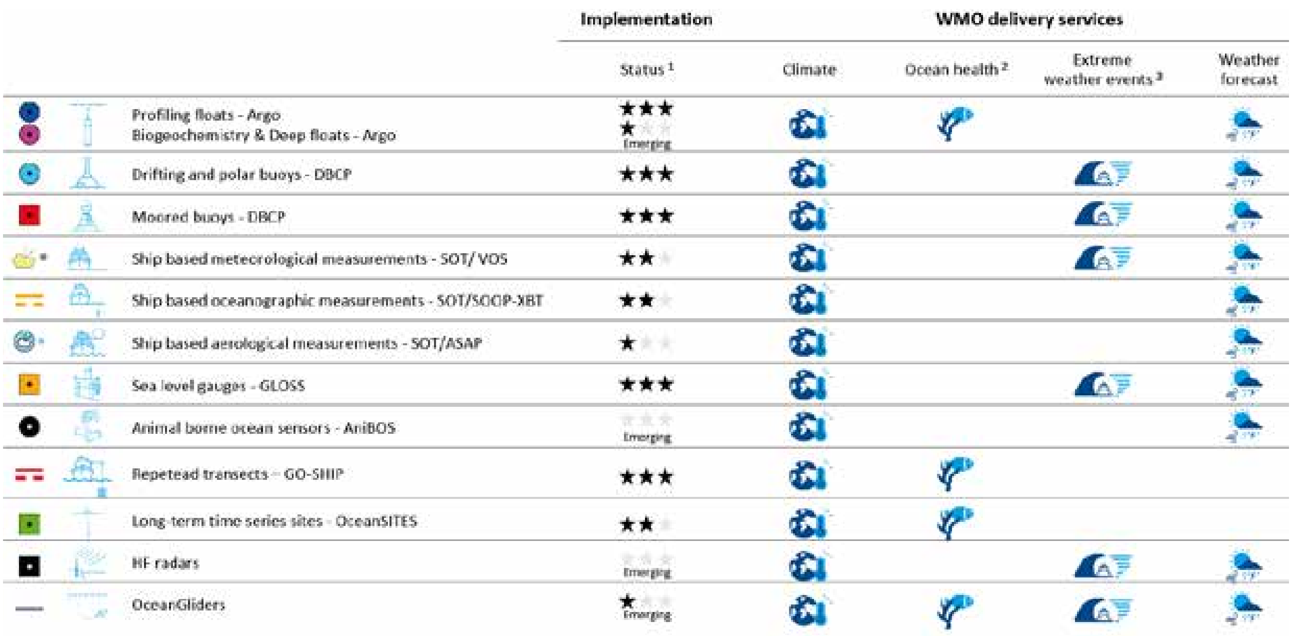
1. Augment the WMO Global Basic Observing Network (GBON) with a *global basic ocean observing system*. This "basic" oceans observing system would be designed to meet WMO's priority needs for observations and data sharing; to focus on pathways to sustain implementation; and to evolve in accordance with both operational and scientific drivers.
2. Engage with and support the GOOS *Ocean Observing Co-Design Programme* in order to build a system that fits the needs of WMO services; for example, developing a WMO-use focused *exemplar* project.
3. Adopt FAIR (findability, accessibility, interoperability, and reusability) data principles for ocean data, to accommodate the diversity in ocean observing systems and data management systems.
4. Enhance connection, cooperation and coordination between the appropriate National Meteorological and Hydrological Service (NMHS) points of contact and the GOOS National Focal Points.
5. Increase cooperation and coordination between IOC GOOS Regional Alliances (GRA) and WMO Regional Associations (RA) to improve the design and collection of ocean observations for WMO applications.

GOOS has been gradually creating an extensive global system of ocean observations since 1991, based on contributions from a large number of organizations and governments, from which nations all over the world benefit. In its first two decades, GOOS focused more narrowly on development to support climate science and to serve as the observational backbone for operational forecast systems. In 2012 its success, coupled with growing concerns about the health of oceans and demand for information products to help nations manage their ocean economies, sparked development of the visionary Framework for Ocean Observing (FOO). GOOS has since led the implementation of FOO with the goal of serving users across climate, operational services and ocean health sectors, with ever more focus on coastal and regional seas.

GOOS has worked interactively with the ocean observing community to define both Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs) based on assessments of feasibility and impact. Observations of both EOVs and ECVs are crucial for providing scientific assessments of climate change and the health of the environment, to enable environmental prediction and adaptation to climate change, and to support more effective protection of ecosystems. (ECVs are discussed in more detail in Article 5.)

Sustainability and reliability of EOV data dissemination are of importance for the delivery of ocean services. The approximately 30 EOVs are roughly equally distributed between the areas of physical, biogeochemical and biological/ecosystem. The physical EOVs are identified as "Core Data'' in the draft WMO *Unified Data Policy*, which means that Members shall exchange them; while all other BioGeoChemical (BGC) and bio/eco EOVs are classified as "Recommended Data", and as such should be exchanged by Members to support Earth system monitoring and prediction efforts.

Today, the GOOS Observation Coordination Group (GOOS OCG), along with the WMO-IOC Joint Centre for Oceanography and Marine Meteorology in situ Observations Programmes Support (OceanOPS), together strengthen and coordinate activities



	Implementation	WMO delivery services			
	Status [1]	Climate	Ocean health [2]	Extreme weather events [3]	Weather forecast
Profiling floats - Argo Biogeochemistry & Deep floats - Argo	★★★ ★☆☆ Emerging	✓	✓		✓
Drifting and polar buoys - DBCP	★★★	✓		✓	✓
Moored buoys - DBCP	★★★	✓		✓	✓
Ship based meteorological measurements - SOT/ VOS	★★☆	✓		✓	✓
Ship based oceanographic measurements - SOT/SOOP-XBT	★★☆	✓			✓
Ship based aerological measurements - SOT/ASAP	★☆☆	✓			✓
Sea level gauges - GLOSS	★★★	✓		✓	✓
Animal borne ocean sensors - AniBOS	☆☆☆ Emerging	✓			✓
Repetead transects - GO-SHIP	★★★	✓	✓		
Long-term time series sites - OceanSITES	★★☆	✓	✓		
HF radars	☆☆☆ Emerging	✓		✓	✓
OceanGliders	★☆☆ Emerging	✓	✓	✓	✓

(1) Status: status vs network's target.

(2) Ocean health area regroup the observations supporting the assessment of the biological and geochemical status of the ocean.

(3) Extreme weather events encompass heat waves, hurricanes and floods.

*Profiling floats: Now an array of 4 000 autonomous floats profiling the ocean to 2 000 m, sampling temperature and salinity for climate, seasonal forecasts and ocean heat content assessment / * Deep and BGC missions are emerging to extend the capacity of floats in depth (to 6 000 m) and Biogeochemical observations*

Drifting and polar buoys: An array of 1 500 drifting buoys that observe surface atmospheric pressure, temperature and currents over the global ocean and are indispensable for global to regional weather forecasts.

Moored buoys: Network of about 400 moored buoys that observe multiple atmospheric and oceanographic parameters, mainly in coastal and tropical areas, for regional weather forecast and ocean operations.

Ship based meteorological measurements: A large fleet of voluntary observing ships that measure marine meteorological parameters for marine weather forecasting and safety at sea, the records go back 150 years and are also used in climate research.

Ship based oceanographic measurements: The Ship of Opportunity Program focuses on underway measurements from voluntary observing ships, including XBT temperature profiles to 1 000 m depth, sea surface temperature, salinity and pCO_2*, on repeated transects or reference lines.*

Ship based aerological measurements: The Automated Shipboard Aerological Programme collects upper-air profile data for operational applications and global climate studies, using voluntary ships.

Sea level gauges: A network of 290 sea level observing stations supporting high-quality long-term time series of sea level for climate research, marine operational user, and hazard warnings.

Animal borne ocean sensors: A network of instruments deployed on marine animals to provide ocean profiles of temperature and salinity, as well as and behavioural data for sustainable management.

Repeated transects Research vessels providing high quality, data collected to the full depth and width of the ocean, on reference lines repeated every decade. They are the benchmark for instruments calibration, climate studies such as carbon cycle studies and marine biogeochemistry and fuel many scientific applications.

across 12 global ocean observing networks. This enormously complex undertaking includes almost 10 000 operational observing platforms, all committed to deliver freely available data, at a quality and latency that is fit for user applications. Observational data include above-ocean atmospheric variables (such as sea surface pressure, sea surface temperature, humidity and wind stress) from every oceanic region, including under-sampled areas (such as the poles and the Southern Ocean). These 12 global and complementary ocean observing networks are operated by more than 80 countries. They include ships, both academic and merchant, surface and subsurface mobile instruments, and fixed platforms.

A technical coordination team at OceanOPS supports the implementation of the global system through integration and harmonization of metadata – basic information about data that makes it easier to find and use. This metadata management allows for accurate monitoring of ongoing global ocean observing activity and ensures that data and metadata can be delivered to stakeholders.

The GOOS OCG, on the other hand, supports the global system through work with the 12 international ocean observing networks to build common strategies across eight areas, which include data management, best practices, metrics, capacity development and requirements. These common strategies act to strengthen the 12 networks, help pilot the system's growth and develop cross-platform implementation.

Regional bodies also play a role in managing GOOS. The GOOS Regional Alliances (GRA), established by the GOOS Regional Council in 1994, have the mandate to connect "Global to Regional to National level". The WMO reform process paved a way via the new WMO-IOC Joint Collaborative Board (JCB) for GRAs and WMO Regional Associations (RAs) to work together on common issues connecting ocean to meteorology.

A note on satellite observations: while this paper focuses on the in situ oceans observing component, it is also important to recognize the impact of very significant investments in ocean observations from space. Since the launch of the first Earth observing satellites in the late 1970s, there has been a tremendous development of remotely sensed ocean data, from altimetry, ocean colour and sea-surface temperature to salinity. The importance of remote sensing data for ocean services cannot be overstated, particularly as they are able to fill gaps in the in situ observing system. For instance, remote sensing data of chlorophyll and temperature are used to fill the gaps in the sparse ocean CO_2 observations to reach the coverage needed to estimate global fluxes of CO_2.

A fundamental aim of GOOS is that ocean data are delivered efficiently: that is, with appropriate latency, quality and with sufficient metadata, ideally adhering to the FAIR principles (Findable, Accessible, Interoperable, Reusable), to the services and users that need it, in a freely and openly available manner. This is no easy task. The ocean observing system is diverse, with a large range of actors delivering data to a large set of data portals designed for different purposes. Although the FAIR data principles are essentially a prerequisite for WMO operational services, they are still not widely implemented for many of the ocean data streams, particularly for the delayed mode data. In response, one of eleven strategic objectives in the GOOS 2030 Strategy calls for FAIR ocean data.

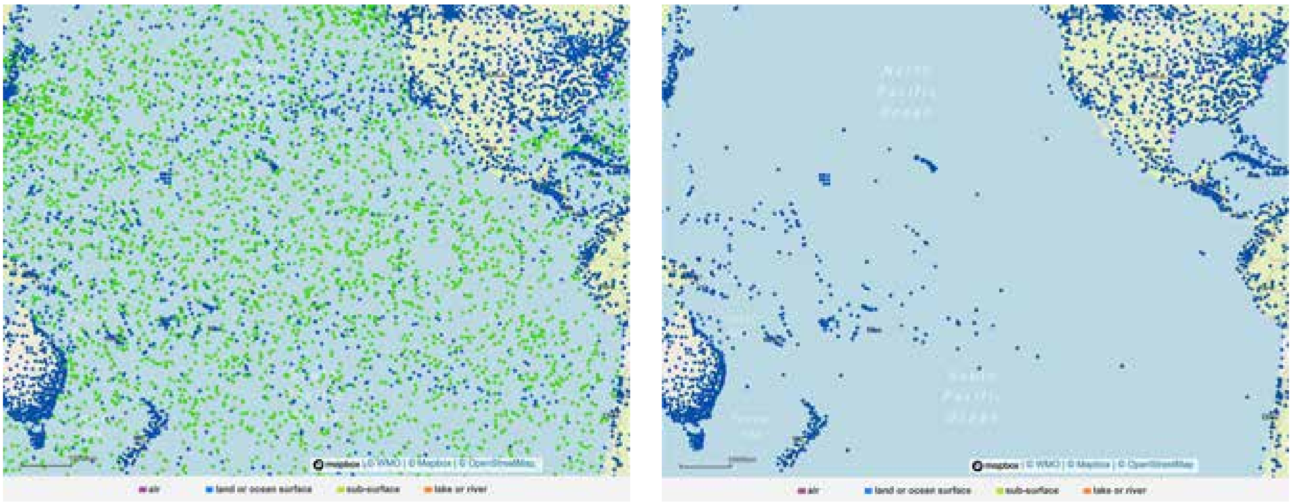
Efficient GOOS data delivery is a key objective that cannot be met without a smoothly functioning, and appropriately connected and funded, data management system. To support such a data management system, GOOS relies on cooperation with the International Oceanographic Data Exchange (IODE) and the Ocean Data and Information System (ODIS) as well as the WMO Information System (WIS). In particular the development of WIS2.0 (see Article 4) offers great potential to radically improve the dissemination of ocean data to an ever larger user group.

Challenges and opportunities

GOOS currently faces a number of challenges and opportunities that are pushing it to innovate and evolve. Resolving these in ways that integrate ocean observation systems into an Earth system approach, and in line with the WMO strategic plan, is critical to improving the weather, climate and water services and products of WMO Members.

A major challenge for both providers and users of ocean observations is to determine which efforts really need to be sustained on a continued basis, and then to establish a commitment for sustained funding and operational support for those. To respond to this challenge, there is a need to extend and build partnerships for the ocean observing enterprise, and to explore development of a global basic oceans observing system.

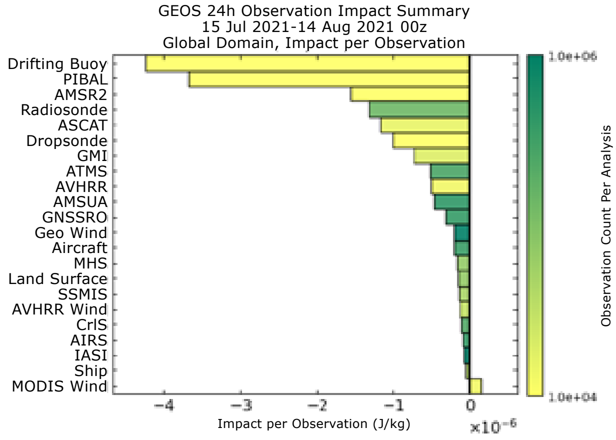
Experimental or mission-based ocean observation systems are justifiable normally for a finite period to



WMO OSCAR Surface Maps Without and with GOOS Ocean Observations

Although the WMO Observing Systems Capability Analysis and Review Tool (OSCAR) calls for surface observations, we are missing 2/3rds of the Earth's surface if we do not include Ocean data. Augmenting GBON with ocean observations is the way forward to improve climate and weather services for lives, livelihoods and properties. In this Figure, the tropical Pacific Ocean region of El Nino, the need to include ocean data into a unified system is obvious, green dots on the right panel are ocean observations.

address a research challenge or to meet a specific need. However, there has been a tendency to develop dependency on research-funded systems that fill a specific gap in measurement or coverage and to consider them as de facto operational systems. The number of players in the ocean observing space drives this diversity of applications and (growing) demand, and vice versa, and contributes to the richness of observations that, if shared, add value to many other domains. However, this diversity can also lead to a lack of coordinated focus on ocean observing priorities, particularly at national levels where the funding largely originates and competition for resources is rife. Additionally, the ongoing use of research funding to support de facto operational systems puts a burden on the research community, since those funds are then not available for new research.



Sea Level Pressure (SLP) Observations
Impact on Improving Numerical Weather Predictions (NWP)

In situ ocean surface drifter sea level pressure (SLP) observations are extremely valuable for anchoring the global surface pressure field and contribute significantly to NWP skill. Forecast sensitivity observation impact analysis (graph) indicates that the SLP drifters provide the largest per-observation contribution to skill.

There is no magic bullet that will deliver new ocean observations funding to support a transition to operations. However, building stronger links between WMO-affiliated national agencies and IOC-affiliated institutions could yield mutual benefits in terms of greater collaboration, increased efficiency and reduction of duplication. Additionally, there is a need to develop an open process, tools and infrastructure to coordinate and prioritize user requirements and assess system capability in order to deliver in a platform-independent manner. A clearer delineation of which elements of global (and, by extension, regional and national) ocean observing systems might constitute an irreducible basic ocean observing system would support better decision-making by the entities who lead development of observing systems. Such entities (for example satellite operators) seek to secure ongoing funding commitments to operate and maintain them for the long term and (often) to freely share the data with the global community. Their fundraising and development work should build on EOVs and other identified ocean data priorities, as well as upon initiatives already underway.

GOOS as well as the WMO-IOC partnership embraces the full breadth of applications of ocean observations. These range from understanding, modelling and predicting the state and structure of the oceans in order to better manage the threats, hazards, productivity and sustainability of the ocean environment, to understanding the role that the oceans play as an integral part of the overall Earth system, across all timescales.

This broad range of applications means that both sustained, ongoing ocean observations and mission-based ocean observations are needed (as outlined in the GOOS 2030 Strategy). Again, however, some prioritization would be helpful. The formalization of a tiered approach to the ocean observing system should be explored, featuring as its foundational component a global basic ocean observing system. Such a global basic ocean observing system would be designed to meet priority needs for observations and data sharing; would evolve and innovate in accordance with operational and science drivers; and would focus on pathways to sustained implementation.

Addressing barriers related to national sovereignty of the seas is another important consideration in design and implementation of a global ocean observing system. The 2019 WMO driven "Ocean-Safe" workshop highlighted the importance of facilitating access to Exclusive Economic Zones (EEZs), in particular, for making and sharing subsurface measurements critical for operational applications like weather forecasting and safety of life at sea. The Argo program, the most abundant source of subsurface observations, has facilitated access for instruments deployed in high seas that drift into an EEZ, but not for deployments directly into an EEZ, which inevitably limits its global data coverage. Bilateral requests for marine scientific research clearance, needed six months ahead of operations, are today mostly not accommodated; and impractical for autonomous instruments deployed from a wide range of multinational opportunities, including from third parties. There is a need to facilitate these critical observations, possibly building on the Argo notification scheme to guarantee transparency for coastal states.

At the same time, a series of opportunities beckon, most notably the WMO *Unified Data Policy*. This substantial update of WMO data policy provides a once-in-a-lifetime opportunity for the ocean research community. It would provide this community with much greater free and unrestricted access to data from non-traditional sources (e.g. weather, atmosphere and cryosphere data) that impact ocean services and research via applications such as coupled modelling. In addition, access to WIGOS and WIS tools will support increased discoverability, standards, station IDs, and exchange that will benefit the objectives of both WMO and the ocean observing community. The WMO *Unified Data Policy* will also lead to increased recognition of data providers through the attribution of research data used for operational purposes. Finally, the revised policy also has the potential to influence national policies, thereby opening up inter-agency sharing and coordination of ocean data at national levels.

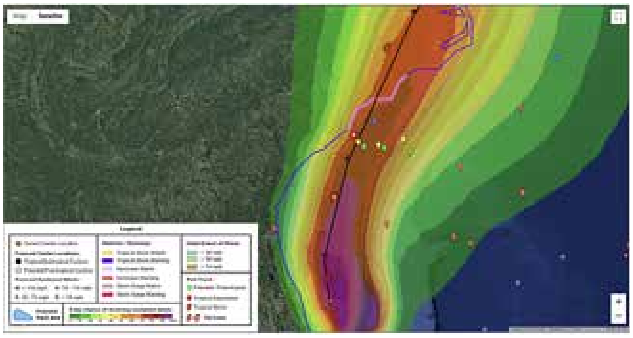
Additionally, cutting-edge projects like *OpenGTS* offer the opportunity to enhance access to free met-ocean data. Such projects will demonstrate the benefits of an integrated and collaborative approach to strategic areas like open data access, met-ocean forecast and environmental warnings. The implementation plan of the WIS2.0 endorsed *OpenGTS* as a demonstration project, and embraces activities that may benefit the WMO community for wider and more comprehensive data accessibility.

A number of additional opportunities have arisen through other international data management projects. To optimize the diversity of funding and satisfy requirements from ocean observing agencies, GOOS is participating in multiple other international data management efforts, which seek to harmonize data and metadata management internationally and to develop a global strategy and unified implementation plan. OCG, OceanOPS, IODE and WMO all play a role in this work. This strategic coordination capacity is supported by the GOOS infrastructure and has already demonstrated fruitfulness and efficiency. It is worth highlighting, in particular, the Ocean Best Practices project, which aims to improve uptake of observations as well as data and meta data.

Practical successes to help improve services

Ocean observations are fundamental to achieve weather ready and climate smart nations. Several examples below demonstrate how ocean data are, or could be, used to deliver more accurate weather forecasts.

- Sea level pressure (SLP) observations acquired by drifting buoys are essential in Numerical Weather Predictions (NWP) delivered by meteorological agencies around the world.
- The *Barometer Upgrade Program* of the Data Buoy Cooperation Panel, supported by NOAA's

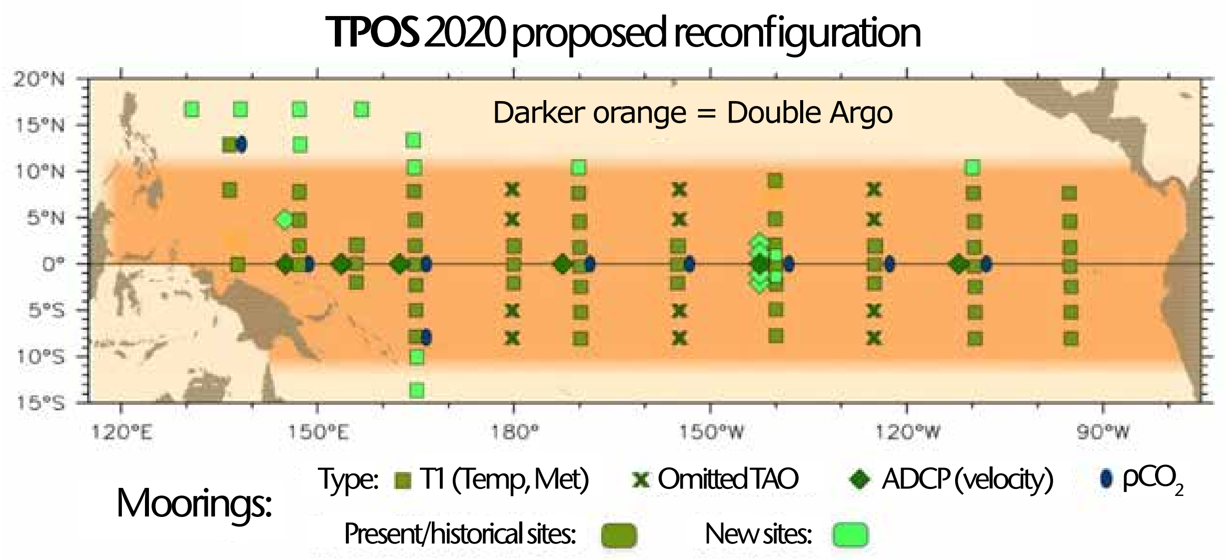


NOAA's Efforts to improve hurricane intensity forecasts were applied in August 2020 to Hurricane Isaias deploying in situ gliders, drifters, and Argo floats

Global Drifter Program, allows users from the meteorological community to measure sea-level air pressure in their areas of interest; the users simply pay the incremental cost of adding a barometer port and pressure sensor to a standard drifter.

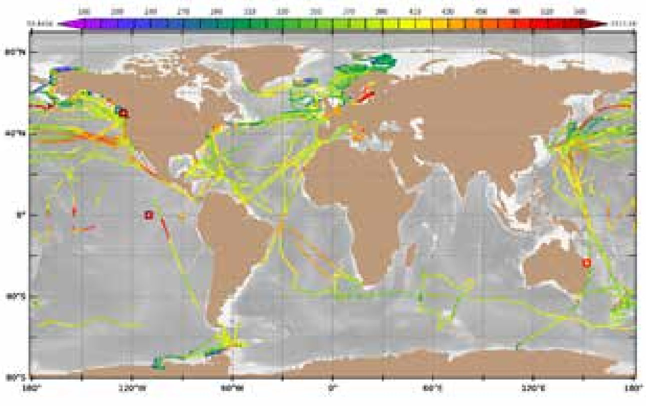
- Progress has been made in the prediction of extreme events by using ocean data. Multiple types of ocean observation stations – drifters, OceanGliders, Argo floats and moored buoys – collect ocean data along the projected tracks of tropical cyclones for real-time assimilation into NWP models.
- Since 2020, North Atlantic Hurricanes are providing real cases for NOAA, allowing the agency to evaluate the ocean component of the full end-to-end hurricane forecast data flow.
- Similarly, India's Meteorological Department (IMD), working with India's National Institute for Ocean Technology, is delivering time-series observations from a network of moored data buoys to help improve forecasts of the track and intensity of cyclones. The high-frequency subsurface ocean temperature observations are extremely useful for the accurate estimation of upper-ocean heat content, and for understanding the role of the ocean in the intensification of tropical cyclones.
- The Tropical Pacific Observing System (TPOS) is being updated as a co-designed atmospheric and oceanic observing system in support of atmospheric teleconnections studies – the studies of how climate anomalies are related to each other at large distances – as well as operational forecasting.

Regarding climate, ocean data are essential to effective prediction, but outstanding data needs remain. The level of carbon dioxide in the atmosphere has increased by about 50% since pre-industrial time; this is the primary driver of climate change. The ocean has taken up an estimated 45% of the cumulative fossil fuel emissions. It is critical to closely monitor the flux of CO_2 between ocean and atmosphere and the accumulation rates of carbon in the interior ocean. However, there are large gaps in the required observations, particularly due to the large seasonal variability in surface ocean CO_2, and the observing effort is currently only weakly coordinated. Data on ocean carbon are currently mainly available through community-driven data



Tropical Pacific Observing System (TPOS)

TPOS is a multinational met-ocean observing system designed to measure the subsurface and surface ocean and the atmosphere spanning the tropical Pacific from approximately 10°S to 10°N. TPOS seeks to accelerate advances in technology, understand and predict tropical Pacific variability, and inform policymakers and benefit society.



The Surface Ocean CO_2 Atlas (SOCAT) is a synthesis product for quality-controlled, surface ocean fCO_2 (fugacity of carbon dioxide) observations.

products: SOCAT (the Surface Ocean CO_2 Atlas) is focusing on surface carbon data, whereas GLODAP (the Global Ocean Data Analysis Project) is delivering interior ocean carbon data.

The common denominator to success and progress in the examples above is collaboration between ocean institutes and meteorological agencies. Without technical, operational, financial and political partnerships, these accomplishments would not be possible. Cooperation between atmospheric and oceanographic communities at all levels is a prerequisite to any effort toward improving weather and climate services.

Ocean Observing Co-Design Process

We need additional ocean observations; but we also need to make sure funding is spent wisely and to establish clear priorities for future investments in ocean observations. Breaking down the silos between ocean institutes and meteorological agencies is critical to providing the largest possible impact of investments, and to effectively advocate for ocean observations at the highest political level. It will also accelerate the application of ocean observations and data delivery into WMO operations, thereby helping Members improve weather and climate forecasts, especially for extreme events.

A promising development is the GOOS *Ocean Observing Co-design*, one of the programs endorsed by the United Nations Ocean Decade. Co-design seeks to engage ocean institutes and meteorological agencies to jointly build the process, infrastructure and tools needed to evolve a truly integrated ocean observing system.

GOOS Co-Design will develop a more user-focused process to design and implement a large range of ocean observations by integrating with the modelling, forecast and services communities. Co-design of a *fit-for-WMO* ocean observing system will require that WMO experts work in close collaboration with GOOS colleagues at every step along the value chain pictured below. *Exemplar* projects, such as extreme event forecasting or carbon accounting, are selected to assess the observations required to deliver improved WMO forecasts.

The WMO *Unified Data Policy* has the potential to influence national policies that will open up inter-agency sharing and coordination of ocean data at national levels. Combined with Systematic Observations Financing Facility (SOFF) investments and partnerships, it is now possible for the first time to augment existing ocean observations into GBON to the inclusion of the remaining 2/3rds of the earth's surface. Co-designing, co-investing, and co-advocacy together will help developing the appropriate ocean observing capacity to deliver the climate and weather forecasts required to support short- and long-term decision-making in the context of climate change.

The furthest and most frigid parts of the globe – cryosphere data for weather, water, climate and the environment

By Árni Snorrason, Director General, Icelandic Meteorological Office and Chair of the Global Cryosphere Watch Advisory Group (GCW-AG), Øystein Godøy, Senior Scientist, Norwegian Meteorological Institute and Chair of the Cryosphere and Data Interoperability – Global Cryosphere Watch, Sue Barrell, Chair, Study Group on Data Issues and Policies, co-chair of the EC Panel on Polar and High Mountain Observations, Research and Services (EC-PHORS), and Rodica Nitu, WMO Secretariat (Global Cryosphere Watch)

WMO has adopted a unified Earth system approach to ensure weather, water and climate decisions are better informed by an integrated monitoring and prediction of all relevant Earth system components. This includes extending its reach to the furthest and most frigid parts of the globe, the Arctic, Antarctica (Figure 1) and the high-mountain regions, where the cryosphere is a prominent feature (IPCC, 2019).

An integrated Earth system approach allows for a better representation of the complex interactions between different components of the system– atmosphere, oceans, hydrosphere and cryosphere. It strongly relies on coupled assimilation to ensure consistency and to enhance the exploitation of interface observations that depend on more than one component, for the benefit of numerical Earth system prediction models.

Data assimilation is a critical component of both uncoupled and coupled Earth system prediction models. As the spatial and temporal resolution of these models steadily increase, improved in situ and remote-sensing observations are required to provide the most consistent representation of the Earth system components. Improvements in the spatial and temporal resolution of observations, as well as extending the number of variables that are observed, are necessary to further improve the performance of numerical prediction systems.

Figure 1. Antarctica -abandoned Base and Observing Station (Photo: Sue Barrell)

In cryosphere regions – whether polar or mountainous – producing accurate and reliable predictions is more difficult at all timescales than it is for other

Cryosphere

The word "cryosphere" comes from the Greek word for cold, "kryos."

The cryosphere is the part of the Earth ‘s climate system that includes solid precipitation, snow, sea ice, lake and river ice, icebergs, glaciers and ice caps, ice sheets and ice shelves, and permafrost and seasonally frozen ground. The cryosphere extends globally. It exists seasonally or perennially at most latitudes, not just in the Arctic, Antarctic and mountain regions, and in nearly 100 countries. It influences the climate of the entire planet. Approximately 70% of the Earth’s freshwater exists as snow or ice.

The Second International Meteorological Congress, held in 1879, drew the attention of meteorologists to the importance of measuring the variations in length and thickness of the glaciers. It recommended to institute continued glacier observations and to publish the results.

regions. Our understanding of and ability to model some of the processes unique to these regions is limited, for example, for small-scale processes occurring during sea-ice formation, snowfall, solid precipitation and within mixed-phase clouds and stable boundary layers. The limiting factors currently include (i) the limited availability of in situ observations, in particular those on snow and ice, (ii) the sub-optimal assimilation over snow and ice-covered surfaces of satellite observations in polar regions, (iii) the limited availability of adequate remote-sensing and satellite observations over polar and mountain regions (snow cover, glaciers, etc.), and (iv) the limited reliable data exchanges and near-real-time access to the available data.

Cryosphere data for hydrometeorological and climatological information and services

Many applications and services within the mandate of WMO Members, as well as those across the wider scientific community, increasingly require sustained access to cryosphere data. Such data complements meteorological, hydrological and ocean data as well as data used in the modelling and reanalysis fields. Climate-related changes in regions with snow, sea ice, glaciers and permafrost could trigger feedback processes and changes in precipitation and freshwater regulation regimes over large regions – up to the continental and hemispheric scale.

Cryosphere data for data assimilation into Earth system models

Snow and ice observations are increasingly used for data assimilation in Numerical Weather Prediction (NWP) models and have substantial impact on the performance of these models. Data on snow, glaciers, sea ice and permafrost are also increasingly used for numerical climate prediction, seasonal forecasting, operational analyses, climate reanalyses and for model verification.

In the context of large-scale coupled models, and in particular for cryosphere data, the exchange of snow and ice data across institutional, sectoral and political boundaries is essential to advancing the development of hydro-meteorological and climate services (Helmert et al., 2018). Insufficient prediction capacity in remote mountain regions may seem irrelevant, but the impacts travel downstream via rivers and the socioeconomic consequences are felt by communities living downstream and in lowlands.

Cryosphere data for hydrology

As all major rivers originate in mountains, these are often referred to as the "water towers of the world" (Immerzeel et al., 2020). The mountain cryosphere – glaciers, snow, permafrost and seasonally frozen ground – plays a fundamental role in providing and regulating freshwater resources for around half of the world's population (Egan and Price, 2017). This notably includes those living in densely populated lowland areas, such as the Ganges–Brahmaputra Delta.

Snow, glaciers, permafrost and seasonably frozen ground act as reservoirs of freshwater. Data on melting snow and ice are essential for understanding the variability of water resources. The short-term cryosphere monitoring is critical for spring melt and flash flood forecasting, for hydropower production planning, for water availability in arid regions (e.g. Andes – Schoolmeester et al., 2018), and for irrigation, while the glacier melt is a key predictor for long-term water scarcity.

Many countries rely on snowmelt forecasts (one to several months in advance) to predict river run-off, flood potential and to provide flood alerts (Figure 2). A rise in the frequency of rain on snow events increases the exposure to avalanche and flood risks. Whereas augmented river discharge into the Arctic brings huge quantities of freshwater to the Arctic Ocean and surrounding seas, thereby influencing the oceanic circulation.

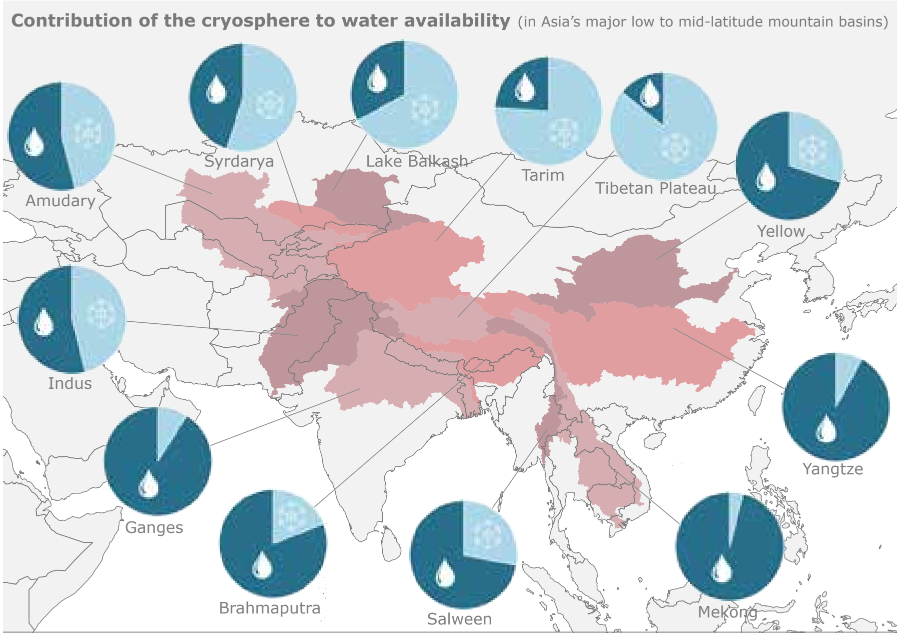
Further improvements to understanding and modelling the hydrological cycle for cold regions, are necessary. Access to observations is critical, for instance to better model the relationship between precipitation and run-off, including the contributions from permafrost and seasonally frozen ground.

Cryosphere data for ice forecasting and services

Reliable estimates of sea-ice extent and volume in the Arctic Ocean and in the Southern Ocean around Antarctica are needed for understanding climate change, for initializing numerical weather forecasts, for sea-ice prediction and in operational ocean–sea-ice reanalyses (Zuo et al., 2019).

Monthly and seasonal outlooks of sea-ice presence and dynamics are in great demand by the maritime industry for safe navigation and operation in polar waters (Figures 3 and 4).

Contribution of the cryosphere to water availability (in Asia's major low to mid-latitude mountain basins)



Data in "Towards mountains without permanent snow and ice" by Huss et al., 2017 (Table 2 - period: from 1998 to 2012).

Figure 2. Contribution of the cryosphere to the water availability in the basins of major rivers in Asia, as estimated based on data from 1998 to 2012 as published by Huss et al., 2017 (Illustration by Nora Krebs, WMO)

Persistent reductions in Arctic sea-ice thickness and in multi-year sea-ice area lead to greater mobility of sea-ice cover and increased variability of sea-ice conditions. These changes necessitate a different approach to timeliness and horizontal resolution of ice charting and weather forecasting for marine transportation in high-latitude areas.

Improvements in sea-ice (and coupled ocean–sea-ice) modelling, both for the Arctic and the Southern Ocean, are needed to overcome current limitations (Figure 5). These limitations are due partly to a general under-sampling of the polar oceans, especially for a wide swath of the Antarctic sea-ice zone, and partly to difficulties in deriving accurate sea-ice products from currently available remotely-sensed data. As younger first-year ice is becoming more dominant – resulting in a seasonal ice regime in the Polar regions – it is critical that operational ice services incorporate more timely and accurate ice data in their monitoring activities.

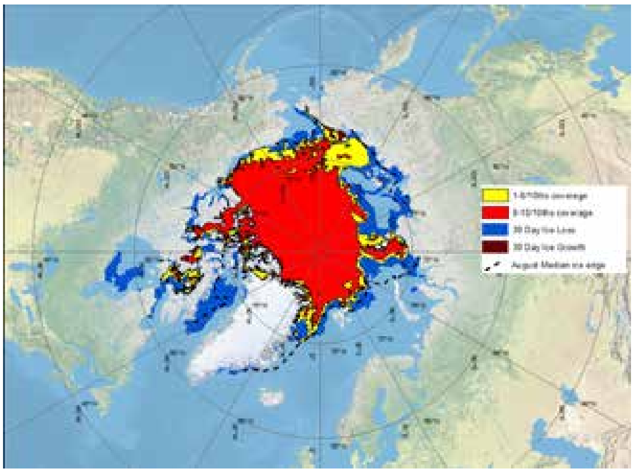


Figure 3. 30-day Ice Extent Change in the Arctic, produced by the U.S. National Ice Center, on 27 September 2021, and accesseååd on 28 Sept 2021 (https://usicecenter.gov/pub/change30day_n.png)

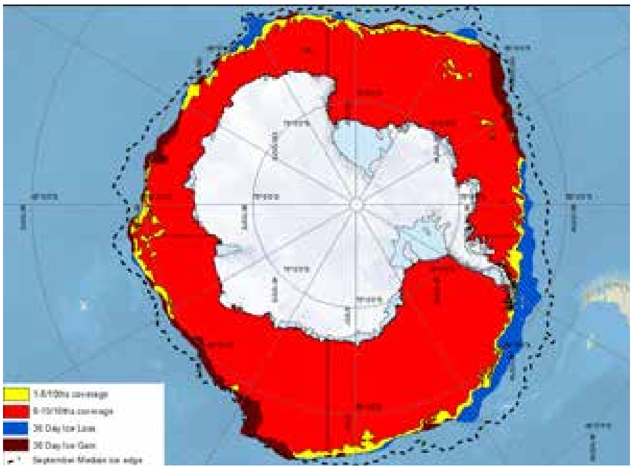


Figure 4. 30-day Ice Extent Change Antarctica - produced by U.S. National Ice Center, on 27 Sept 2021, accessed on 28 September 2021 (https://usicecenter.gov/pub/change30day_s.png)

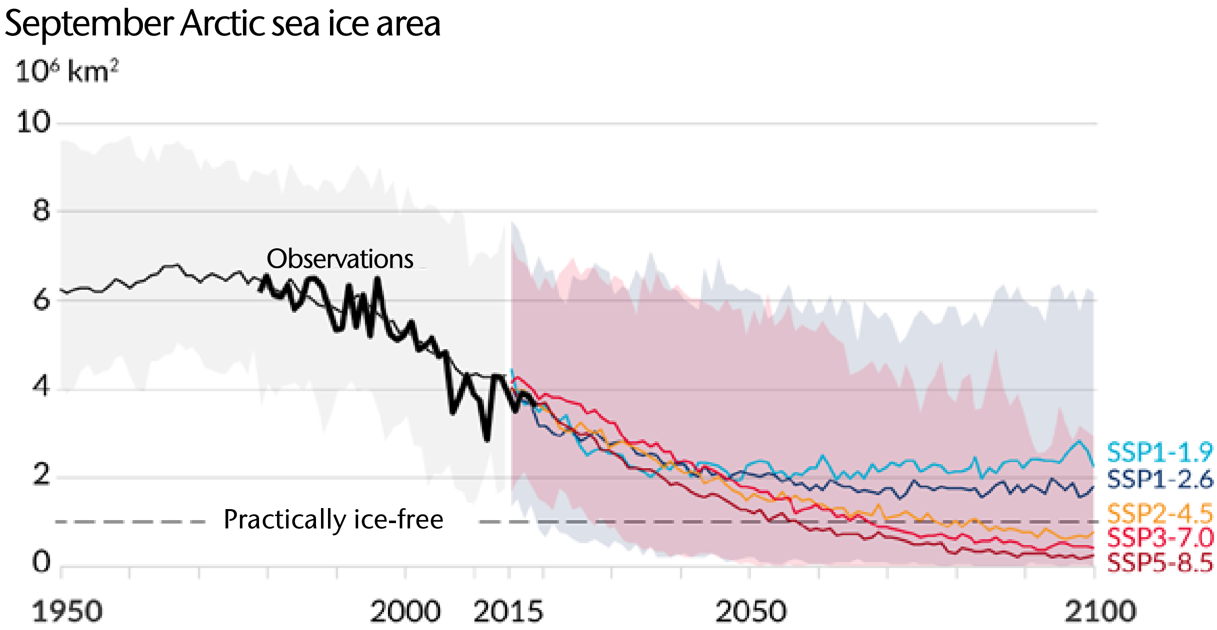


Figure 5. September Arctic sea ice area in 106 km² based on satellite-based observations and CMIP6 model simulations. Very likely ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under mid and high GHG emission scenarios. The figure is adapted from Figure SMP.8 in IPCC (2021). Observations added by Prf Ed Hawkins (http://www.climate-lab-book.ac.uk/2021/adding-observations/) (Courtesy: Thomas Lavergne).

Cryosphere and the changing climate

Data on the changing ice sheets of Antarctica and Greenland (Figure 6) and on mountain glaciers are essential to understanding and modelling sea-level rise. More than a billion people – as well ecosystems – whether on small-island communities in the Atlantic, Indian and Pacific Oceans or in the large coastal cities of the world, are concerned.

Systematic climate datasets on snow and ice also are necessary for reliable engineering design of infrastructure in cold climates, for example, for transportation, buildings, water supply, etc. They are also essential for addressing the effects of coastal erosion and subsequent changes in coastlines. Data on ground-ice conditions are emerging as critical for land-use planning and for assessing the potential release of greenhouse gases.

Figure 6. Climate change significantly changes the infrastructure design conditions in the regions where snow and ice are present, and adaptive strategies are needed (Ittoqqortoormiit Village – Eastern Greenland) (Photo: Sue Barrell)

Cryosphere changes and natural hazards

Integrated approaches to monitoring hydrometeorological changes that include cryosphere information are essential for developing early warning systems to warn of impending related risks and extreme events. These range from avalanches, catastrophic snowmelt floods (Rössler et al., 2014), glacial lake outburst floods (GLOFs or jökulhlaups), ice jams on rivers and lakes, river damming from surging glaciers, coastal decay, landslides and slope failure to the increased presence of icebergs on navigation routes, and other cryosphere related hazards. Glacial lakes have caused some of the world's most devastating floods, for example, in the Andes (Huggel et al., 2020) and the Hindu Kush Himalayas. In a rapidly changing climate, access to accurate inventories and descriptions of past events and to robust climate datasets are critical to underpin hazard assessments (GAPHAZ, 2017) and prepare adaptation strategies (Figure 7).

Extending data exchange into polar and mountain regions

With its development of the Unified Data Policy, WMO is recognizing and responding to the need to broaden access to cryosphere data at a global level to further improve and sustain critical hydrometeorological and climate services provided by its Members. The Policy will help realize the WMO vision and strategy for an integrated Earth system approach to monitoring, modelling and prediction. The end goal is to further inform and enable WMO Members to provide services critical to protecting the safety and well-being of their citizens.

Figure 7. The Palcacocha Glacier lake (Peru) is drained using siphons to avoid Glacier Lake Outburst Floods (GLOF) (Photo: Christian Huggel)

The new Policy recognizes that, unlike long-standing weather, climate, and hydrological monitoring infrastructure and systems, the systematic monitoring of cryosphere has emerged only in recent decades, driven by climate system research, and mostly through a bottom-up approach.

However, despite the increased interest, many mountain and polar regions remain insufficiently monitored due to high costs, difficult access (Figure 8), extreme operating conditions, insufficient local capacity, multi-state jurisdictions, and weak or absent institutional mandates. Even meteorological stations are sparse in these regions. This shortfall negatively impacts model performance, leading, for example, to an altitudinal bias in precipitation forecasting in high mountains.

Progress has been made on addressing the cryosphere observing needs with space-based systems, mostly for polar regions, less so for mountain regions. Many gaps remain in what is observed as well as in the access to and the assimilation of cryosphere space observations.

In many countries, cryosphere observing systems continue to be operated by multiple institutions with diverse mandates – from research, academia, hydropower production agencies, naval and ice services to space agencies, National Meteorological and Hydrological Services (NMHSs) and others – with research entities continuing to play a key role. In many developing countries, cryosphere observations and research continue to be part of internationally funded projects with limited or no links to national institutions, including the NMHS.

Figure 8. High Mountain Observations – Station Mueller Hut, 1818 m elevation, New Zealand – accessible only by helicopter and experiencing annual snow accumulations of over 4 metres. Image courtesy of Christian Zammit; contribution to the WMO Solid Precipitation Intercomparison Experiment (SPICE), WMO Report No. 131 (Nitu et al., 2018)

Cryosphere data in the WMO Unified Data Policy

Data sharing is important for research organizations (Pan et al., 2021) in their quest to increase our understanding of the interactions among the atmosphere, cryosphere, hydrosphere and biosphere. This is especially so as they seek to provide answers to increasingly complex questions on the socioeconomic and environmental impacts of unprecedented changes in the climate.

The international scientific community is actively taking steps to facilitate broader access to research data. The FAIR (Wilkinson et al., 2016) data principles, with four pillars – Findable, Accessible, Interoperable, and Reusable – provide a set of high-level guidelines for research data holders. FAIR places emphasis on enhancing the ability of machines to automatically find and use the data, in addition to supporting reuse by individuals, while attributing ownership and protecting intellectual property, for example, through licenses.

Through its Unified Data Policy, WMO recognizes the wealth of cryosphere data that exist across this broader scientific community and the contribution that these can make to the WMO Earth system strategic focus. The policy therefore emphasizes the need for strengthened two-way engagements and data exchange between operational and research agencies, and it seeks to articulate clearly its principles and the benefits it confers to all stakeholders. In particular, the unified data policy calls for priority Earth system data (i.e. both 'core' and 'recommended' data) to be freely exchanged by WMO Members, including for the purposes of public research, without conditions. This reflects the importance of research outcomes and insights on driving ongoing advances in capability across all aspects of WMO's mandate.

The policy also calls on Members to honor requests for attribution of data ownership whenever possible, as a means to provide recognition and protect the intellectual property rights of the owner of the data as feasible. Where appropriate, Digital Object Identifiers (DOI) may be used for scientific data access, tracking, and citation. Recognition of ownership is mutually beneficial for owners and users of data, and citation allows the scientific community to show to document to their funding agencies how their data are used.

WMO Global Cryosphere Watch (GCW) – facilitating access to cryosphere observations and data

The WMO Global Cryosphere Watch (GCW) acts as a convener for developing coordinated approaches across operational and research communities in support of key cryospheric in situ and remote-sensing observations as well as the access to data and information on the state of the cryosphere. The observing component of GCW is an integral part of the WMO Integrated Global Observing System (WIGOS). The GCW Data Portal is hosted by the Norwegian Meteorological Institute and supported by the WSL Institute for Snow and Avalanche Research (Switzerland). Through its Data Portal, GCW strives to provide access (Bavay et al., 2020) to cryospheric and ancillary data, both real-time and archived (in the form of climate consistent time series), via cost-efficient mechanisms within the framework of the WMO Information System (WIS), by building on existing data exchange within and external to WMO. Complementary to WIS, GCW fosters the inclusion of cryosphere specific functions as part of the WMO Global Data Processing and Forecasting System (GDPFS), supporting specialized services for polar and high mountain regions.

Cryosphere data are sourced from NMHSs and from other operational and scientific entities (Figure 9), with the latter using a range of different data management approaches, often quite different from those used in the WMO community. GCW is using the tools and procedures available through WIGOS and WIS to establish links between the cryosphere scientific communities and WMO data providers and users. These include (1) allocation of WIGOS station identifiers for observing facilities, (2) the use of WIGOS metadata to document observing facilities, (3) standardization and registration of cryosphere observing facilities alongside meteorological, climate and other observing facilities, in the WMO OSCAR/Surface database, (4) the documentation of cryosphere observing requirements and capabilities in the OSCAR/Requirements database, (5) standardization and interoperability supporting the discoverability of cryosphere datasets within WIS, (6) exchange of the cryosphere data for operational purposes through WIS, and (7) providing access to the free and unrestricted WMO data to the non-NMHS community.

The implementation of the WMO Unified Data Policy offers incentives to improve connectivity between providers of cryosphere data and NMHSs. While the adoption of tools brokered by GCW may come at a cost for many data providers, the aspiration is that they would benefit, in return, by gaining access to data for multiple providers and to capabilities to monitor what data are exchanged, the use and reuse of shared data as well as being able to influence further developments of tools relevant to them. The ability to report on the data available will also help to identify observational gaps and capabilities. For example, mutual benefits are anticipated if snow data collected at the regional level would be shared by default with agencies at the national level and NHMSs (Vionnet et al., 2021).

At the practical level, GCW supports and enables contributions from data providers with limited resources and capabilities for data management, by making a software package for transforming data from unstructured to structured NetCDF/CF (FAIR compliant) available through the GCW Data Portal (Bavay, Fiddes and Godøy, 2020).

Partnerships for access to data from polar and high-mountain regions

Significant steps have been taken by GCW as a broker of data for polar and high mountain regions. For polar regions, the existing engagements between GCW and the joint Arctic Data Committee (ADC) of the Sustaining Arctic Observing Network (SAON) and the International Arctic Science Committee (IASC), as well as the Scientific Committee for Antarctic Data Management (SCADM) of the Scientific Committee for Antarctic Research (SCAR) provide opportunities for enhancing the collaboration, leading to increased access to available data. It is notable that SCAR, as the scientific committee of the Antarctic Treaty System, is mandated to facilitate free and unrestricted access to Antarctic scientific data and information. As documented by ADC, data on the Arctic exist and flow independently within a complex Arctic Information Ecosystem (AIE – Pulsifer et al., 2020) of institutions and data centres, but it aims to build capacity to support relevant applications and link to the global data needs to meet regional needs and enhance disaster resilience in the Arctic.

Figure 9. Field work and installation of new sensors at the permafrost monitoring station at Janssonhaugen (78°N) on Svalbard on a cold day in mid-February. (Photo: Ketil Isaksen)

For high mountain regions, the data landscape is much more fragmented (Thornton et al., 2021, Shahgedanova et al., 2021). Collective efforts are being made (Adler, Pomeroy and Nitu, 2020) to address barriers through mechanisms such as those facilitated by the Mountain Research Initiative and its flagship activity, such as GEO Mountains, and the International Network or Alpine Research Catchment Hydrology (INARCH). In 2019, GCW signed a 5-year Memorandum of Understanding with the Third Pole Environment program, with a dedicated focus on establishing interoperability with the Third Pole Environment Data Center (Xin Li et all, 2021, also # 10). Similar engagements are being pursued with other research data centres to further facilitate the access to critical streams of cryosphere and ancillary data.

These partners recognize that WMO is well-positioned to play a key role regarding data policies and practices by fostering greater integration beyond specific regions and domains. To this end, if enacted, the Unified Data Policy will translate into practice the principles of engagement between partners holding cryosphere data who are willing to share and exchange their data internationally. The Policy will once again set an example for partner communities, just as was the case for the International Polar Year (IPY) 2007–2008 when WMO, jointly with the International Council for Science, established an innovative data management framework to underpin the goals of the stakeholder communities. Since IPY, the WMO-partner communities have made significant progress in data and information management, with the notable increased relevance of the FAIR guiding principles.

These areas of progress offer potential benefits for WMO Members, as the Unified Data Policy is designed to be fit for its current purposes and to adapt to future needs.

Conclusions

The focus of WMO on Earth system monitoring, modelling and prediction is increasing the need to integrate cryosphere data in support of all weather and climate-related service delivery. The Unified Data Policy paves the way for a more systematic approach to the exchange and use of cryosphere data in conjunction with data from the more traditional domains of WMO. It is anticipated that the implementation of the Policy will be instrumental in enhancing data access and in fulfilling the spatio-temporal resolution required by users. At the same time, the current holders of those data, including cryosphere data, that reside outside the domain of NMHSs, will receive tangible benefits.

Mutual benefits to WMO, research and other communities are expected as a result of the improved data exchange triggered by the Unified Data Policy. Access to descriptive inventories of past events and to robust climatic data that is the underpinning of hazard assessments will allow scientists and NMHSs to better help the global community with some of major challenges posed by a rapidly changing climate (Figure 10).

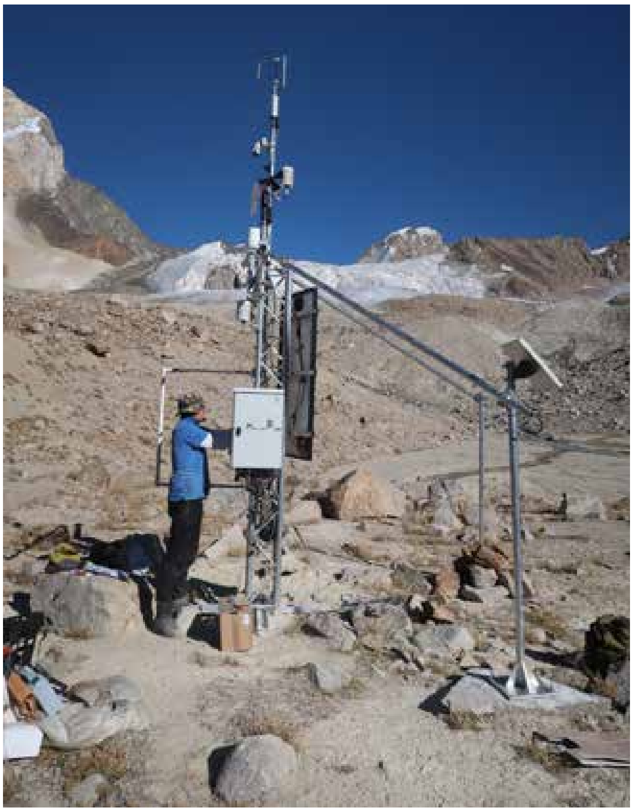


Figure 10. Sept 2021 installation of a new high mountain observation site in the Western Pamir, Tajikistan as part of the "Cryosphere Observations and Modelling for improved Adaptation in Central Asia" (CROMO-ADAPT) funded by the Swiss Development Corporation and co-led by University of Fribourg and WSL Institute of Snow and Avalanche Research SLF (Switzerland) (Photo: Joel Fiddes).

Strengthening of partnerships in support of effective cryosphere data exchange in the framework of WIGOS, WIS and GDPFS is essential for meeting the ambitious goals of the WMO Earth system approach. The benefits will be tangible and substantial, but success will critically depend on our ability to establish mutually beneficial engagements across the diverse community and data holders in the cryosphere domain.

Attribution of data ownership wherever requested, as called for in the Policy, ensures the recognition and the protection of the individual intellectual property rights and is an important aspect for improving the effectiveness and the longevity of partnerships.

WMO has a long-standing and innovative collaboration with the research community, and the success of the data policy of the International Polar Year 2007–2008 is a testament to this. The Unified Data Policy will set an example for the partner communities. It demonstrates a clear aim to ensure continued successful collaboration with the cryosphere community in the future.

References online

Space Weather, Extending the Borders Beyond the Earth

By Larisa Trichtchenko, Canadian Space Weather Forecast Centre, Natural Resources Canada, and Kenneth Holmlund, WMO Secretariat

Space Weather describes a series of changing conditions in the natural space environment of our solar system. Space weather phenomena are triggered by events occurring on the Sun and in interplanetary space, which eventually impact the natural Earth environment. Although not posing direct risk to human life on Earth, space weather affects a number of today's critical technologies, therefore, the global economy. The adverse effects on energy infrastructure, transport, radio communication, observation, navigation and communication satellites, etc., result in reduced reliability of critical systems with potential effects on human safety.

Space weather monitoring and prediction services are already regularly used by commercial airlines, the satellite industry, drilling and surveying operations, power grid operators, pipeline designers, and users of satellite-based navigation systems. Emergency management agencies are developing procedures to manage the risks of severe space weather events as part of their overall risk management approach. Since November 2019, three (soon to be four) Global Space Weather Centres have been providing space weather services to International Civil Aviation Organization (ICAO).

WMO recognizes that there is an increasing demand for space weather services as society is becoming ever more dependent on technologies adversely impacted by space weather events. Procedures are being developed by a number of countries to manage the risks of severe space weather events as part of multi-hazard disaster risk reduction approaches. It is anticipated that the demand for space weather information will expand with broader awareness of the impacts of space weather events, the increasing exposure of society, and the evolution of space weather products and services.

The Four-Year Plan for WMO Coordination of Space Weather Activities 2020-2023 (FYP2020-2023) was approved by the Eighteenth World Meteorological Congress (Cg-18) in 2019. The implementation of the FYP2020-2023 will provide significant benefits to WMO Members in terms of more precise observations and improved services.

WMO has also incorporated space weather observations into the new WMO Unified Data Policy. The new Policy will provide the foundation for identifying core observations required for Space Weather Services, which will be detailed in the WMO Technical Regulations.

This article introduces this relatively new area of work at WMO, specifically the related societal impacts, and observations and data requirements. It further expands on space weather services and international collaboration.

Space weather: A new hazard of the technological era

Space weather, for the most part, cannot be observed or felt directly by humans, except for the occasional spectacular displays of the aurora borealis (Figure 1) or australis, caused by disturbances of the natural electromagnetic fields and ionized particles in the upper layer of atmosphere (ionosphere). In contrast, many technologies interact with the Earth's natural electromagnetic environment, so regularly experience the detrimental effects of space weather.

Figure 1. Aurora Borealis over Kilpisjarvi, Finland. (Source: Lionel Peyraud)

These effects have been observed for a long time. The accuracy of pointing needles in compasses (invented over 2000 years ago and used for navigation/orientation since then) is hindered by space weather. The telegraph, an eighteenth-century invention, made the effects of space weather on technology broadly apparent. Telegraph wires are essentially long linear conductors at the surface of the Earth, as such they are sensitive to the natural variations of the Earth electromagnetic field. By coincide, the telegraph developed on a global scale during a period of high solar activity. Severe geomagnetic storms from 28 August to 2 September 1859 (known as the "Carrington event", the largest space weather episode in modern history) caused widespread disruption of the telegraphic systems in Europe and North America.

As presented in historical book by Prescott (1866), Mr O.S. Wood, Superintendent of the Canadian telegraph lines, reported: "I never, in my experience of fifteen years ... witnessed anything like the extraordinary effect of the aurora borealis ... last night. The line was in most perfect order, and well-skilled operators worked incessantly from eight o'clock last evening till one o'clock this morning ...; but at the latter hour, so completely were the wires under the influence of the aurora borealis, that it was found utterly impossible to communicate between the telegraph stations, and the line was closed for the night."

Wireless communication started in the early twentieth century with invention of radio. However, the absence of the long conductors did not eliminate the space weather impacts. Radio communication is subject to the interaction of the radio waves with the ionosphere, electrically conductive layer of the atmosphere, which become severely disturbed during space weather events, causing interference with the radio signal propagation. According to L. Lanzerotti (2001), Marconi in 1928 commented on this phenomenon as "...times of bad fading [of radio signals] practically always coincide with the appearance of large sun-spots and intense aurora-borealis usually accompanied by magnetic storms..."

High frequency (HF) radio communication in the Arctic/Antarctic areas is affected more strongly than in other locations because of the higher intensity of the disturbances close to the magnetic poles.

Space weather effects were observed on power grids, according to Davidson, as early as in 1940. The most severe case was recorded in 1989, when the Hydro-Québec power system collapsed due to a geomagnetic storm on 13/14 March, 1989. The event unfolded over just a few minutes, but left hundreds of thousands of people and businesses without power for nine hours.

One of the strongest space weather events occurred in October 2003. It had widespread effects on vulnerable infrastructure and significantly influenced public attitudes on space weather. Excerpts from the report published by U.S. National Research Council in 2008:

"On October 30, 2003, the House Committee on Science, Subcommittee on Environment, Technology, and Standards held a hearing on space weather and on the roles and responsibilities of the various agencies involved in the collection, dissemination, and use of space weather data. (...) Questions included, What is the proper level of funding for agencies involved in space environmental predictions? and, What is the importance of such predictions to industry and commerce? Coincidentally, and rather remarkably, at that very time the Sun exhibited some of its strongest eruptive activity in the last three decades. Enormous outbursts of energy from the Sun during late October and early November 2003 produced intense solar energetic particle events and triggered severe geomagnetic storms...Due to the variety and intensity of this solar activity outbreak, most industries vulnerable to space weather experienced some degree of impact to their operations...These events reminded scientists and policy makers alike how significantly the space environment can affect human society and its various space- and ground-based technologies."

Presented in the same report are some estimations of the socio-economic impacts of October 2003 space weather event on vulnerable technology: "The Sydkraft utility group in Sweden reported that strong geomagnetically induced currents (GIC) over Northern Europe caused transformer problems and even a system failure and subsequent blackout. Radiation storm levels were high enough to prompt NASA [National Aeronautics and Space Administration] officials to issue a flight directive to the ISS [International Space Station] astronauts to take precautionary shelter. Airlines took unprecedented actions in their high latitude routes to avoid the high radiation levels and communication blackout areas. Rerouted flights cost airlines US$ 10 000 to US$ 100 000 per flight. Numerous anomalies were reported by deep space missions and by satellites at all orbits. GSFC [Goddard Space Flight Centre] Space Science Mission Operations Team indicated that approximately 59% of the Earth and Space science missions were impacted. The storms are suspected to have caused the loss of the US$ 640 million ADEOS-2

Advanced Earth Observing Satellite spacecraft. On board the ADEOS-2 was the US$ 150 million NASA SeaWinds instrument."

Today, thousands of satellites in near-Earth space are enabling weather forecasts, communication, navigation, TV broadcast and lots more. Hazardous space weather conditions directly impact the satellite systems and interfere with the services they provide. One of the most widely used satellite-based services is provided by the Global Navigation Satellite System (GNSS), with applications ranging from navigation to timing, and with users from a broad range of economic sectors from aviation to banking. This service is also vulnerable to severe space weather. For example, the events of October 2003 had a major impact on the services of GPS-based [Global Positioning System] Wide Area Augmentation System (WAAS) for about 30 hours.

It should be noted that the Carrington event of 1859 was several times larger than any event experienced over the past 50 years. A similar event today would lead to much deeper and more widespread socioeconomic disruptions than any of examples presented above. The growing global vulnerability to space weather is an issue of an increasing concern. Many studies have been undertaken from 2008 to 2021 to evaluate the economic and societal impacts of severe space weather events and the required level of services.

Sources of space weather events and essential space weather observations

In order to provide essential services, the space weather needs to be observed all the way from the Sun to the Earth with high accuracy, and the data need to be exchanged in a timely manner. This is a challenging task, given the spatial extent of the space weather domain and the limited observing capabilities to cover the space between the Sun and the Earth as well as Earth surface itself. The wide variety of physical processes governing space weather requires development of new instrument capabilities. Numerically complex models of the propagation of space weather disturbances play an essential role in the provision of the forecasts for such events.

Space weather observations rely on ground-based and space-borne operational and research instruments, which monitor the conditions of

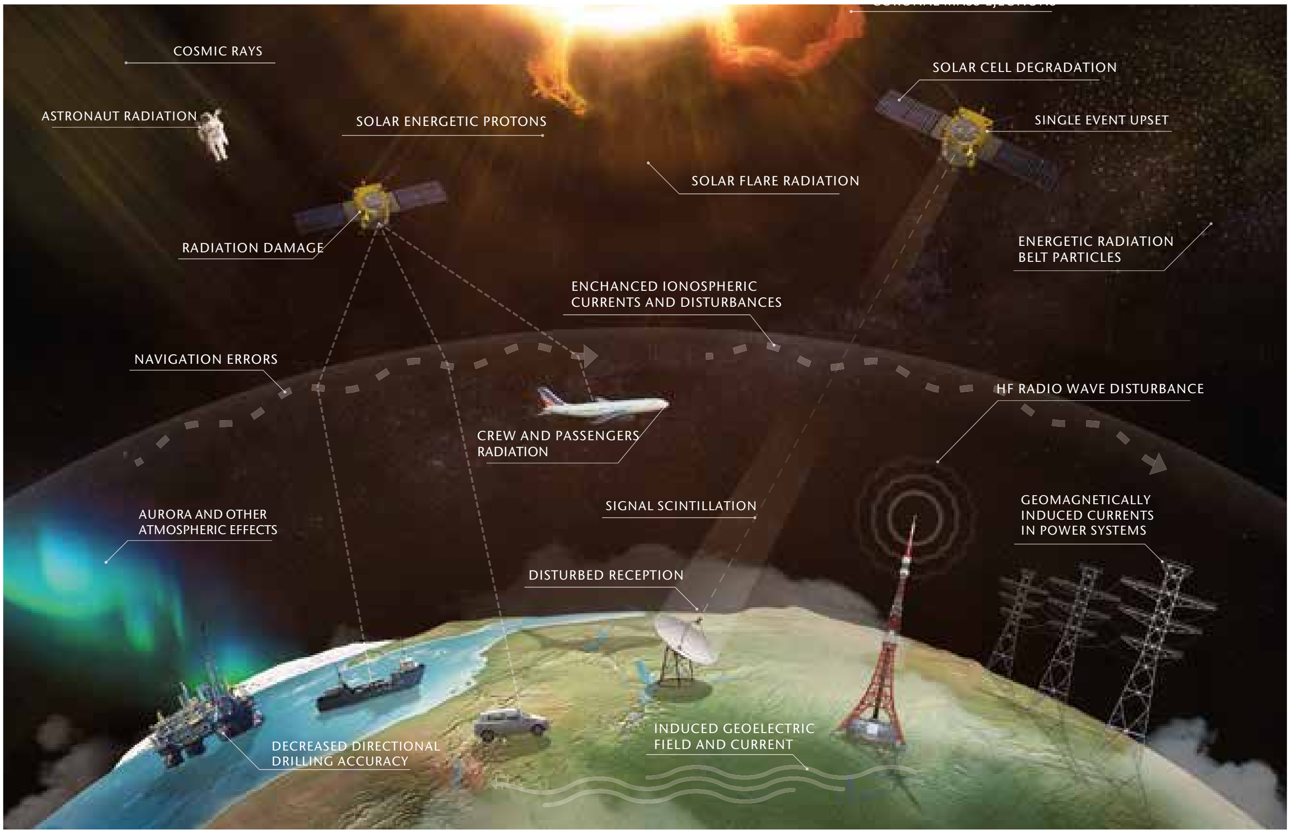


Figure 2. Space weather phenomena and affected assets in space and on earth. (©ESA/Science Office, CC BY-SA 3.0 IGO)

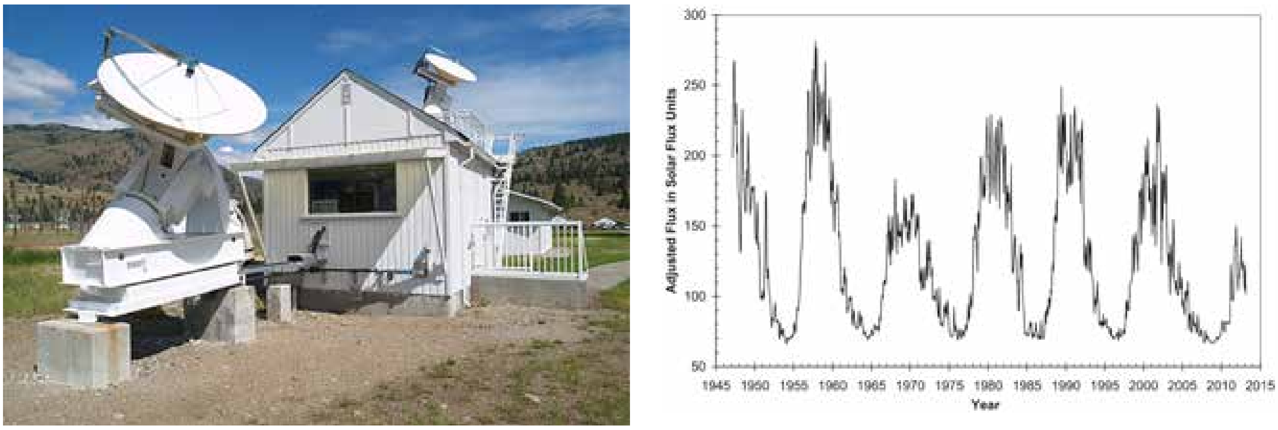


Figure 3. Radio observatory in Penticton, Canada (left) and its long-term observation of solar radio signal at 10.7 cm wavelength (right), showing the 11-year solar cycles (from Tapping, K. 2013)

(starting from the most distant) the Sun, solar wind and heliosphere, magnetosphere, ionosphere, thermosphere and the ground geomagnetic field.

There are multiple types of solar disturbances, which result in different phenomena in the near-Earth space and on the ground and different impacts on technologies (Figure 2). Two solar phenomena are the sources of the most immediate space weather effects: solar flares, with their impacts seen on the Earth in minutes, and solar energetic particles (or SEP), reaching the Earth in hours. Both of these fast-moving phenomena interfere with satellite operations and disturb the ionosphere, affecting the radio communication and GNSS signals. In addition, they can both increase radiation at the near-Earth space and even at high altitudes.

Slower than the first two, Coronal Mass Ejections (CME) are emissions of plasma that reach the Earth within one to several days after the event onset on the Sun. They are responsible for the most powerful geomagnetic and ionospheric storms, impacting multiple systems operating in space and on the ground such as satellites in various orbits, communication, navigation and power grids.

In addition, there are regularly recurring phenomena corresponding to the solar rotation (~ 27 days) that have lower-magnitude impacts on technology. Longer periodicity of the solar activity is often characterized by a sunspot number (and solar radio flux at 10.7 cm wavelength). They recur approximately every 11 years and have served as a solar "climatology" index for many centuries – the earliest records date back to roughly 200 BC.

Some solar observations are provided by ground-based observatories – both optical and radio frequency. These observations are essential for many space weather applications, including monitoring long-term and short-term solar activity, and as input data for numerical prediction models of space weather (Figure 3). There are currently more than 80 ground-based solar observatories in operation as per the International Astronomical Union.

Space-based solar observations add essential measurements of the Sun, without obstruction from the Earth's atmosphere, and allow in situ monitoring of the propagation of disturbances of solar wind plasma and solar energetic particles (Figure 4).

Space missions provide in situ observations of the critical parameters of solar disturbances, such as magnetic field and characteristics of charged particles, before they hit the Earth (Figure 5). However, surface-based measurements are equally important as they provide critical situational awareness and, in many cases, serve as essential inputs in forecast models.

Ground geomagnetic variations, which affect ground infrastructure, are monitored by the geomagnetic observatories (Figure 6). There are more than 100 such observatories in the Intermagnet consortium and more beyond the Intermagnet, operated, for example, by universities. Ground enhancements of neutrons due to highly energetic particles interaction with the atmosphere are observed by neutron monitors (~35 stations) and are used in radiation models at different altitudes.

Ionospheric "weather" is monitored from the ground using both active and passive methods by some 80 ionosondes, about 40 riometers and numerous GNSS receivers around the globe (approximately 500). Ionospheric "hybrid" measurements are provided by ground receivers of GNSS satellite signals (Figure 7).

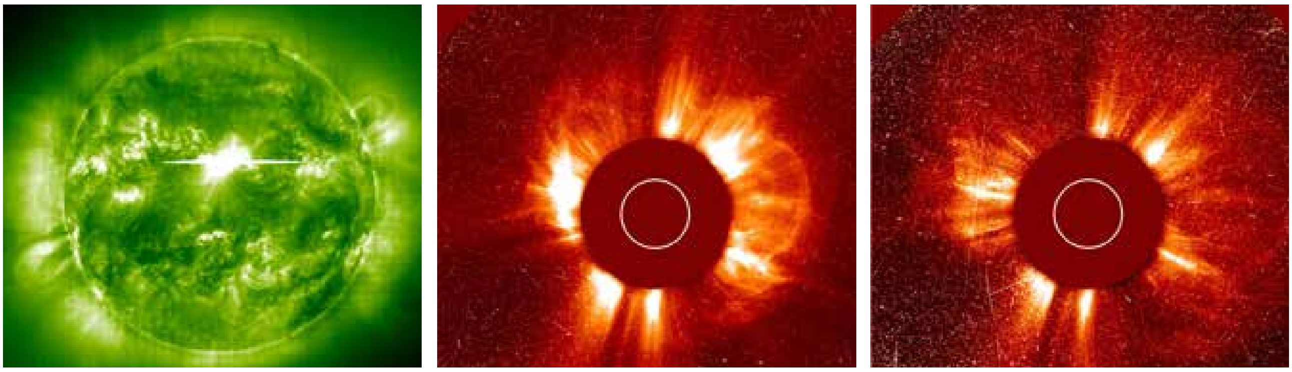


Figure 4. SOlar and Heliospheric Observatory (SOHO) satellite observations of the 14 July 2000 space weather event in different wavelengths. Left: flash of the solar flare at 10:24 UT; Middle: full halo Coronal Mass Ejection at 10:54 UT (the brightest central part of the Sun is covered); Right: "snow" due to the subsequent Solar Energetic Particles impact on the satellite imager at 11:30 UT. (Courtesy NASA/ESA)

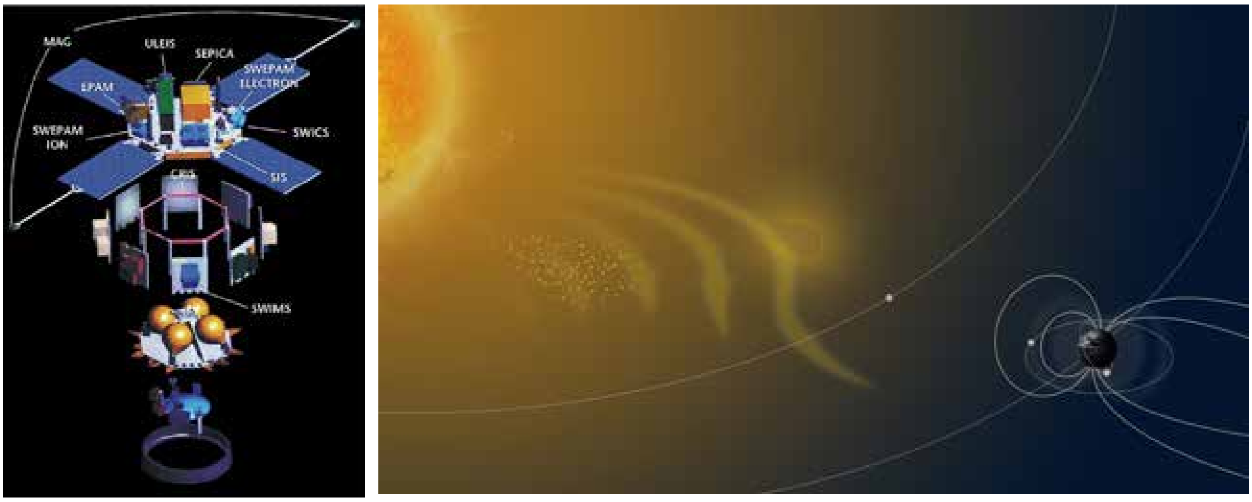


Figure 5. Left: components of ACE satellite with the numerous particle detectors in the centre and magnetometers attached to the solar panels (courtesy of NASA); Right: artist illustration of satellites observing space weather at different orbits from https://www.nesdis.noaa.gov/content/top-5-times-solar-activity-affected-earth

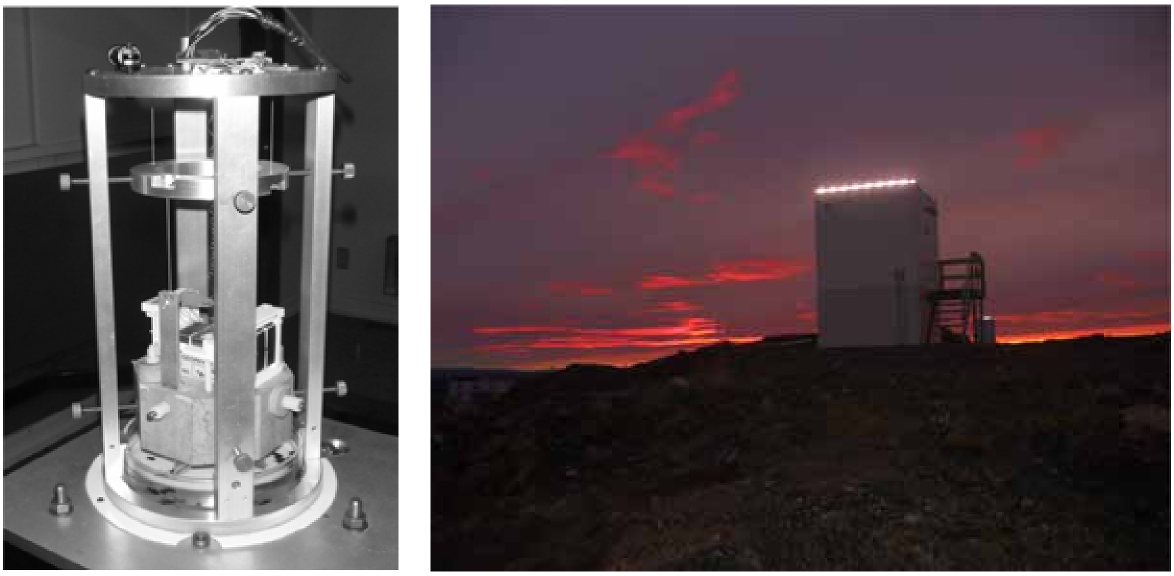


Figure 6. Left: Magnetometer (from Hrvoic and Newitt); Right: Photo of the Geomagnetic observatory at Iqaluit, Canada (Courtesy of Mark Lamothe)

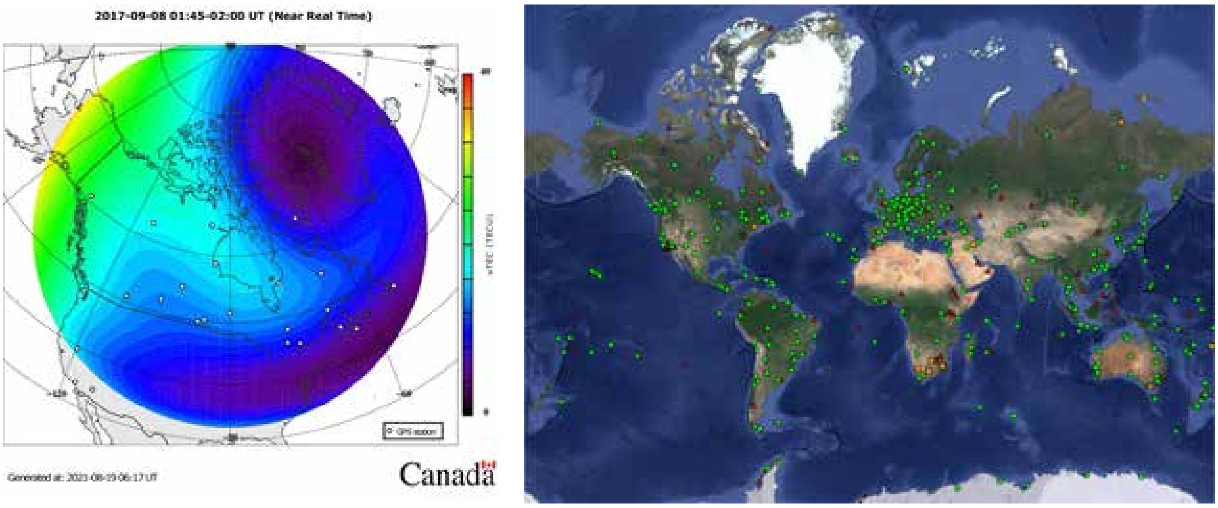


Figure 7. Left: Map of Total Electron Content of the ionosphere over Canada obtained using GNSS data (https://www.spaceweather.gc.ca/data-donnee/ionosphere/index-en.php). Right: Map of GNSS tracking stations (https://igs.org/network/).

It should be emphasized that the lack of sufficient in situ (i.e. space-based) monitoring of the initiation and propagation of the solar disturbances is a problem that will not to be fully resolved in the near future. However, progress can be made through a coordinated approach to the identification of the observational gaps and prioritization of coordinated space missions.

Similarly, ground-based observational networks, operated by diverse entities from governments to university research groups, provide limited geographical coverage. They have different priorities and capabilities, and their efforts are not currently coordinated within a unified space weather system for timely provision of robust operational quality data. In order to successfully mitigate the detrimental impacts of space weather, efforts should be made to provide the sufficient observational capabilities on Earth and in space, together with the numerical modelling capabilities of both the phenomena and their technological impacts. The scope of these efforts is beyond the capabilities of any individual country. The issue is, therefore, being addressed through coordinated efforts guided by WMO (Figure 8).

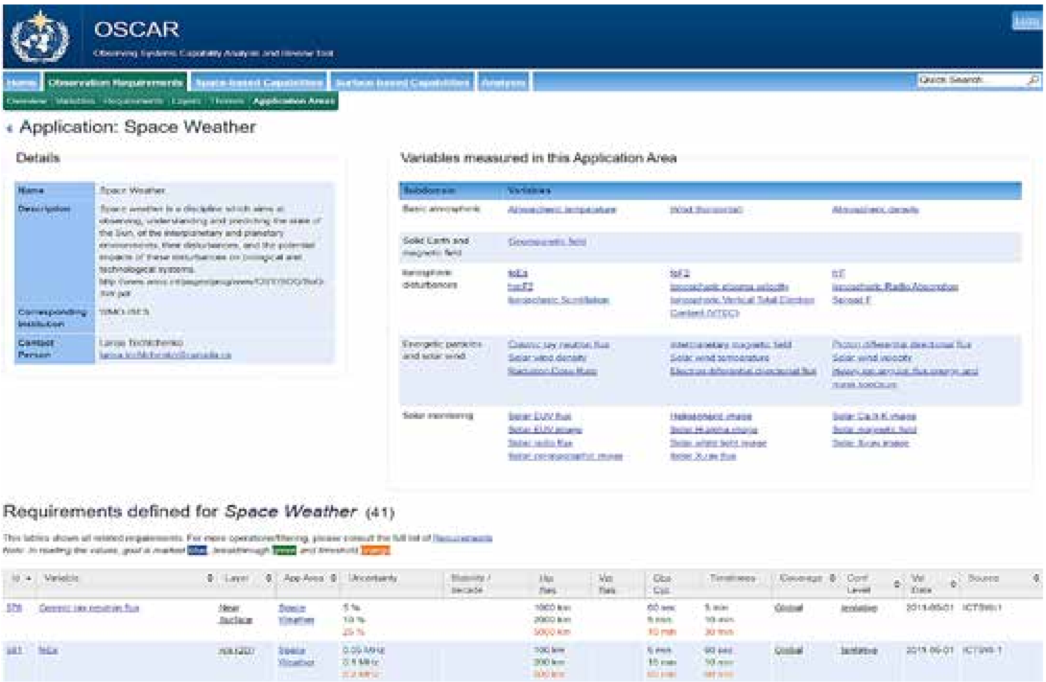


Figure 8. Requirements defined for space weather observations presented as part of WMO OSCAR Tool https://space.oscar.wmo.int/applicationareas/view/space_weather.

In the same manner as for Earth system observations, such as weather, climate and atmospheric composition, space- and surface-based space weather observing systems would be best coordinated using principles of the WMO Integrated Global Observing System (WIGOS). Consistent, quality-assured space weather products should be made freely and openly available to Members and wider audience through WMO Information System (WIS) in accordance to WMO standards.

Space Weather services and WMO: consistent progress towards Space Weather Watch

The first prediction of a space weather phenomenon (i.e. an aurora) was performed in the mid-1700s, as presented in Cade. The first predictions of the impact of space weather on technology, according to presentation of G. Major in 2016, was associated with the telegraph. It was published in 1879 (when the sunspot number started to rise) in the Journal of the Society of Telegraphic Engineers and Electricians, in order to warn the telegraph community of a possible increase in geomagnetic activity and associated problems with telegraph operations.

The start of the regular prediction of space weather conditions was initiated by the International Union of Radio Science (URSI). It recognized that changes in the space environment would affect radio signals and suggested that a daily service of radio-cosmic bulletins (URSIgrams) should be broadcast. The first broadcast of the radio propagation conditions was in 1928 from the Eiffel Tower.

Currently, space weather services are provided by 20 Space Weather Centres operated in different countries. Since 1962, the International Space Environment Service (ISES) has served as the primary "umbrella" organization for space weather services, acting as a forum to share data, to exchange and compare forecasts, to discuss user needs and to identify the highest priorities for improving services.

Given the planetary scale of space weather events, global coordination is essential and will play a key role in improving the resilience of countries to space weather effects. WMO is one of the few organizations that fosters operational global collaboration. As such, the Organization has the capabilities to arrange for the relevant space weather information to be available to all WMO Members as part of capacity building.

In 2008, the WMO Executive Council (EC-LX) noted the considerable impacts of space weather on critical infrastructure and important human activities and acknowledged the potential synergy between meteorological and space weather services to operational users. The Sixteenth World Meteorological Congress (Cg-16) acknowledged the need for a coordinated effort by WMO Members to protect the society against the global hazards of space weather. In May 2010, WMO established the Inter-programme Coordination Team on Space Weather (ICTSW), which, in turn, developed the first Four-year Plan for WMO Coordination of Space Weather Activities (FYP 2016-2019).

In May 2015, the World Meteorological Congress (Cg-17) agreed that WMO should undertake international coordination of operational space weather monitoring and forecasting in order to support the protection of life, property and critical infrastructure and to mitigate the impacts on economic activities. In 2016, the 68th session of the Executive Council (EC-68) approved FYP2016-2019 and the establishment of an Inter-Programme Team on Space Weather Information, Systems and Services. An updated FYP2020-2023 was approved by Cg-18 in 2019.

With the emerging need for improved space weather services and hence for space weather relevant observations WMO is also addressing the need for space weather observations in the new WMO Unified Data Policy. The new Policy will provide the foundation for identifying core observations required for space weather services and will be detailed in the WMO Technical Regulations.

Currently, work is ongoing to integrate space weather within core WMO activities, with the aim to develop a global Space Weather Watch. For that, the space-based and ground-based space weather observing systems should be coordinated using principles of WIGOS and consistent, quality-assured space weather products available to Members through WIS.

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No Member Left Behind – Part 1. A developing country perspective on data exchange in meteorology

Agnes Kijazi, Permanent Representative of the United Republic of Tanzania to the WMO and Third Vice-President of the WMO, Daouda Konate, Permanent Representative of Cote d’Ivoire to the WMO and President of WMO Regional Association I (Africa), Arona Ngari, Permanent Representative of the Cook Islands to the WMO, Arlene Laing, Permanent Representative of the the British Caribbean Territories to the WMO and Member of the WMO Executive Council

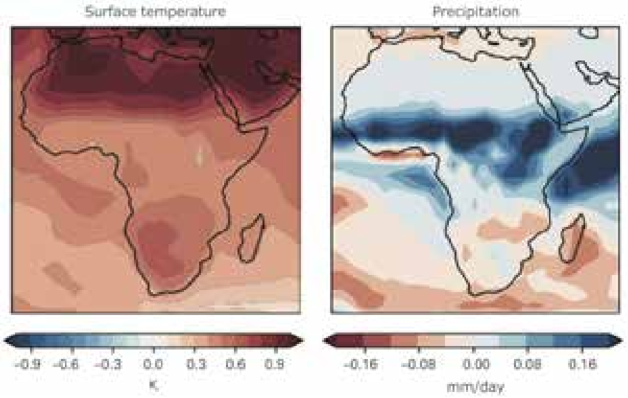
A defining characteristic of meteorology is its fundamentally global nature, from both the scientific and operational perspective, as was mentioned in the first article of this Bulletin. All countries therefore have a shared interest in collaborating and in gathering and exchanging data that are necessary for the monitoring and prediction of weather and climate. All countries recognize this and agree with it in principles, yet the international data exchange continues to be inadequate, especially in many developing countries. This article highlights some of the main reasons for this situations and provides a developing country perspective on the new WMO Unified Data Policy and its expected impact on capacity development and service delivery in these countries.

The importance of data exchange for developing countries: challenges and timeliness (Daouda Konate)

The steady increase in climate-related natural disasters all over the world clearly points to a need for strengthening the international cooperation on systems and services that help save lives and protect property. The most essential elements are the systems established to acquire and exchange the observations needed for the global numerical models that are used to underpin monitoring and prediction of the Earth system. The ultimate responsibility for making the actual observations and for the initial link in the data exchange communication chain resides with the individual WMO Member State or Territory. However, per its Convention, WMO has the responsibility for the fundamental task of coordinating and facilitating the design, implementation and operation of these systems. WMO’s main tools for this are its data policy (e.g. Resolution 40 (Cg-XII)) and its Technical Regulations.

Today, not all required Earth system observations are exchanged on a free and unrestricted basis by all stakeholders, due to various national data access restrictions. In their attempt to remedy this situation, developing countries are faced with three major challenges:

- A low level of investment in the observing network, resulting in a low spatial density of observations
- Concerns about free and unrestricted exchange of data leading to a loss of potential revenue that would otherwise have been an important,



Multi-model average forecasts of near surface temperature and precipitation for the five-year period 2020–2024. Colours show anomalies relative to the period 1981–2010 for the average of several international forecasts contributing to the WMO Lead Centre for ADCP (https://hadleyserver.metoffice.gov.uk/wmolc/). Forecasts are initialized with observations and start on or after 1 November 2019. (Source: Met Office, United Kingdom) complementary source of funding, for example, for the maintenance of the observing network

- Insufficient resources for human and material capacity building needed to improve the provision of value added climate services.

These challenges can be explained in large part by the low level of financial resources allocated by the governments of developing countries to their observing and data exchange systems.

Many of us in the developing countries see a glimmer of hope in the new WMO Unified Data Policy, which represents a global commitment to supporting and strengthening the free and unrestricted exchange of data. One example is the mechanism implemented via the Systematic Observations Financing Facility (SOFF), which will be an important lever for providing technical and financial support for the implementation of free and unrestricted exchange of key observational data. We hope that the new data policy can enable similar capacity building initiatives along the entire value chain, including the collection, processing, archiving and production of data for climate services, and thereby help strengthen the resilience of all economic sectors of developing countries.

A full, free and open access to data as defined in the WMO Unified Data Policy will help us to optimize product quality and maximize societal impact in developing countries. The gaps in Earth system observations need to be filled through increased engagement between NMHSs and partner communities. Much mutual benefit will derive from such engagement. Thus, strong public-private partnership is important, as it can open new opportunities along the Earth system monitoring and forecasting value chain. In order to facilitate this, WMO encourages its Members to adopt or adjust requisite legislation and to create business models that for the implementation of public-private partnerships as called for in the 2019 Geneva Declaration. This will require commitment from all stakeholders to get involved and to support the WMO Unified Data Policy.

The importance of return flows to developing countries (Agnes Kijazi)

Developing countries, including Least Developed Countries (LDCs), Land-Locked Developing Countries (LLDCs) and Small-Island Developing States (SIDS) and Territories, are among the most vulnerable to the impacts of climate change. This is due to diverse factors, including geography, location (in tropical and subtropical zones), limited resources and low adaptive capacity (Adejuwon et al., 2000; UN, 2009; WHO, 2018; IOM, 2019). Many of these countries already are experiencing increasing climate variability and the devastating impacts of climate change, especially from increasingly frequent extreme weather events. The situation is exacerbated by the huge infrastructure capacity gaps for weather observation and monitoring, data processings and weather forecasting and dissemination in developing countries that limit their ability to effectively provide quality weather, climate and hydrological services. Many also lack adequate resources to maintain and sustain the operations of the required infrastructure (WMO 2021: Hydromet Gap Report).

In view of these circumstances, it is high time to take action to strengthen weather and climate service delivery capabilities in developing countries and to thereby assist in their effective adaptation to climate change. Urgent measures are called for to strengthen the entire meteorological value chain in developing countries (WMO 2021: Hydromet Gap Report). In support of this, the 18th World Meteorological Congress adopted Resolution 34, on the Global Basic Observing Network (GBON), which will require WMO Members to implement a minimum set of surface-based observing stations for which international exchange of observational data will be mandatory. This is a necessary step to ensure that the global Numerical Weather Prediction (NWP) systems that underpin all weather and climate services receive adequate observational input from all parts of the globe.

The WMO "Strategic Plan 2020–2023", adopted in 2019, also lays out a vision of a world in which all Members, particularly the most vulnerable, will be resilient to weather, climate and water related shocks by the year 2030. To realize this vision, access to high quality and improved weather, climate and hydrological products and services needs to be broadened and increased for all stakeholders. This will allow for better planning of government-led adaptation measures and will support informed decision-making towards improving resilience and productivity across all economic sectors. In this manner, WMO will also assist government in achieving the goals of the 2030 Agenda for Sustainable Development, the Paris Agreement of the United Nations Framework on Climate Change, and the Sendai Framework for Disaster Risk Reduction 2015–2030 (WMO, 2019: Strategic Plan).

The WMO Strategic Plan 2020–2023 has defined five long-term goals with objectives for addressing specific capacity gaps across the full meteorological value chain:

i. Enhancing meteorological observing and modelling systems by embarking on an integrated Earth system approach to monitoring and prediction;
ii. Enhancing data availability, data management and data processing by integrating Earth system data from various domains to improve forecasts (long-term goal 2);
iii. The rapid transfer of new scientific knowledge to operational use, thereby leading to improvements in weather, climate, hydrological and related environmental services;
iv. Address key services delivery challenges by improving the accessibility, timeliness, reliability and applicability of meteorological information.

Achievement of these goals will enhance the quality of services and help ensure the availability of essential weather, climate and hydrological information and services to all stakeholders, including governments, the business sector and citizens (WMO, 2019).

The strengthening of the international data exchange supporting the generation of high-resolution NWP products will be a particularly important milestone. This will create a two-way data flow between main stakeholder groups: On one side the National Meteorological and Hydrological Services (NMHSs) and other providers (including space agencies) of observational data who will share core observational data and should also share recommended data. On the other side, the global NWP centres who will use the shared observational data to run global models that produce high resolution analysis and prediction datasets for both weather and climate services.

From a developing country perspective, we welcome the fact that the new WMO Unified Data Policy calls for high-resolution NWP data products to be shared and made accessible to all WMO Members on a free and unrestricted basis. This will be useful to improve forecasts and other weather and climate services to stakeholders. Satellite data products provided by the space agencies will be useful not just for assimilation into NWP models and for research purposes, but may also be used to support verification at national, regional and global levels.

Another issue that will have to be addressed in optimizing the value chain is enhancing the capability of developing countries to continuously monitor their end-to-end forecast production system. Developing and maintaining operational verification systems that focus on quality control of data and verification of NWP model output that comes out of the exchanged data sets could achieve this.

In recent years, impact-based forecasting and warnings have become the norm in supporting decision-making by users. However, certain elements in the provision of impact-based forecasting still remain subjective. Improved understanding and modelling of hazard and impacts is needed in order to complete the last mile in the full meteorological value chain, hence the importance of return flows to developing countries.

Data coverage from SIDS and their EEZs in particular (Arona Ngari)

Observational data coverage from many Small Islands Developing States (SIDS), especially those in the Pacific, is very poor and is relentlessly deteriorating. Monitoring data collected by WMO indicate that the situation in certain areas may soon reach a stage where the number of observations can no longer sustain meaningful meteorological services.

Pacific SIDS, in particular, have very large Exclusive Economic Zones (EEZs) that in some cases cover millions of square kilometres, areas for which they have, amongst others, the responsibility to provide observational data. These SIDS are facing enormous difficulties in gathering data over their EEZs, and in maintaining the robust communication systems required to transfer the data.

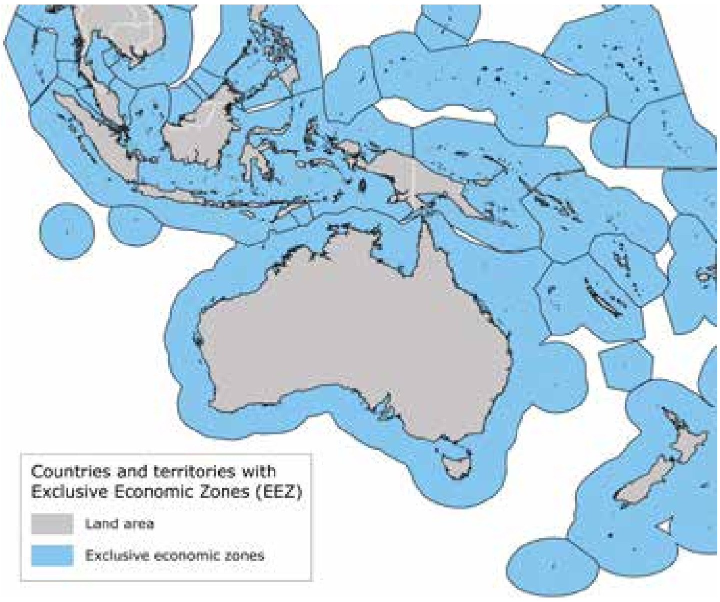
The lack of observational data from these areas is a matter of significant concern – and not only for the SIDS themselves, where it has a significant negative impact on the quality of model output used for climate analysis and weather prediction. It is also a matter of concern to the entire global community, since it impacts the quality of monitoring and prediction data everywhere.

It is a major economic burden for SIDS to operate NMHSs with even fairly basic levels of service delivery capabilities. In fact, for some very small, fragile island economies, an NMHS is impossible to sustain based on local resources alone. This situation is exacerbated by the fact that many SIDS are exposed to a range of disasters related to natural phenomena such as tsunamis, tropical cyclones, floods and others. The most recent report (WG1,AR6) of the Intergovernmental Panel on Climate Change (IPCC) indicates that these threats will not diminish in the future.

Three initiatives undertaken by WMO offer possibilities to cater these shortfalls for SIDS and thereby also address some of the main the issues raised in the SAMOA Pathway (http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/69/15&Lang=E). The first is Global Basic Observing Network (GBON), which will help improve the quality of monitoring and prediction data over SIDS and their EEZ. The second is the Systematic Observations Financing Facility (SOFF), which will provide the necessary support to SIDS to enable them to implement and operate their GBON contribution. The third is the new WMO Unified Data Policy, which will allow all Members to fully benefit from these capabilities.

WMO Unified Data Policy as enabler of data exchange for developing Members – (Arlene Laing)

The WMO Unified Data Policy promises to be of enormous benefit for developing Members. Developing countries already now receive far more data free of charge than they provide – data that they would not be able to provide for themselves. This is actually true for all WMO Members, even the very wealthiest, since no single Member can on its own gather all the data that it needs for monitoring and prediction. Everyone benefits when data are



shared, and thereby made available to clever and innovative individuals and organizations all over the world, who can experiment with it and develop improved ways to use it. For example, freely available global reanalysis data and global climate model output have allowed developing countries with endemic vector-borne diseases to correlate certain environmental conditions with the risk of epidemics, which has enabled better-informed public health decisions. A review of relevant studies for Africa is found in Githeko et al. (2014) and Thomson et al. (2018). The developed countries that provide the global reanalyses and model data are not themselves directly affected by this problem, and they would therefore have been unlikely to explore and develop this particular use of their data.

The Caribbean, one of the most hazard-prone regions of the world, is already experiencing warmer surface temperatures and is vulnerable to the adverse impacts of climate change. Effective disaster risk reduction and climate adaptation require integrating data from multiple sectors and across national borders, and this drives the need for a data policy that enables effective data sharing. These considerations served as the impetus for a session entitled "Data availability for effective policy-making and decisions" at the 11th Meeting between the Caribbean Community (CARICOM) and Associated Institutions and the UN System, held on 20–21 July 2021. At the event, the Caribbean Meteorological Organization (CMO), a specialized agency of CARICOM, noted the WMO's role in coordinating data exchange globally and emphasized the public good of the WMO's policy – demonstrated over many decades. CARICOM Member States were reminded of the benefits of the WMO data sharing policy, which supports many sectors. Of particular importance is the sharing of real-time data for the safety of transportation by air and sea, which is critical to tourism, the primary economic driver of many Small Island Developing States (SIDS) in the Caribbean and Pacific regions.

It has been shown that data from developing countries in the tropics are critical to ensuring the efficacy of global weather models and better forecast skill in the mid-latitudes, where most global NWP centres are located. For example, the positive impact of more radiosonde observations over West Africa propagated downstream to have a positive impact on weather forecast skill over Europe (Faccini et al. 2009, Agusti-Panareda et al. 2010). Additionally, dropsonde observations in the poorly observed Tropical Eastern Pacific led to improved global forecasts (Solomon and Compo 2016). Therefore, there are incentives for observations to be provided by the SIDS and for the SIDS to receive, in return, the outputs from the global models to aid in their decision-making and societal development. The WMO Unified Data Policy is the vehicle that enables the exchange of these critical data.

Researchers in the developing world also benefit from the free exchange of data through the WMO Unified Data Policy. For example, climate variability and climate change studies are based on data provided freely by WMO Members to researchers. The Climate Studies Group at Mona, The University of the West Indies, for example, led studies showing that a 1.5 °C increase in global mean temperature is a tipping point for climate impacts in the Caribbean

(Taylor et al. 2018). Those results have helped to shape national, regional, and international understanding of vulnerability to climate change and guided policy at the United Nations Framework Convention on Climate Change's (UNFCCC) Conference of the Parties (COP) and the International Panel for Climate Change (IPCC), helping to bolster the perspective of developing countries.

The value of data is in its use for better decision-making, enabled when data are accessible in a manner that is appropriate for customized decision-making timelines. For most Caribbean SIDS, the density of their land surface observation networks meets the requirements of the GBON, and they mainly need support to keep their data transmitting to the global centres. What is extremely valuable to Caribbean SIDS is to have more marine observations, products and services, especially to better monitor tropical cyclones, to support the "blue economy" and to contribute to the UN Decade of Ocean Sciences for Sustainable Development. It is hoped that initiatives such as the SOFF, will support the deployment and sustainability of marine observations for Caribbean SIDS.

Summary

In order to address the many concerns of developing WMO Members and to help realize the vision for the WMO Strategic Plan improving the international exchange of Earth system data, the WMO Unified Data Policy (Resolution 1(Cg-Ext(2021)) , is a much-needed first step. The implementation of the policy will facilitate access to high-resolution NWP products and other model data that will support NMHSs of developing countries to provide high quality and improved services. These services will support better decision-making for the benefit of both present and future generations.

References online

No Member Left Behind – Part 2. Development partners' perspectives on overcoming sustainability challenges in observing networks and data exchange – lessons learned

By Lorena Santamaria and Lars Peter Riishojgaard, WMO Secretariat, John Harding, Head, Climate Risk and Early Warning Systems (CREWS) Initiative, Benjamin Larroquette, Regional Technical Advisor for UNDP's Nature, Climate and Energy team and Jochem Zoetelief, Head, Climate Services and Capacity Building Unit Science Division UN Environment Programme (UNEP)

Over the last two decades, development agencies[1] have invested hundreds of millions of US dollars in projects aimed at improving meteorological observing networks in developing countries. Their goal was, and remains, to assist those developing countries that cannot meet commitments to consistently operate and maintain their national observing networks and data exchange. Weather, water and climate services rely on a consistent, coordinated worldwide system for real-time gathering and exchange of observations, and all WMO Members are committed to contributing to this exchange. The failure of any Member to meet these commitments adversely impacts the quality of weather and climate monitoring and prediction products, both locally and globally.

Persistent capacity gaps have led to a growing number of development projects aimed at strengthening meteorological observing networks. However, the results have often been suboptimal. This article highlights some of the main reasons why observing networks supported by development agencies often fail to gain permanent traction in developing countries, and it offers a few examples of pathways for improving the support.

Lack of surface-based observations – a persistent global problem

Despite several decades of significant investments in strengthening the meteorological sector in developing countries, many areas of the globe remain far from the goal of continuous, robust, real-time international exchange of surface-based observations. Figure 1 shows the international exchange of in situ observations of surface pressure – a key input variable for Earth system numerical modeling – as of 9 September 2021. The situation is dire, especially in areas with observing stations shown in black (no observations exchanged), red (sporadic exchange of observations) or with too few stations altogether. Not only will it be nearly impossible to provide high-quality forecast products in those areas; it will also be difficult to assess how good the forecasts are since there are no observations against which they can be verified. Satellite observations can help ensure a realistic model representation of large-scale atmospheric dynamics in the upper layers of the atmosphere, but cannot be used to verify forecasts of surface weather. Without the exchange of surface-based observations, the rest of the meteorological value chain (see Article 1, Figure 1) has little to build on.

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[1] This article draws significantly on the World Bank Project on initiative and report under peer review, A Vision: Charting a Course For Sustainable Meteorological and Hydrological Observation Networks in Developing Countries, by Tsirkunov, Grimes, Rogers, Varley, Schumann, Day and contributions from HMEI, 2021.

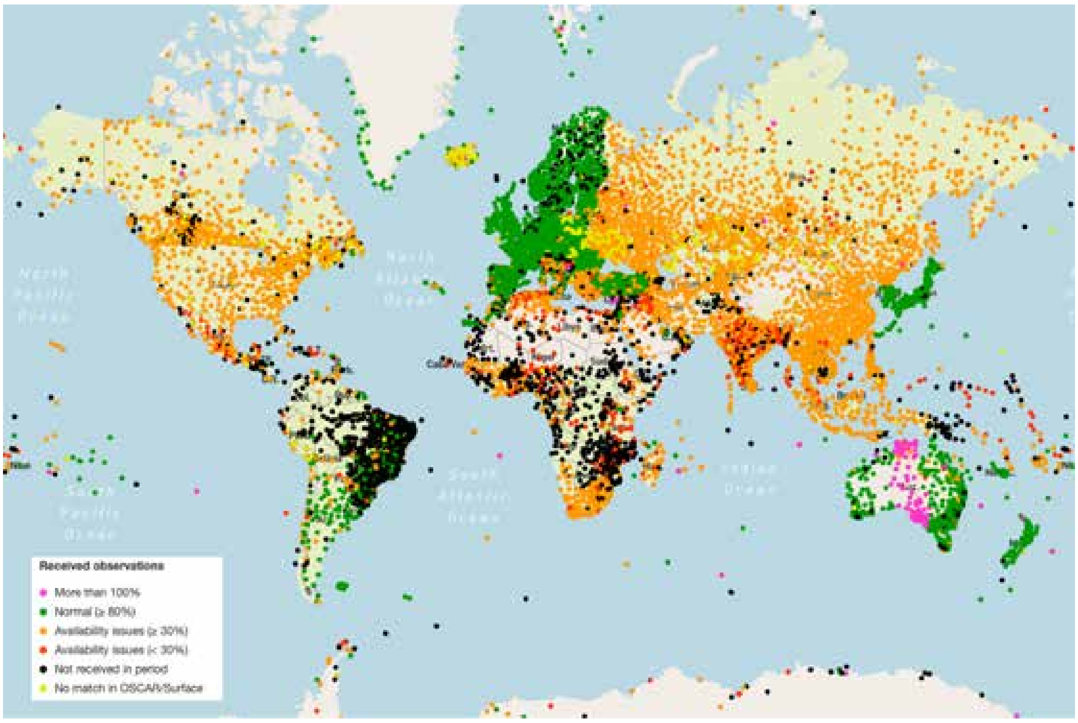


Figure 1. Surface pressure observations received by global NWP centres on Sept 9 2021 (Source: WIGOS Data Quality Monitoring System)

The WMO community has been concerned about the lack of observations from developing countries for decades, and many attempts have been made to address the problem. However, despite these efforts in many places, the data gap has been growing. For instance, the number of radiosonde observations over Africa provided to the global models decreased by roughly 50% between 2015 and early 2020. Why have substantial investments in observing systems not translated into increased observational data sharing?

Lack of a global approach

A significant part of the shortfall in results can be attributed to the lack of a *global approach*. Development projects are typically single-country focused and, therefore, whenever such projects include an observing system component, it will be focused on the national observing infrastructure. However, the action that is needed to establish a functioning data exchange is rarely purely national. Rather it involves collaboration with – and sometimes investment in – systems and entities working outside the country, for example Regional Telecommunication Hubs, Global Information System Centres and Regional WIGOS Centres. Single-country projects in general, therefore, cannot address data exchange issues.

Since observations that are not exchanged have little impact on prediction, this leads to a lack of incentive for the National Meteorological and Hydrological Services (NMHSs) to maintain and operate the observing networks once the projects are completed and the support ceases.

An overly narrow approach hampers other project types. Last-mile projects (such as early warning systems) rely heavily on the use of global model data. While the importance of these data is well understood by project implementers, the role of local observations in the global models generally is not. The critical link between the availability of local observations and the local quality of model data is generally not recognized, nor is the importance of observations for forecast verification. Furthermore, the observations that are most important for weather forecasts in smaller countries often come from outside their borders. Single-country, last-mile focused projects generally have no coordination with similar projects in neighbouring countries, and implementing an observing network in a single country without any guarantee that the surrounding countries will do likewise is likely to provide limited value. Ongoing failure to address this problem of missing international coordination of observing system activities has been highly detrimental to the availability of radiosonde observations, especially over Africa.

Box 1. Distinguishing between observing networks and observational data exchange

Hydromet development project in Malawi:

A comprehensive network of 50 state-of-the-art Automated Weather Stations (AWS) was installed in Malawi with the support of the United Nations Development Programme (UNDP). The installation was completed in 2019, and the final evaluation rated the project as successful, i.e. all stations operating and delivering observations. However, the initial Global Basic Observing Network (GBON) gap analysis undertaken by WMO in 2020 showed observations being exchanged internationally only sporadically from a single station in Malawi, and none from the AWS network. WMO in collaboration with UNDP conducted an internal assessment of the situation that concluded that "while the equipment on the ground is functioning and providing data to the national servers, there is a technical challenge that is still preventing the connection of this data to the regional and global servers housed by WMO". Upon further investigation by WMO starting in 2021, it was found that no observations from the AWS network were available at the NMHS headquarters, that due to increasing national capacity and budgetary constraints no observations were being internationally exchanged, that the network was unable to deliver the data in WMO standard (BUFR) data format, and that the telecommunication capabilities were inadequate.

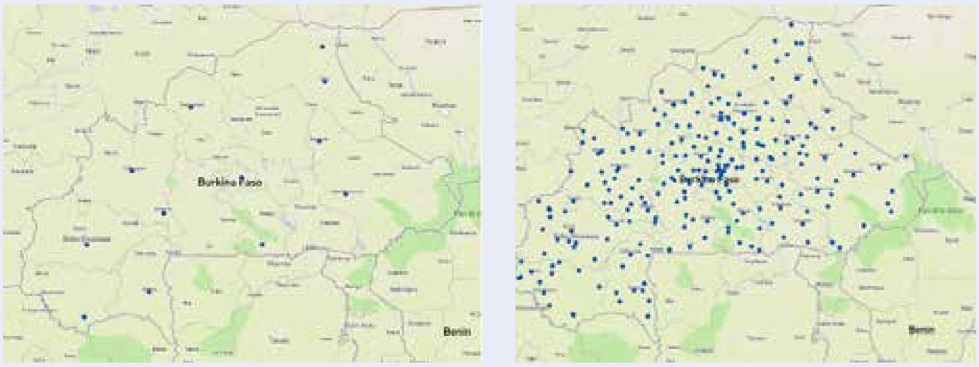
CREWS Western Africa project:

In 2020, five countries in Western Africa (Burkina Faso, Chad, Mali, Niger and Togo) carried out assessments of their observation infrastructure and data management systems. These efforts, part of a multi-year regional investment by the Climate Risk and Early Warning Systems (CREWS) Initiative,[2] were carried out to strengthen the countries' access to essential data for predictions and risk information for effective early warnings.

The assessments showed that of there were 341 observation stations with pressure sensors available in the five countries but only 60 (17%) were registered in the WMO Observing Systems Capability Analysis and Review (OSCAR) Surface station database. This limits the international exchange of data and therefore the quality of forecast products available in the countries. The low level of contribution comes from historical factors: many of the stations were established primarily to provide data for predicting food insecurity and are therefore not connected to other regional and global systems. Capacity and resourcing were also identified as challenges.

The five countries have started addressing the issue. Measures include development of maintenance plans for observing infrastructures, updating metadata in the OSCAR database and connecting stations to the WMO Information System (WIS), a process that is now simplified by Internet-based connectivity. In Burkina Faso, a step change was achieved. The figure below reflects a before and after context of the number of stations registered in OSCAR Surface database in Burkina Faso between April and August 2021. These efforts are being scaled-up, to cover all 24 countries in West and Central Africa, building on the effective model of South-South sustainable cooperation with financial support by CREWS.

Number of surface stations (blue dots) registered in the WMO Observing Systems Capability Analysis and Review (OSCAR) database before and after the CREWS project



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[2] CREWS is a financing mechanism to strengthen impact-based, people-centred, early warning systems in LDCs and SIDS. The current portfolio is USD 75 million. Projects are led by countries and regional institutions with operational support by the World Bank, WMO and the UN Office for Disaster Risk Reduction. Australia, Finland, France, Germany, The Netherlands, Luxembourg, Switzerland and the United Kingdom contribute to the Trust Fund.

Lack of appropriate measure of success

While the lack of observations from developing countries is recognized and frequently cited in project rationales and design documents, the problem of missing observations is often mistakenly interpreted as being a problem of missing observing stations (Box 1). However, since observational data exchange is the ultimate goal, metrics of success for observing system projects should be defined accordingly, and not in terms of local installation and operation of stations.

Lack of structural adjustment

Automatic weather stations (AWSs) are seen by donors and implementing entities as a modern, high-efficiency, low-cost means of providing surface-based meteorological data, but they often fail to gain traction in developing countries. NMHSs in developing countries continue to rely on manual observations made by human observers and transmitted by outdated communication methods even after AWS networks have been installed. There are structural reasons for this, as well as institutional barriers that are not easily removable via short-term project approaches.

Lack of coordinated and integrated implementation approach

A recurring issue faced by many developing Members is having several development partners independently of each other attempting to address the issue of missing observations via separate projects within their country. Many developing countries thus find themselves with disparate observing networks relying on vendor support from different donor countries, providing data in different proprietary formats, and requiring separate stocks of spare parts, etc. Such systems are difficult to sustain, even for NMHSs in developed countries.

Another coordination problem stems from the lack of recognition of the role of NMHSs in international data exchange. NMHSs act as the national node in the international exchange of observations as per WMO regulations and practice. However, in some cases, implementing entities only recognized the critical role of the NMHS in the data exchange after all project resources had been expended – hardware purchased and installed – but no data was flowing. Insufficient institutional, technical or financial support had been foreseen for the NMHS. This led to a lack of incentives, and as a result, no observational data were exchanged.

Lack of a realistic financing model undermines sustainability

In developing countries, in particular the Small Island Developing States (SIDS) and Least Developed Countries (LDCs), the lack of observations is often closely linked to the lack of ability to fund the necessary observing networks. Figure 2 shows the horizontal density of national observing networks (left panel), and available financial resources, measured by Gross Domestic Product (GDP) per km^2 surface area (right panel); a larger surface area implies a larger observing remit. Since SIDS often have Exclusive Economic Zones (EEZ) that are many times larger than their land areas, calculations for SIDS were made including both EEZ and land areas. The difference in "ability to pay" between rich and poor countries is striking: The richest countries make more than one million times more money per km^2 than the poorest countries. Scarce local resources lead to scarcity of observations, as shown by the similarity between the left and right panels in Figure 2.

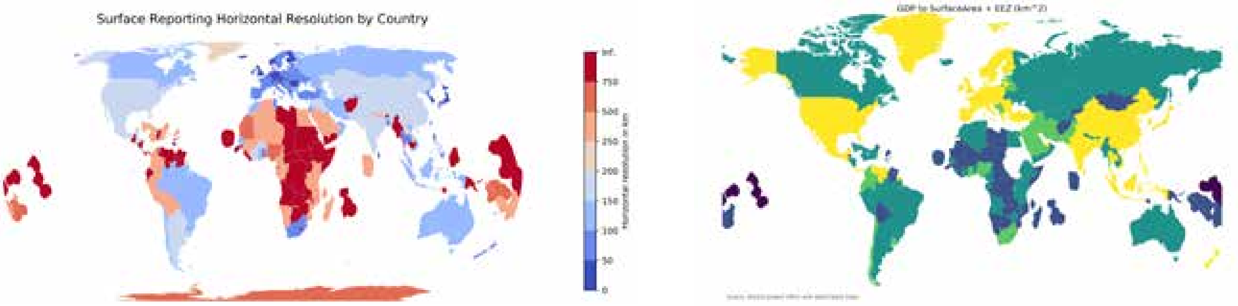

Figure 2. Ability to pay versus the ability to observe: Left panel: density of observations by nation (red do not meet requirements). Right panel: National GDP/km^2 of surface area; darker colors (blue and purple) show fewer resources per unit area (Source: WMO, 2021)

Finally, commercial approaches to generate revenues to cover the cost of certain government services are often extremely difficult to reconcile with the need for free and unrestricted international exchange of observations. Due to the role of observations at the beginning of the value chain and to international data sharing agreements, observational data are difficult for national governments to monetize, and a wealth of economic analyses have shown that doing so would severely limit the use and, therefore, also the impact of the data.[3] However, in their quest for revenue, some national governments have attempted to limit the freedom of their NMHSs to exchange data, including observations.

A new support mechanism for observing networks in developing countries – the Systematic Observations Financing Facility

In many parts of the world, even with improved management and practices, it is unlikely that countries can sustain and operate adequate observation networks on their own (see Box 2). Recognizing this, the global community under the leadership of WMO, UNDP and UNEP and its partners in the Alliance for Hydromet Development are establishing a new financing mechanism, the Systematic Observations Financing Facility (SOFF).

SOFF is a dedicated mechanism that will provide long-term grants and technical assistance, with a focus on SIDS and LDCs, to enable sustained compliance with the Global Basic Observing Network (GBON – see Article 11) requirements. SOFF will (i) deploy a global approach with sustained international data exchange as a measure of success; (ii) provide long-term finance toward sustained data sharing results; (iii) enhance technical competency through peer-to-peer advisory, harnessing the operational experience of the most advanced national meteorological services around the globe; and (iv) leverage partners' knowledge and resources.

SOFF will focus exclusively on the initial part of the meteorological value chain (see Article 2), while working in partnership with other development agencies that focus on other links in the chain, to help ensure that its investments will ultimately translate into end-user benefits. SOFF funding will be embedded within larger hydromet/climate projects. This will ensure that countries will be further supported in developing the capacity to effectively use improved forecast and climate products to create adaptation and resilience development benefits.

SOFF will be structured as a "UN coalition fund". WMO, the UN Development Programme (UNDP) and the UN Environment Programme (UNEP) will co-create the fund and the UN Multi-Partner Trust Fund Office will administer SOFF funds.

SOFF has a well-defined theory of change. SOFF support will be provided in three consecutive phases with outputs designed to achieve sustained GBON compliance.This in turn will contribute to the ultimate goal of strengthened climate adaptation and resilient development through improved weather forecasts, early warning systems and climate information services crucial to saving lives and fostering economic prosperity. The three phases of SOFF support include:

- The Readiness Phase- beneficiary countries – SIDS, LDCs and other Official Development Assistance (ODA)-eligible countries – will be able to access analytical and advisory assistance provided by national meteorological services as peer advisors to define their GBON gap, and develop a GBON National Contribution Plan.
- The Investment Phase- SIDS and LDCs will receive grants for investments and advisory support to establish the stations network of stations and strengthen human and institutional capacity for GBON compliance.
- The Compliance Phase- SIDS and LDCs will receive results-based grants in support of operation and maintenance expenses for GBON data data-sharing compliant stations.

SOFF will be operationalized in three periods implemented over 10 years designed to achieve sustained GBON compliance of all SIDS and LDCs and provide technical assistance on GBON to all developing countries. The Facility will be legally

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[3] See examples and references on the benefits of open data policies: (i) WMO Permanent Representative of Hungary presenting at the Data Conference how and why the country switched to an open data policy: https://meetings.wmo.int/WMO-Data-Conference/Documents/06_Konelia%20Radics_RK_WMODataConference.pdf; (ii) WMO Data Conference preparation workshop lists the benefits of the Copernicus open data policy and includes a reference to the underlying economic analysis: https://meetings.wmo.int/WMO-Data-Conference/PublishingImages/SitePages/Preparatory%20Workshops/Copernicus%20Data%20Policy%20Benefits%20for%20Environmental%20Services.pdf; (iii) Open data access approaches in the Group on Earth Observations and the research community: https://meetings.wmo.int/WMO-Data-Conference/PublishingImages/SitePages/Preparatory%20Workshops/Robert%20Chen_Open%20Data%20Access%20Approaches%20in%20GEO%20and%20the%20Research%20Community.pdf

established under the UN Multi-Partner Trust Fund Office by the end of October 2021. The creation of SOFF will be announced at the 26th session of the Conference Of Parties (COP26) to the UN Framework Convention on Climate Change in a high-level event jointly with the initial funders. SOFF is envisaged to become operational by mid-2022.

Achieving sustained compliance with the GBON regulations and hence a sustained improvement in the international exchange of observational data will require substantial investments, strengthened capacity and long-term resources for operation and maintenance in many countries. To close their GBON gaps, the observations in SIDS and LDCs need to increase 28 times over their current levels for surface stations and 12 times for upper air stations. Reaching this ambitious target with the urgency needed requires an accelerated and dedicated international effort. SOFF responds to this critical need.

Summary

All WMO Members are committed to international data exchange, however, structural, political and financial constraints currently prevent some of the developing country Members from fully living up to their commitment under the WMO Convention. The new WMO Unified Data Policy, and associated initiatives like the GBON regulations and SOFF, provide an opportunity for WMO, development

Box 2. The unique sustainability challenges of observation networks in Pacific SIDS countries – UNEP/GCF programme

In November 2020, the Green Climate Fund (GCF) approved a UNEP programme for five Pacific SIDS: Cook Islands, Niue, Palau, Republic of Marshall Islands (RMI), and Tuvalu, with a total value of US$ 49.9 million. The initiative supports the development of integrated climate and ocean information services, people-centred hydromet services and multi-hazard early warning systems. The five countries were selected as initial case studies for the GBON country gap analyses. The objectives will be achieved through four inter-related components: (i) a sustainable business delivery model for climate, hydromet, and early warning services; (ii) strengthened observations meeting GBON requirements and impact-based forecasting; (iii) improved community preparedness, response capabilities and resilience to climate risks, including forecast-based financing; and (iv) enhanced regional cooperation and knowledge management for climate services.

The GCF Board and the Independent Technical Advisory Panel assessment of the programme considered that compliance with GBON was an innovative approach that strengthened the programme's value proposition and noted the sustainability challenges for the proposed networks in the programme countries.

As Pacific SIDS, the countries face unique challenges in assuring the sustainability of their hydrometeorological observation networks. The current expectation that each country should provide the resources to sustainably operate and maintain the observation network within their national territory (including ocean zones) is impracticable for Pacific SIDS with low incomes, small land masses and vast ocean areas. For example, the land area of the Marshall Islands (RMI) (181 km^2) constitutes just 0.009 % of its EEZ (2 131 000 km^2). The small size, remoteness and insularity of the countries pose a significant challenge to transport logistics. The cost of travel, transactions and general operations in the Pacific region are comparatively higher than in other parts of the world. Communication with outer islands can also be expensive and unreliable. This in turn translates to increased costs at each stage of network investment, operation, maintenance and replacement.

In addition, the environmental conditions (i.e., warm temperatures, high humidity, and salt winds) in hot tropical locations such as the South Pacific are often unfavorable for meteorological sensors and automatic equipment – cheap weather stations often fail within 12 months. This necessitates the installation of more sophisticated and robust equipment to ensure accurate operation over long periods with only limited maintenance, which is more economical in the long-term but requires more significant up-front costs.

Disruption and damage caused by increasingly frequent or intense extreme weather events, brought about by climate change, further impede sustainable operations. Yet without systematic in situ observations across widely dispersed outer islands, local forecast products cannot be validated, and Pacific SIDS cannot implement timely actions to reduce extreme climate impacts.

partners and the Members of the Alliance for Hydromet Development to help developing country Members to address these issues for the mutual benefit of all. This will lead to a dramatic increase in the amount of observational data that are exchanged internationally, and therefore also to significantly improved model products for monitoring and prediction. The new policy also, for the first time, clearly articulates the principle that developing Members, in return for their observations, must be given free and unrestricted access to the model products that are supported by their observations. This will help improve the service delivery capabilities of all WMO Members in all areas of Earth system monitoring and prediction.

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