Vision for the WMO Integrated Global Observing System in 2040

2019 edition

WEATHER CLIMATE WATER

WORLD
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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at http://public.wmo.int/en/resources/meteoterm.

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1. INTRODUCTION

1.1 Purpose and scope

This document provides high-level targets to guide the evolution of the World Meteorological Organization (WMO) Integrated Global Observing System (WIGOS) in the coming decades. This vision (henceforth referred to as the "Vision for WIGOS in 2040" or simply the "Vision") replaces the "Vision for the Global Observing System in 2025", which was adopted by the Executive Council at its sixty-first session in June 2009. In many ways, the 2025 Vision foreshadowed the development of WIGOS, whereas the current document anticipates a fully developed and implemented WIGOS framework that supports all activities of WMO and its Members within the general areas of weather, climate and water.

The aim of this document is to present a likely scenario of how user requirements for observational data may evolve in the WMO domain over the next several decades and an ambitious, but technically and economically feasible vision for an integrated observing system that will meet them. With this information, National Meteorological and Hydrological Services (NMHSs), space agencies and other observing system developers will be able to adapt their planning efforts accordingly, and WMO Members providing funding will be able to make the decisions necessary to implement this integrated system. This document also informs users of weather, climate, water and other related observations about what to expect over this time frame and provides guidance relating to the planning of information technology and communication systems, research and development efforts, staffing, and education and training. For example, it provides information regarding the anticipated evolution of systems in numerical modelling and prediction centres, as well as a set of guiding principles to promote active engagement among the public, private and academic sectors in order to better serve governments, businesses, and citizens.

In extending all the way to 2040, the Vision takes a long-term view. To a large extent, this time horizon is driven by the long programme development and implementation cycles of specific components such as operational satellite and radar replacement programmes. However, WIGOS is an integrated system, and the space-based and surface-based components complement each other. As such, the full value of the Vision will only be delivered by addressing both components to the extent possible.

In this document, the space-based and surface-based observing system components are treated separately due to the fundamentally different ways in which these two components tend to evolve. Operational satellite (space-based) programmes are characterized by a high degree of central planning, long development cycles and well-structured formal mechanisms for engagement with the WMO user community. On the other hand, some surface-based observing programmes, especially over the last decades, have been driven by a number of unanticipated technological innovations. Since contributions to these programmes are made by a broad community of stakeholders with a correspondingly wide range of motivations, the programmes are less influenced by centralized planning or coordination efforts than operational satellite programmes.

This document is divided into three parts. Part I introduces the Vision and describes its purpose and scope. It discusses key drivers for weather, water and climate services, trends in capabilities and requirements for service delivery. It also outlines the principles and design drivers for WIGOS. Part II describes the space-based observing system component. Part III addresses the surface-based observing system component.

1.2 Key drivers for weather, water and climate services

In keeping with the WIGOS philosophy of user-driven observing systems, the starting point in the formulation of the Vision is the expected evolution of user requirements. In this section, an analysis of current and projected trends in societal requirements for weather-, climate- and water-related services is presented.

In general, WMO breaks down the meteorological value chain into four links: (i) observations, (ii) information exchange and data dissemination, (iii) data processing, and (iv) service delivery. The observations, as well as the observing systems used to acquire them, are typically driven by end-user requirements for service delivery. Determining the appropriate requirements for the observing systems, in turn, depends on a number of assumptions about the two intermediate links in the chain. These assumptions are made explicit wherever possible.

Many of the main drivers for meteorological and related environmental service delivery are linked to human activity. The global population continues to grow, and the United Nations Department of Economic and Social Affairs projects it to reach nine billion by the year 2045.[1] This will put additional strain on the resources of our planet, and long-term issues such as food security, energy supply and access to clean water are likely to become even stronger drivers for weather and climate services than they are today. Population growth is also likely to contribute to overall vulnerability to short-term weather events as an increasing proportion of the population may chose or be forced to live in areas exposed to phenomena such as coastal or river flooding, landslides, and so forth.

Accompanying population growth is a tendency towards increased urbanization. In 1900, some 10% of the world's population lived in cities. Today, more than 50% live in urban areas, and it is estimated that by 2050, this figure will reach 66%[2] or even 75%[3]. This massive migration will require metropolitan areas to absorb close to 3 billion additional people over the next 30 years.[4] Large agglomerations, especially so-called megacities with more than 10 million inhabitants, are inherently vulnerable, as are their infrastructures. Food, water and energy supplies will need to be secure, and advance planning for responses to a wide range of potential natural, or partly human-induced disaster scenarios will provide very strong drivers for meteorological and environmental service delivery and for the temporal and spatial resolution of the required data products.

Another major driver linked to human activities is climate change. Overwhelming scientific evidence suggests that global warming (and with it, consequences such as sea level rise, increased frequency of various extreme weather and climate events, geographic shifts in major agricultural growing zones, and so forth) will continue. Guidance and policy-related decisions on climate change resilience, adaptation and/or mitigation will drive requirements for an improved understanding of climate processes and for long-range prediction capabilities. An increased frequency of extreme weather events will exacerbate human vulnerability to weather and will impose additional requirements on traditional weather forecast and warning services. The growing recognition of the value of extended-range weather forecasts will lead to an increased demand for related products and services, even more so in a changing climate, since expectations of 'normal' seasonal weather will have to yield to reliance on quantitative seasonal predictions and outlooks.

Some of the most serious challenges and threats to the world's population are associated with water. According to the United Nations World Water Development Report 2019, some 106 million people are affected by flooding each year, with the associated economic damage costing approximately US$ 31.4 billion.[5] River floods, in particular, currently affect an average of 39 million people per year, and the most extreme estimates indicate that this figure may rise to 134 million people per year by 2050.[6] At the same time, droughts currently affect approximately 55 million people annually and cause approximately US$ 5.4 billion in economic damages.[7] These challenges will intensify with future climate change and population growth. Water features

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[1] https://www.un.org/development/desa/en/key-issues/population.html

[2] http://www.unfpa.org/world-population-trends

[3] https://www.sipri.org/events/2016/stockholm-security-conference-secure-cities/urbanization-trends (cited from The Urban Age Project, London School of Economics)

[4] https://www.unfpa.org/urbanization

[5] The United Nations World Water Development Report 2019: *Leaving No One Behind*. Paris, United Nations Educational, Scientific and cultural Organization, https://unesdoc.unesco.org/ark:/48223/pf0000367306

[6] Ward, P.J. and H. Winsemius, 2018: *River Flood Risk*. Institute for Environmental Studies, Vrije Universiteit Amsterdam, https://www.pbl.nl/sites/default/files/downloads/pbl-2018-the-geography-of-future-water-challenges-river-flood-risk_3147.pdf

[7] The United Nations World Water Development Report 2019: *Leaving No One Behind*. Paris, United Nations Educational, Scientific and cultural Organization, https://unesdoc.unesco.org/ark:/48223/pf0000367306

heavily in the new United Nations Sustainable Development Goals, not only in the explicit aim to ensure the availability and sustainable management of water and sanitation for all (Sustainable Development Goal 6), but also because of the underpinning nature of water-related issues across many development areas.

Managing and monitoring climate change resilience, mitigation and adaptation as a follow-up to the 2015 Paris Agreement will require observations of greenhouse gas concentrations as well as additional measurements related to the global carbon cycle. Recent estimates by the World Health Organization link seven million premature deaths annually to exposure to air pollution. The aspects of WIGOS relating to atmospheric chemical composition, including both ground-based and space-based observations, must be reinforced and strengthened.

1.3 Trends in capabilities and requirements for service delivery

As late as the early 1990s, weather forecasting still relied heavily on human forecasters and their ability to produce, interpret and extrapolate hand-drawn analyses. The useful forecast range was limited, and although a handful of global numerical weather prediction (NWP) centres were already issuing routine 10-day forecasts, relatively few users were making decisions of substantial economic impact based on weather forecasts beyond two to three days at the most. Since that time, our capabilities have improved dramatically thanks to scientific progress in areas such as ensemble (or probabilistic) forecasting, model physics and data assimilation, advances in computational capabilities, and additional sources of observations, especially from satellites. Major shifts in weather patterns are routinely predicted 7–10 days out, landfall of tropical cyclones is predicted several days in advance, and even warnings of high-impact, localized severe weather are often provided with sufficient lead time to avoid or limit the loss of life.

As a result, the demand for meteorological and related environmental information from the user community (both public and private sectors and citizens) has evolved dramatically. A latent demand for this information was already present, but it was not explicitly articulated until the capabilities to satisfy it began to materialize. A wide range of users from all economic sectors and from all levels of government now routinely make decisions with very significant consequences entirely based on weather forecast, climate and hydrological outlook information. Not only are users more demanding about the content and quality of the environmental information they receive, they are also more demanding about how, when, and where they receive it, and in what form.

All indications are that the trend towards increasing the demand for meteorological information will continue into the future. As Earth system prediction capabilities continue to improve, new application areas will emerge and new markets for services and products will open up, which means that the observing systems under the WIGOS umbrella will need to evolve to meet the needs of ever more demanding and ever more knowledgeable user communities.

Common to all observing system components is the drive towards new business models, especially with respect to the role of the private sector. As both the demand for and an appreciation of the economic value of meteorological and related environmental information increase, the private sector is showing a growing interest in becoming involved in all elements of the meteorological value chain. This document does not assume specific policy positions around this issue, nor does it speculate on how the boundaries between the respective responsibilities of private versus public sector entities might shift in the future. The Vision presented here contains a number of core elements that are expected to materialize, irrespective of who will ultimately be responsible for implementing and operating the systems.

While detailed long-term extrapolations based on any of these major trends will be highly uncertain, the trends themselves are well established and largely undisputed. It is therefore reasonable to base a vision for future observational requirements and future observing systems on the assumption that the trends will continue.

1.4 **WIGOS principles and design drivers**

The development of WIGOS is focused on ensuring that the provision and delivery of meteorological and other environmental services responding to the societal needs discussed above will rest on a solid basis of observations of adequate density and quality, procured in a manner that is efficient, cost-effective and sustainable.

A key WIGOS principle is to design and implement observing systems in response to specific requirements. The primary guidance comes from the WMO Rolling Review of Requirements (RRR), in which observational requirements for all WMO application areas (see Table 1) are gathered, vetted and recorded, and reviewed against observational capabilities. The resulting guidance is formulated at both the tactical and the strategic levels. Tactical level guidance for each individual application area can be found in the corresponding WMO Statement of Guidance, found on the RRR webpage. The present document represents long-term strategic guidance.

Observing systems must be designed with adequate resilience to a variety of natural and human-induced hazards. For instance, the near-universal reliance on electronics for sensing, telecommunication and data processing has significantly increased the vulnerability of these systems to natural events such as solar storms. As a consequence, space weather, which describes the impact of solar activity on the Earth's environment, has become an officially recognized WMO application area. Observational data, especially satellite data, is necessary to monitor space weather, and space weather events may also potentially have an effect on WIGOS components.

A fundamental principle of the RRR is that the requirements are expressed in terms of geophysical variables and thus do not directly pertain to specific observing systems. For example, the RRR will cite requirements for measurements of atmospheric temperature, but it will not provide system requirements for the various temperatures measured by satellite radiometers or in situ temperature sensors. Specific requirements for observing systems can and should be derived from the overall requirements listed in the RRR. However, it is primarily the responsibility of the implementing organizations and agencies to assess them. While the guidance material provided by the RRR does include references to available technologies, it strives to remain impartial with respect to which particular technologies will be used to meet the requirements.

It is not enough to implement a system that meets the requirements in terms of coverage and quality. In order to be useful, the observations from WIGOS also need to be discoverable by users, and those observations that are deemed essential must be made available to users with the required timeliness. As a result, the continued evolution of the WMO Information System (WIS), and the leadership of NMHSs in its operation will be critically important to the success of WIGOS, and the two systems will need to evolve in parallel.

Widespread reliance on information technology also leads to vulnerability to malicious human activity in the form of "cyberattacks". WIS is expected to provide critical guidance on the issue of network resilience, in particular regarding information technology security. Another important role of WIS will be to continue its work on protecting important parts of the electromagnetic spectrum in order to safeguard vital communications and remote sensing capabilities.

Table 1. WMO application areas

No.	*WMO application area*
1	Global NWP
2	High-resolution NWP
3	Nowcasting and very short-range forecasting (see Note 1 below)
4	Sub-seasonal to longer predictions
5	Aeronautical meteorology
6	Forecasting atmospheric composition (see Note 2 below)
7	Monitoring atmospheric composition (see Note 2 below)
8	Providing atmospheric composition information to support services in urban and populated areas (see Note 2 below)
9	Ocean applications
10	Agricultural meteorology
11	Hydrology
12	Climate monitoring (Global Climate Observing System (GCOS)) The following GCOS reports are considered Statements of Guidance: - Status of the Global Observing System for Climate - GCOS-195 - The Global Observing System for Climate: Implementation Needs - GCOS-200
13	Space weather
14	Climate science
n/a	Climate applications (other aspects, addressed by the Commission for Climatology) (See Note 3 below)

Notes:

1 The Synoptic meteorology application area has been merged into the Nowcasting and very short-range forecasting application area.

2 The Atmospheric chemistry application area has been replaced and split into three new application areas: (i) Forecasting atmospheric composition, (ii) Monitoring atmospheric composition, and (iii) Providing atmospheric composition information to support services in urban and populated areas. Statements of Guidance for the three new application areas are under preparation. The old version of the Statement of Guidance for Atmospheric Chemistry is available here.

3 At the third meeting of the Commission for Basic Systems Inter-programme Expert Team on Observing System Design and Evolution (January 2018), it was decided that the Climate applications (other aspects, addressed by the Commission for Climatology) application area would be discontinued, but that the Statement of Guidance would be kept updated and would be accessible from this webpage. The Commission for Climatology was responsible for keeping the Statement of Guidance updated and ensuring that requirements that were important from a Commission for Climatology/climate applications perspective were not missing. However, there is no intention to submit quantitative observational user requirements to the Statement of Guidance since it is assumed that such requirements are principally addressed in the GCOS 'Climate Monitoring' application area as well as in other existing application areas.

Observational data provided by WIGOS are expected to be made available for free and unrestricted international exchange among WMO Members per the policies established in Resolution 25 (Cg-XIII) – Exchange of hydrological data and products, Resolution 40 (Cg-XII) – WMO policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities, and Resolution 60 (Cg-17) – WMO policy for the international exchange of climate data and products to support the implementation of the Global Framework for Climate Services, as well as the relevant WIGOS regulatory material. The WIGOS guidance is that generally, data sharing has been found to be an effective multiplier for maximizing the overall benefit to society of the data. The more widely data are shared, the larger the community that will be able to exploit them, and the larger the overall economic return on the investment made in providing the observations. Thanks to the long history of success of the Global Observing System of the World Weather Watch, the value of international data sharing of weather observations is well recognized in the WMO community. Furthermore, international data sharing has been found to be valuable with respect to other Earth science disciplines as well, and several case studies have also shown the economic advantages of open data exchange at the national level.[8]

1.5 The role of integration in WIGOS

The notion of integration is central to WIGOS. It refers to the integration of the observing networks, not to any integration of the observations themselves. (Integration of the observations, for example through data assimilation or generation of end-user products, remains outside the scope of WIGOS.) Five specific aspects of WIGOS integration are highlighted.

1.5.1 *Integrated network design*

When designing observing networks, it is imperative to do so taking into account not only the requirements that these networks will meet, but also what other WIGOS elements component observing systems will deliver and how to optimally complement the observations provided by those systems. This is articulated in the WIGOS network design principles, which are part of the Manual on WIGOS.

1.5.2 *Integrated, multi-purpose observing networks*

Many application areas share requirements for observations of certain geophysical variables, for example atmospheric temperature or surface pressure. WIGOS aims to establish integrated, multi-purpose observing networks serving several application areas wherever possible, rather than setting up separate networks for climate monitoring, nowcasting and numerical weather prediction, flood and drought forecasting, and so forth, all of which require observations of many of the same variables, albeit with somewhat different requirements.

1.5.3 *Integrated observing system providers*

WIGOS strives to integrate NMHS and partner observations into one overall system to the extent possible. In most countries, the NMHS is no longer the sole provider of observations. Instead, typically a variety of organizations are now running observing systems of relevance to WMO application areas. These may be different government agencies operating under the ministries of agriculture, energy, transport, tourism, environment, forestry, water resources, and so forth. In developing countries especially, they may be non-profit organizations or commercial entities. It is in the interest of NMHSs to partner with these external operators in order to be able to base their services on the most comprehensive observational dataset possible, assuming that technical issues related to data quality, data formats, communication lines and data repositories can be sorted out and agreements regarding data policy can be concluded.

1.5.4 *WIGOS as a system of tiered observing networks*

WIGOS consists of tiered observing networks providing integration across different levels of performance. The specific breakdown of the tiers may vary by discipline or by application area, but the overall network can be seen as consisting of three tiers: comprehensive, baseline and reference.[9]

The comprehensive network is characterized by the ubiquity of data in time and space, and it is largely self-organized, with a very low degree of central management and control. Its metadata may be incomplete, especially with respect to the quality of the data. The comprehensive network for weather, for example, may include crowdsourced observations and data from mass-produced commoditized sensors, such as those now used in smartphones and cars.

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[8] See *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services* (WMO-No. 1153), available at https://library.wmo.int/doc_num.php?explnum_id=3314.

[9] See *Guide to the WMO Integrated Global Observing System* (WMO-No. 1165), 5.2 Guidance on the observing network design principles, available at https://library.wmo.int/doc_num.php?explnum_id=10040.

The baseline network is the Global Observing System as we know it today. Its coverage is less dense in time and space, but due to some degree of active management and coordination, its assets can target regions not covered by the comprehensive network. Metadata are expected to comply with WIGOS standards, and the quality of the data is controlled.

The reference networks include selected observing stations at the highest level of performance. The observation coverage is typically sparse in space and time, and instruments require appropriate calibration and high-quality data. Uncertainty estimates are included as part of the observations, and the measurements are traceable to the International System of Units (SI). Full compliance with the WIGOS standards for metadata is also required. WIGOS reference networks are, for instance, the reference networks operating under the Global Climate Observing System.

Users can decide whether or not to use observations, and how to use them for a given application area, based on the tier to which the observing platform belongs. For instance, when monitoring the onset of active severe weather, timeliness and spatial and temporal resolution are more important than low uncertainty of measurements, and a comprehensive network is desirable. For detailed monitoring of long-term trends in temperature or background atmospheric composition, the converse is true, and observations from a reference network may be required.

1.5.5 *Integrated space-based and surface-based observing systems*

WIGOS treats the space-based and surface-based components as parts of the overall system contributing to meeting the requirements of the application areas. Certain observational user requirements are more readily met from space, for instance global coverage and high spatial resolution over large areas. On the other hand, certain variables are either difficult to measure from space or the required technology may not yet be available, for instance surface pressure, or the chemical composition of the boundary layer. Here, surface-based measurements will continue to play an essential role. Fine-scale vertical resolution is also generally better achieved via surface-based observations, as evidenced by the continued high impact of aircraft and radiosonde observations in spite of their relative sparsity.

For example, in the planned operational carbon monitoring system, the space-based component is expected to provide global clear sky observations of greenhouse gas concentrations at high spatial resolution in cloud-free regions, while the surface-based component will provide data in persistently cloudy regions and at night, as well as additional information needed to form a solid basis for attributing anthropogenic emissions.

Even in areas where space-based capabilities are strong, surface-based observations remain important for calibration and validation, especially if the systems providing these observations can be maintained continuously throughout the lifetime of space missions. Providing surface-based observations is also a way for non-space-faring nations to become actively involved in satellite programmes. At the same time, surface networks can benefit from satellite observations since these may be used as a reference.

1.6 Conclusion

The Vision for the WMO Integrated Global Observing System in 2040 contains specific descriptions of the space-based and surface-based components. The complementary nature of these components and recognition of their individual strengths and limitations will shape the overall implementation of WIGOS.

WIGOS provides the global framework and the management and design tools so that all providers of meteorological and related environmental observations can optimize their investment in user-driven measurement capabilities. When used in combination, these capabilities will help meet user requirements as effectively and efficiently as possible.

WIGOS is an essential feature of the infrastructure that enables WMO and its Members to accomplish their shared mission of helping to save lives, protect property, increase prosperity throughout the world and provide relevant data and information for policymaking and decision-making in support of sustainable development.

The evolution of WIGOS as described in this document will help ensure that the observing system will continue to meet the needs of users in the coming decades.

2. SPACE-BASED OBSERVING SYSTEM COMPONENT

2.1 Introduction

This chapter describes the space-based component of WIGOS in 2040. It responds to evolving user needs for observations in all WMO application areas and is guided by the expected evolution of space-based observing technology.

While it is addressed primarily to Members who actively participate in space programmes, it is also important for those Members who do not. All Members rely on satellite data to provide critical services to their constituencies; those Members who do not directly participate in space programmes may still contribute by providing ground-station services or surface-based observations in support of calibration and validation. The information presented here may therefore also inform the planning of aspects of the surface-based component of WIGOS.

2.2 Trends and issues

2.2.1 *User requirements*

Compared to their current requirements, it is expected that by 2040, users will require:

(a) Higher resolution observations and better temporal and spatial sampling/coverage;

(b) Improved data quality and consistent characterization of uncertainty;

(c) Novel data types, allowing insight into hitherto poorly understood Earth system processes, including space weather;

(d) Efficient and interoperable data representation and dissemination methodology given the anticipated continued growth in data volumes.

Even in the near term, certain additional observations using existing technology are required to address immediate needs and gaps in several specific WMO application areas. These include:

(a) Atmospheric composition: limb sounding for the upper troposphere and stratosphere/mesosphere, nadir sounding using short-wave infrared (SWIR) spectrometry, trace gas light detection and ranging (lidar);

(b) Hydrology and cryosphere: laser and radar altimetry, visible multifrequency synthetic aperture radar (SAR) and passive microwave imagery;

(c) Cloud phase detection for NWP: sub-mm imagery;

(d) Aerosol and radiation budget: multiangle, multipolarization radiometry; lidar;

(e) Wind: lidar and hyperspectral capabilities;

(f) Solar wind/solar eruptions: solar wind monitor, magnetometer, energetic particle sensor, solar extreme ultraviolet (EUV) imagery, heliospheric imagery (at L5) and in situ energetic particle flux (at L1).

To monitor climate change and assist in mitigation efforts in support of the Paris Agreement, observations of greenhouse gases and other factors affecting the carbon budget must be integrated into a global carbon monitoring system. This system will consist of several elements, including ground-based observations, space-based observations and modelling tools to assimilate these data into atmospheric transport models in order to estimate greenhouse gas fluxes.

In addition, new and better information relevant for renewable energy generation, such as near-surface wind and solar irradiance, will be required.

These and other emerging needs, including the monitoring of air pollution, which has grown increasingly important due to the impact of air pollution on human health, and the monitoring of global precipitation will require significant augmentations to existing operational satellite constellations.

2.2.2 *System capabilities*

The following sections describe trends in satellite systems and programmes relevant to WMO. These trends, together with the anticipated user needs outlined above, have given rise to a vision for the space-based component of WIGOS in 2040 that represents an ambitious, yet realistic and cost-effective target.

Sensor technology

It is expected that rapid progress in remote sensing technology will lead to the development of sensors with higher signal sensitivity, which will result in potentially higher spatial, temporal, spectral and/or radiometric resolution. New types of sensors will ensure that the electromagnetic spectrum is used more extensively.

Key sensor technology trends include:

(a) Sensors with improved geometric/radiometric performance;

(b) Better exploited electromagnetic spectrum: ultraviolet (UV), far infrared (IR), microwave (MW);

(c) Hyperspectral UV, visible (VIS), near IR (NIR), IR, MW sensors in geostationary Earth orbit (GEO) and elsewhere;

(d) New space sensors with climate-sensitivity detection capabilities;

(e) State-of-the-art sensors/missions to establish traceability in orbit;

(f) Lidar;

(g) Combination of active/passive techniques;

(h) Expanded polarimetric measurement capability (including SAR imagery);

(i) Polarization or incidence-angle pairing;

(j) Diverse radio occultation techniques;

(k) Near-IR measurements of molecular oxygen and water vapour to provide clear-sky surface pressure and cloud top height estimates with accuracies near 1 hectopascal (hPa) and column water vapour estimates with accuracies near 1 millimetre.

The information content and coverage of satellite observations are constrained by observation techniques. For example, high-resolution spectra of emitted radiation yield estimates of trace gas concentrations in the middle troposphere and above on both the day and night sides of the planet but provide little information about near-surface concentrations. In contrast, high-resolution spectra of reflected sunlight provide more information about trace gas concentrations near the surface but only work over the sunlit hemisphere and are more dependent on clouds and aerosols and on illumination and viewing geometries.

It is expected that operational meteorological satellite systems will remain the key features of a space-based climate observing system capable of unambiguously monitoring indicators of changes in the Earth's climate. Satellite agencies are therefore encouraged to develop new satellite instruments with climate applications in mind. In particular, observations spanning the electromagnetic spectrum from near-UV to microwave need to be of sufficient accuracy and duration, traceable to the International System of Units, and sampled to ensure global representation in order to detect changes on as short a timescale as possible. Significant improvements, up to an order of magnitude, in aspects such as calibration and uncertainty, will be required for robust climate observations. Rigorous instrument characterization and improved pre-flight calibration are prerequisites for an improved uncertainty characterization of the observations. SI-based reference standards, both on the ground and in orbit, will enhance the quality of data from the whole system. Measurement traceability will be essential for the use of observations for climate monitoring that will require access to raw data. Dedicated reference missions to provide standards with adequate spatial and temporal coverage to tie disparate observations together are needed; these will require the coordinated efforts of international space agencies in support of global climate system observations. GCOS climate monitoring principles must be followed. Essential Climate Variables (ECVs) should be produced in accordance with established key requirements for climate monitoring. Space agencies should develop research missions to address existing gaps in ECV monitoring.

Observing capabilities to monitor the Earth's energy, water and biogeochemical cycles and associated fluxes need to be enhanced, and new techniques to measure relevant physical and chemical aspects need to be developed, as documented in the 2016 GCOS Implementation Plan (GCOS-200 (GOOS-214)).

Orbital scenarios

Satellite observations are also constrained by the choice of orbit. The growing number of space-faring nations contributing to the space-based observing system component will require a high-level planning and coordination effort undertaken by the Committee on Earth Observation Satellites (CEOS) and the Coordination Group for Meteorological Satellites (CGMS), taking into account the requirements of WMO, with the goal of maximizing the complementarity and interoperability of individual satellite programmes as well as the robustness of the overall system.

A future space-based observing system will rely on proven geostationary and low-Earth orbit (LEO) sun-synchronous constellations and will include:

(a) Highly elliptical orbits providing permanent coverage to the polar regions;

(b) LEO satellites with a low or high inclination for a comprehensive sampling of the global atmosphere;

(c) Lower-flying platforms, for example, platforms with small satellites serving as gap fillers or platforms that are specially designed for specific missions; and

(d) Constellations, including low-cost CubeSats.

For example, measurements from a large constellation (for instance, 3-10 LEO satellites, at least one of which carrying CO_2 and CH_4 lidar, and three or more GEO satellites) would be needed in order to obtain robust, operational, full-column observations of CO_2 and CH_4 at daily to weekly intervals in all but the most persistently cloudy regions. The total number of satellites needed could likely be reduced by replacing some of the LEO satellites with highly elliptical orbit (HEO) satellites.

Manned space stations, such as the International Space Station, may be used for demonstration purposes and for cross-reference calibration/validation of geostationary satellite instruments; in the overlap region of space-based and surface-based observing systems, sub-orbital flights of balloons or unmanned aerial vehicles will contribute.

The strong capability from geostationary orbit to resolve diurnal cycles will be complemented by more frequent observations from lower orbits. A diversity of orbits will increase the overall robustness of the system but will require a special emphasis on interoperability (on the provider side) and agility (on the user side). The diversity of mission concepts should be accompanied by a diversity in programmatic approaches: the overall system should be based on a series of recurrent, large satellite programmes providing a stable and sustainable long-term foundation, complemented by small satellite programmes with shorter life cycles, a limited scope, experimental payloads, and faster, more flexible decision-making processes.

Given the continued pressure to use the electromagnetic spectrum by commercial entities, especially for communication, continuing efforts by the satellite community to protect critical parts of the electromagnetic spectrum will be required.

The need to maintain continuous data records for real-time and reanalysis purposes requires robustness of the whole data chain. Contingency plans built on the collective capabilities of all contributing space-faring nations are needed in order to ensure continuity and thus minimize the risk of gaps in data records.

2.2.3 *Evolution of satellite programmes*

In addressing how the space-based observing system component will form a part of the Vision for WIGOS in 2040, the following assumptions were made with regard to the evolution of satellite programmes:

(a) The space-based observing system will continue to rely on both operational and research and development missions pursuing different objectives and having different priorities;

(b) Growing numbers of satellites and space-faring nations will lead to increased diversity of data sources, which will require improved documentation, processing and real-time data delivery mechanisms;

(c) International fora such as CGMS and CEOS will provide regular and formal opportunities to address joint planning, coordination and cooperation issues.

2.3 Description of the space-based observing system component

The proposed space-based component consists of four main subcomponents. Three of these are applicable to the Vision for WIGOS in 2040. The fourth includes additional capacities and capabilities that may emerge in the future.

Rather than giving strict stipulations for each subcomponent, a balance has been struck between providing enough specificity to describe a robust and resilient system and accommodating potential new capabilities arising from unanticipated opportunities.

Subcomponent 1: Backbone system with specified orbital configuration and measurement approaches

- This subcomponent shall provide the basis for Members’ commitments and should respond to their vital data needs;

- It shall build on the current CGMS baseline (CGMS Baseline – Sustained contributions to the Global Observing System, Endorsed by CGMS-46 in Bengaluru, June 2018, CGMS/DOC/18/1028862, v.1, 20 December 2018) but have fully deployed (global) coverage and newly maturing capabilities.

Subcomponent 2: Backbone system with open orbit configuration and flexibility to optimize implementation

- This subcomponent shall be the basis for the open contributions of WMO Members and shall respond to target data goals.

Subcomponent 3: Operational pathfinders and technology and science demonstrators

- This subcomponent shall respond to research and development needs.

Subcomponent 4: Additional capabilities

- This subcomponent shall include additional contributions by WMO Members, as well as from the academic and private sectors.

The division of the observing capabilities into four subcomponents does not imply sequential priorities, that is, it is not expected that all Subcomponent 1 systems will necessarily be realized before elements of other subcomponents are addressed.

The main distinction between the various subcomponents is the current level of consensus about the optimal measurement approach, especially the demonstrated maturity of that approach: there is stronger consensus for the capabilities included in Subcomponent 1 compared to those in Subcomponent 2, and so forth. It is likely that the boundaries between the groups will shift over time, for instance, some capabilities currently listed in Subcomponent 2 could transfer to Subcomponent 1.

Table 2. Backbone system with specified orbital configuration and measurement approaches (Subcomponent 1)

Instruments	*Geophysical variables and phenomena*
Geostationary core constellation with a minimum of five satellites providing complete Earth coverage	
Multi-spectral VIS/IR imagery with rapid repeat cycles	Cloud amount, type, top height/temperature; wind (by tracking cloud and water vapour features); sea/land surface temperature; precipitation; aerosol content and physical properties; snow cover; vegetation cover; albedo; atmospheric stability; fire properties; volcanic ash; sand and dust storms; convective initiation (combining multispectral imagery with IR sounders data)
IR hyperspectral sounders	Atmospheric temperature, humidity; wind (by tracking cloud and water vapour features); rapidly evolving mesoscale features; sea/land surface temperature; cloud amount and top height/temperature; atmospheric composition (aerosols, ozone, greenhouse gases, trace gases)
Lightning mappers	Total lightning (in particular, cloud to cloud), convective initiation and intensity, life cycle of convective systems, NOx production
UV/VIS/NIR sounders	Ozone, trace gases, aerosol, humidity, cloud top height
Sun-synchronous core constellation satellites in three orbital planes (morning, afternoon, early morning)	
IR hyperspectral sounders	Atmospheric temperature and humidity; sea/land surface temperature; cloud amount, water content and top height/temperature; precipitation; atmospheric composition (aerosols, ozone, greenhouse gases, trace gases)
MW sounders	
VIS/IR imagery, realization of a day/night band	Cloud amount, type, top height/temperature; wind (high latitudes, by tracking cloud and water vapour features); sea/land surface temperature; precipitation; aerosol properties; snow and (sea-) ice cover; ice-flow distribution; vegetation cover; albedo; atmospheric stability; volcanic ash; sand and dust storm; convective initiation
MW imagery	Sea-ice extent and concentration and derived parameters, such as ice motion; total column water vapour; water vapour profile; precipitation; sea-surface wind speed and direction; cloud liquid water; sea/land surface temperature; soil moisture; terrestrial snow
Scatterometers	Sea-surface wind speed and direction; surface stress; sea ice; soil moisture; snow cover extent and snow water equivalent (SWE)
Sun-synchronous satellites at three additional equatorial crossing times for improved robustness and improved time sampling, particularly for monitoring precipitation	
Instruments on other satellites in low-Earth orbit	
Wide-swath radar altimeters and high-altitude, inclined, high-precision orbit altimeters	Ocean surface topography; sea level; ocean wave height; lake levels; sea- and land-ice characteristics; snow over sea ice
IR dual-angle view imagers	Sea-surface temperature (of climate monitoring quality); aerosols; cloud properties
MW imagery for surface temperature	Sea-surface temperature (all weather)
Low-frequency MW imagery	Soil moisture; ocean salinity; sea-surface wind; sea-ice thickness; snow cover extent and SWE
MW cross-track upper stratospheric and mesospheric sounders	Atmospheric temperature profiles in the stratosphere and mesosphere

Instruments	*Geophysical variables and phenomena*
UV/VIS/NIR sounders, nadir and limb	Atmospheric composition (ozone, aerosol, reactive gases)
Precipitation radars and cloud radars	Precipitation (liquid and solid); cloud phase; cloud top height; cloud particle distribution, amount and profiles; aerosol; dust; volcanic ash
MW sounder and imagery in inclined orbits	Total column water vapour; precipitation; sea-surface wind speed and direction; cloud liquid water; sea-/land-surface temperature; soil moisture
Absolutely calibrated broadband radiometers and total solar irradiance and solar spectral irradiance radiometers	Broadband radiative flux; Earth radiation budget; total solar irradiance; spectral solar irradiance
Global Navigation Satellite System (GNSS) radio occultation (basic constellation)	Atmospheric temperature and humidity; ionospheric electron density; zenith ionospheric total electron content; total precipitable water
Narrow-band or hyperspectral imagers	Ocean colour; vegetation (including burned areas); aerosol properties; cloud properties; albedo
High-resolution multi-spectral VIS/IR imagers	Land use, vegetation; flood, landslide monitoring; ice floe distribution; sea-ice extent/concentration; snow cover extent and properties; permafrost
SAR imagers and altimeters	Sea state; sea-surface height; sea-ice motion; sea-ice classification; ice floe geometry; ice sheets; soil moisture; floods; permafrost
Gravimetry missions	Groundwater; oceanography; ice and snow mass
Other missions	
Solar wind, in situ plasma, energetic particles and magnetic field at L1	Particle flux, energy spectrum and magnetic field (radiation storms, geomagnetic storms)
Solar coronagraph and radio spectrograph at L1	Solar imagery and radio wave spectrum (detection of coronal mass ejections and solar activity monitoring)
In situ plasma probes, energetic particle spectrometers and magnetometers at GEO and LEO; magnetic field at GEO	Energetic particle flux and energy spectrum; geomagnetic field (radiation storms, geomagnetic storms)
X-ray spectrograph at GEO	Solar X-ray flux (solar flare)
On-orbit measurement reference standards for VIS/NIR, IR; MW absolute calibration	

Table 3. Backbone system with open orbit configuration and flexibility to optimize the implementation (Subcomponent 2)

Instruments	*Geophysical variables and phenomena*
GNSS reflectometry (GNSS-R) missions; passive MW; SAR	Surface wind and sea state; permafrost changes/melting; terrestrial water storage variations; ice sheet altimetry; snow depth; SWE; soil moisture
Lidar (Doppler and dual/triple-frequency backscatter)	Wind and aerosol profiling
Lidar (single wavelength) (in addition to radar missions mentioned in Subcomponent 1)	Sea-ice thickness; snow depth (only if pointing accuracy is very precise)
Interferometric radar altimetry	Sea-ice parameters; freeboard/sea-ice freeboard
Sub-mm imagery	Cloud microphysical parameters, for example, cloud phase
NIR/SWIR imaging spectroscopy	Spatially-resolved two-dimensional maps of CO_2, CH_4 and CO over sunlit hemisphere
Trace gas lidars	CO_2 and CH_4 column at night and high latitude winter
Multiangle, multipolarization radiometers	Aerosol properties; radiation budget
Multipolarization SAR; hyperspectral VIS	High-resolution land, ocean, and sea-ice extent; sea-ice types
Constellation of high-temporal frequency MW sounding	Atmospheric temperature, humidity and wind; sea/land surface temperature; cloud amount, water content and top height/temperature; atmospheric composition (aerosols, ozone, trace gases)
UV/VIS/NIR/IR/MW limb sounders	Ozone; reactive trace gases; aerosol properties; humidity; cloud top height
VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica)	Sea-ice motion; ice type; cloud amount; cloud top height/temperature; cloud microphysics; wind (by tracking cloud and water vapour features); greenhouse gases and other trace gases; sea/land surface temperature; precipitation; aerosols; snow cover; vegetation cover; albedo; atmospheric stability; fires; volcanic ash
Solar magnetograph, solar EUV/X-ray imagery and EUV/X-ray irradiance, both on and off the Earth-Sun line	Solar activity (detection of solar flares, coronal mass ejections and precursor events); geomagnetic activity
Solar wind, in situ plasma, energetic particles and magnetic field off the Earth-Sun line	Solar wind; energetic particles; interplanetary magnetic field; geomagnetic activity
Solar coronagraph and heliospheric imagery, both on and off the Earth-Sun line (for example, at L5)	Solar heliospheric imagery (detection and monitoring of coronal mass ejections travelling to the Earth)
Magnetospheric energetic particles and magnetometers	Energetic particle flux, energy spectrum and geomagnetic field (radiation storm, geomagnetic storms)

Table 4. Operational pathfinders and technology and science demonstrators (Subcomponent 3)

Instruments	*Geophysical variables and phenomena*
GNSS radio occultation; additional constellation for enhanced atmospheric/ ionospheric soundings (including polarimetric), including LEO-LEO radio occultation for additional frequencies optimized for atmospheric sounding	Atmospheric temperature and humidity; precipitation detection; ionospheric electron density; zenith ionospheric total electron content; total precipitable water
NIR spectrometer	Surface pressure; cloud top height; aerosol property (thickness, height)
Differential absorption lidar (DIAL)	Atmospheric moisture profiling
Radar and lidar for vegetation mapping	Vegetation parameters; above-ground biomass
Hyperspectral MW sensors	Atmospheric temperature, humidity and wind; sea/land surface temperature; cloud amount, water content and top height/temperature; atmospheric composition (aerosols, ozone, trace gases)
	Ocean surface currents and mixed layer depth
	High-resolution surface water and ocean topography measurements
Hyperspectral UV/NIR sensors	Water quality
Solar coronal magnetic field imagery; solar wind beyond L1	Solar wind; geomagnetic activity
UV spectral imagery (for example, GEO, HEO, medium Earth orbit, LEO)	Ionosphere, thermosphere and aurora
Neutral and ion mass spectrometer	Thermospheric neutral and ionospheric constituents
Mass accelerometers	Neutral density
Miniaturized instruments on micro satellites	

Table 5: Additional capabilities (Subcomponent 4)

Instruments	*Geophysical variables and phenomena*
GNSS radio occultation	Atmospheric temperature and humidity; precipitation detection; ionospheric electron density; zenith ionospheric total electron content; total precipitable water

3. SURFACE-BASED OBSERVING SYSTEM COMPONENT

3.1 Introduction

This chapter addresses the surface-based component of WIGOS, here defined to include any observing system not flying in space. It complements the equivalent chapter for the space-based component.

3.2 Trends and issues

The number of user applications and the geophysical variables observed will continue to increase. This increase will be noted in application areas such as space weather and in observations to support ECV monitoring according to GCOS climate monitoring principles. The following changes are also expected to occur:

(a) New elements added to the surface-based component will be sustainable, with some mature research and development capabilities transferring to operational status;

(b) The range and volume of observations exchanged globally (rather than locally) will substantially increase;

(c) Regional observing networks will be developed to improve the forecasting of mesoscale phenomena;

(d) In response to the local meteorological or environmental situation, there will be a certain level of targeting of observations, whereby additional observations are acquired or usual observations are not acquired;

(e) New information will become available through the miniaturization of sensors, cloud technology, crowdsourcing, and the "Internet of Things". There will be enhanced interactions between observation providers and users, including feedback concerning information on observation quality from data assimilation centres.

Automation and technology trends are expected to include the following:

(a) The trend to develop fully automated observing systems using new observing and information technologies will continue, where such systems can be shown to be cost-effective and consistent with user needs;

(b) Access to real-time and raw data will be improved;

(c) Observing system test beds will be used to compare and evaluate new systems and to develop guidelines for integrating and implementing observing platforms;

(d) Observational data will be collected and transmitted in digital form and will be highly compressed where necessary. Observation dissemination, storage and processing will take advantage of advances in computing, satellite and wireless data telecommunication, and information technology;

(e) Efficient and interoperable technologies will be developed to manage and present observational data; products for users will be adapted to their needs;

(f) Traditional observing systems providing high-quality observations will be complemented by small inexpensive sensors that are mass-produced and installed on a variety of platforms; observations from these devices will be communicated automatically to central servers or databases; automated and autonomous calibration systems will be developed for some of these systems;

(g) Commodity sensors will be developed for a broader range of geophysical variables;

(h) Basic and reference networks will be consistent, continuous and homogenous;

(i) There will be increased standardization of instrumentation and observing methods;

(j) There will be a growing reliance on reference networks to develop and establish standards serving as reference baselines;

(k) There will be improvements in calibration and reduced uncertainty of observations together with the provision of metadata; this will ensure data consistency and traceability to the SI and will ensure that data are understood;

(l) There will be improved methods of quality control and of characterizing errors and uncertainty of observations;

(m) There will be improvements in procedures to ensure continuity and robustness in the provision of observations, including managing transitions when technologies change;

(n) There will be increased interoperability between existing observing systems and with newly implemented systems;

(o) There will be improved homogeneity of data formats and dissemination via WIS.

3.3 Evolution of the surface-based observing system component

Planning for surface-based observing systems differs substantially from planning for space-based observing systems, which is more centralized and can be organized decades in advance. The development cycle of space-based observing systems allows for a robust, tiered approach; however, for surface-based observing systems, a tiered approach for different types of instruments or observations (for example, surface weather or climate observations) is adopted on case by case basis. Table 6 below provides information on the anticipated evolution of and trends concerning surface-based observing systems in different domains (upper-air observations, near-surface observations over land, rivers, lakes and oceans, ocean underwater observations, cryospheric observations, space weather observations, and research and development observing systems and operational pathfinders).

Table 6. Anticipated evolution of and trends concerning instrument and observation types and the geophysical variables they measure

Instrument/ observation type	*Geophysical variables and phenomena*	*Evolution and trends*
Upper-air observations		
Upper-air weather and climate observations	Wind, temperature, humidity, pressure	• Radiosonde networks will be optimized, particularly in terms of horizontal density, which will decrease in some data-dense areas, and taking into account the need for observations in the stratosphere and the availability of observations from other profiling systems. • Profiles from all radiosondes will be delivered at higher vertical resolution and from descents after balloon burst and used by applications as required. • The GCOS Upper-Air Network will be fully supported as part of the Regional Basic Observing Network (RBON). • The GCOS Reference Upper-Air Network will be extended and will deliver observations of reference quality in support of climate and other applications. • There will be an increase in the number of automated radiosonde systems, in particular those deployed at remote locations. • Targeted dropsondes will continue to be used and may increase in use through the evolution of air-deployed unmanned airborne vehicles (UAVs). • Remote radiosonde stations will be retained and protected. • Support for small islands and developing states will include improved communications, sustainable power supplies, and training in measurement methods and instrument maintenance. • Monitoring of the upper troposphere and lower stratosphere will be improved by carrying out humidity reference measurements, for example, by using frost-point hygrometer and Lyman-alpha techniques. • Facilities for drone-based observations (land, coastal and ship-based) will be developed.

Instrument/ observation type	*Geophysical variables and phenomena*	*Evolution and trends*
Aircraft-based observations	Wind, temperature, pressure, humidity, turbulence, icing, precipitation, volcanic ash and gases, and atmospheric composition variables (clouds, aerosol physical properties and chemical composition, ozone, greenhouse gases, precipitation chemistry variables, reactive gases)	• A large variety of automated operational, cost-effective and optimized aircraft-based observing (ABO) systems will be part of a wider observing system providing high-quality global upper-air data and will be complementary to other operational upper-air observing systems. • The global aircraft-based observing system will be an integrated system, based on requirements defined by both the meteorological and the aeronautical user communities, regulated by their respective international organizations and jointly managed by WMO and its international partners. • Aircraft on-board weather radar data will be downlinked to ABO systems to supplement fixed-site weather radars. • Profiles from ABO systems will be provided according to user requirements, in particular at high vertical resolution, and will be geographically selectable. Profiles will be provided via a system optimized at the regional level in collaboration with the aviation industry. • Extended profiles will be available since some aircraft will be able to fly at higher altitudes. • The range of meteorological and atmospheric composition variables provided by ABO systems will be extended. For example, research programmes such as the In-service Aircraft for a Global Observing System programme, which also provides humidity observations from aircraft, will eventually transition from research to operational status. • ABO systems will deliver improved water vapour information with global coverage. • Standard turbulence information will increasingly be provided by ABO systems in cooperation with the relevant international aviation organizations.

Instrument/ observation type	*Geophysical variables and phenomena*	*Evolution and trends*
Remote sensing upper-air observations	Wind, cloud base and top, cloud water, temperature, humidity, aerosols, fog, visibility	• Radar wind profiler networks are well established in some countries and will be extended. • Wind measurements from cost-effective Doppler lidar systems will be increasingly used for measurements in the boundary layer. • Raman lidar systems will deliver highly accurate measurements of aerosol properties and humidity and temperature profiles in an operational manner. • DIAL systems will deliver high-resolution measurements of aerosol properties and humidity profiles for operational use. • Microwave radiometers will deliver information on temperature and humidity (with limited vertical resolution), total column water vapour and cloud liquid water path. • Ceilometers will increasingly be used to provide information on cloud and aerosol profiles and may partly be replaced by low-cost DIAL systems. • Cloud radar (Ka-band or W-band) will be used for improved quantitative monitoring of the structure of fog, clouds and precipitation. • There will be an increased use of video cameras (for example, at airports) to support local forecasting, including nowcasting and aviation meteorology. • There will be an increased use of infrared video cameras to support cloud identification and cloud height, as well as local forecasting and nowcasting. These cameras will also provide downward infrared measurements.

Atmospheric composition upper-air observations	Atmospheric composition variables (aerosol properties, ozone, greenhouse gases, precipitation chemistry variables, reactive gases)	• A full global network of operational ozone sondes will be restored, maintained and extended through the Global Atmosphere Watch (GAW) and in cooperation with international partners. • Automated drones will be used more extensively to carry out air quality measurements. • Atmospheric sampling systems (for example, AirCore) will be used to measure trace gas from the middle stratosphere to the ground. • Ground-based Fourier transform spectrometers retrieving column-averaged abundances of greenhouse gases will be used. The Total Carbon Column Observing Network (TCCON) is an example of a network providing such data. • More lidars will be used to retrieve aerosol variable profiles. • Other remote sensing techniques (such as differential optical absorption spectroscopy (DOAS)) will be introduced to measure the profiles of reactive gases in the troposphere and low stratosphere.
GNSS receiver observations	Total column water vapour, humidity, snow depth, soil moisture, snow water equivalent	• Networks of ground-based GNSS receivers will be extended across all land areas to provide global coverage of total column water vapour observations and other variables, and the data will be exchanged internationally.
Lightning detection systems	Lightning variables (location, density, rate of discharge, polarity, volumetric distribution)	• Networks of ground-based lightning detection systems will evolve to be complementary to new space-based systems. • Long-range lightning detection systems will provide cost-effective, global data with improved location accuracy, significantly improving coverage in data-sparse regions, including oceanic and polar areas. • Lightning detection systems with a higher location accuracy and with cloud-to-cloud and cloud-to-ground discrimination will support nowcasting and other applications in selected areas. • Common formats and lightning observation archives will be developed.

Weather radars	Precipitation (hydrometeor size distribution, phase, type), wind, humidity (from refractivity), sand and dust storm variables, some biological variables (for example, bird densities)	• There will be an expansion of Doppler and polarimetric weather radars to developing countries, including training on processing and interpretation and capacity development to handle the extremely large amounts of data. • Emerging technologies will gain widespread use. Electronically-scanning (phased-array) adaptive radars will acquire data in unconventional ways, necessitating adaptation by data exchange and processing infrastructure. • A weather radar data exchange framework will serve all users and achieve homogeneous data formats for international exchange. • Radar technology and data will be exploited for various other purposes, for example, urban weather, atmospheric environment, volcanic ash plume monitoring, and so forth.
Automated Shipboard Aerological Platform (ASAP) observations	Wind, temperature, humidity, pressure	• Commercial ships will be designed to facilitate making metocean observations, including installing and using ASAP systems.

Near-surface observations over land		
Surface weather and climate observations	Surface pressure, air temperature, humidity, wind; visibility; clouds; precipitation; precipitation type; surface radiation variables; soil temperature; soil moisture; snow depth; snowfall; snow density	• Tiered networks will be established: climate reference networks, baseline networks (including RBONs), and comprehensive networks including non-NMHS and volunteer observing networks/national mesonets. • Crowdsourced near-surface observations will be collected and disseminated and integrated with NMHS and other observations. • Automated Climate Reference Network stations (temperature and precipitation) will be deployed in all WMO Regions to improve measurements of national variability and trends. • Climate quality daily, hourly and sub-hourly (to five-minute) data will be collected and disseminated internationally. • Synergy will be maintained between manual and automated observations, especially for elements such as precipitation, as needed to ensure sufficient spatial coverage. • There will be expanded use of automated networks to improve the temporal resolution of observations. • There will be an expansion of wireless or satellite data transmission for real-time dissemination from the station to the central facility. • There will be an expansion of non-NMHS networks, including volunteer and private sector networks, with automated dissemination/collection to national archive centres. • A management scheme will be put in place to preserve the life cycle of measurements, from the collection to the archiving of data and their metadata, in recognition of the importance of data stewardship and in compliance with the corresponding requirement. • There will be an increased use of video cameras (for example, at airports) to support local forecasting. • There will be an increased use of GNSS surface networks to obtain humidity, snow depth, and snow water equivalent information. For example, it is expected that there will be an increased use of vehicles to make surface observations.

Atmospheric composition surface observations	Atmospheric composition variables[10] (aerosol properties, greenhouse gases, ozone, total atmospheric deposition, reactive gases)	• More regional networks will be integrated in the quality-controlled observing network. • Low-cost sensors will play more a prominent role in the delivery of air pollution data, and more facilities will be developed for the characterization and calibration of these data. • Meteorology/climate measurements will be collocated with air quality measurements. • There will be an expansion of global and regional measurements, including through GAW, with a special focus on data-sparse regions and on the provision of data for applications with a high societal impact (for example, human health, food security, biodiversity loss). • An atmospheric composition baseline reference network will be developed.
Application-specific observations (road weather, airport/heliport weather stations, agrometeorological stations, urban meteorology, and so forth)	Application-specific variables and phenomena	• Urban reference networks will be established to provide observations important for urban meteorology/climatology. • Road weather networks will transmit in near-real-time, with data collected and archived at national archive centres. • Soil moisture/temperature measurements from near-surface to 100 cm will be maintained and expanded at agrometeorological stations. • Aerodrome observing systems will be enhanced for aviation-specific observations such as wind shear, wake turbulence and slant visibility.
Land-based (fast-) ice observatories	(Fast-) ice extent, ridging, motion, leads	• There will be affordable autonomous radar and visual observing systems. • Observatories will be deployed as part of a sustainable network in the Arctic and Antarctic Oceans and in their marginal seas.
Observations of the biosphere	Vegetation, carbon (above ground and soil)	

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[10] The full list of atmospheric composition variables includes more than 80 variables listed in the GAW Implementation Plan 2016-2023. This list may be extended to reflect the need for new products and services, for example in relation to the carbon or nitrogen cycle.

Near-surface observations over rivers and lakes		
Hydrological and cryosphere observations	Precipitation, snow depth, snow cover, snow water equivalent and glaciers, evaporation and evapotranspiration, vapour pressure/relative humidity, lake and river ice thickness, date of freezing and break-up, melt onset, water level, water flow, surface water storage, water quality, water use, vegetation type, soil moisture/soil wetness, soil temperature, sediment transport (suspended sediments and bedload), river discharge Basin characteristics Precipitation, snow depth, snow water equivalent, lake and river ice thickness, date of freezing and break-up, melt onset, water level, water flow, water quality, soil moisture, soil temperature, sediment loads, river discharge Lake and river ice concentration, class (pack, fast ice), stage of development; areal extent of floated/grounded ice, ice surface temperature, ice openings (leads, polynias, cracks), ice deformation, ice ridge (height, cover), ice stratigraphy, river ice jams and dams, river icing (aufeis), maximum level	• Hydrological data exchange will be improved to support operational water resource management, in particular at the basin scale, with a special focus on transboundary catchments. • Automated snowfall/snow depth measurements will further augment manual measurements. • Existing snow monitoring sites will be maintained, with data exchanged internationally. • Sensors will be installed at existing sites to increase the number of automated soil moisture/temperature measurements. • Volunteer observations of lake/river ice freeze/thaw dates will be disseminated internationally and archived. • Reference observing stations will be established and maintained. • Concurrent measurements of river channel geometry will be taken; water quality data (temperature, turbidity, algae, and so forth) will be gathered, river discharge gauging stations, bedload monitoring stations and turbidity meters will be installed. • There will be crowdsourcing of information on flooding and river drying via the development of public observing networks and social media (including impact reporting). • Satellite data will augment high spatial and temporal resolution data in some key regions (for example, forested areas). • Several satellite-based methods will be further improved to map the extent and duration of flooding in floodplains or large riverine systems. • Improved digital elevation data will increase observations on surface water storage for wetlands, large floodplains and estuaries. • Information from satellites and the precipitation network emerging through virtual constellation networks will provide improved precipitation information that can be used for flood forecasting. • Better use will be made of radar-based rainfall information collected in real time in order to provide more accurate flash flood forecasting.

		• A global in situ network for soil moisture measurements will be operated by consolidating the existing infrastructure through expansion and standardization, dedicated soil moisture missions, and improved coordination of soil moisture data network planning, observing standards, and data exchange. • The establishment and maintenance of conventional terrestrial observation methods, together with satellite-based systems, will allow additional information to be gathered on snow cover, snow depth, snow water equivalent and glaciers. • Information on water use will be consolidated on a national and local basis, thereby improving the management of water resources as well as assessments concerning the potential natural flow of water in rivers.
Groundwater observations	Groundwater level, groundwater fluxes, groundwater chemistry, aquifer characteristics	• Groundwater monitoring networks will be established at the national level, and the data gathered will be exchanged internationally. • The effectiveness of gravimetric observation techniques for large groundwater bodies will be demonstrated in operational circumstances. • Crowdsourcing of information on water levels in active wells and wells that have gone dry will be acquired and used by water management agencies. • The results of aquifer monitoring will be made available online to support groundwater flow modelling and integrated surface-subsurface flow modelling.
Near-surface observations over oceans		
Ground-based observing stations at sea (ocean, island, coastal and fixed platform/station locations) and coastal stations, including ice radar	Surface pressure, temperature, humidity, wind; visibility; cloud amount, type and base height; precipitation; sea-surface temperature; directional and 2D wave spectra; tide; sea ice; surface radiation variables; surface currents Ice thickness, type, topography and motion Atmospheric composition variables related to atmosphere-ocean exchange	• Higher data rates and cheaper satellite data telecommunication will be established for remote automated stations. • More coastal high-frequency radars will be used, there will be a better standardization of the instruments, and the data will be shared internationally. • Arctic: Coastal stations will potentially be established near fast ice and drifting sea ice. • Antarctic: Antarctic Fast-Ice Network (AFIN) sites will potentially be sustained thanks to an already existing infrastructure. • Costal stations will provide measurements of the atmospheric composition constituents (such as CO_2 and DMS) to help characterize the atmosphere-ocean exchange of trace gases.

Ship observations	Surface pressure, temperature, humidity, wind; visibility; cloud amount, type and base height; precipitation; weather; sea-surface temperature; wave direction, period and height; salinity; currents; bathymetry; CO_2 concentration; surface radiation variables Sea-ice thickness, concentration, type, floe size, and topography Iceberg observations	• Commercial ships will be designed and equipped to facilitate making metocean observations. • There will be an increased use of X-band radar for wave observations and sea-ice ridges. • More systematic infrared radiometer measurements will be made from ships for satellite validation. • More systematic use will be made of thermosalinographs and of acoustic Doppler current profilers (ADCPs) (shipboard ADCPs (SADCPs) and lowered ADCPs (LADCPs)) for near-surface current profiles from research vessels. • Use will be made of tourist ships sailing in data-sparse regions (for example, polar regions, Southern Ocean). • Use will be made of fishing vessels, assuming a proper data policy can be negotiated. • Ship security issues will be addressed (to remove ship identification masking to end users). • The number of autonomous automatic weather station onboard ships sailing predefined or targeted routes will be increased. • Highly accurate, high-resolution data from research vessels will be distributed in real time. • Autonomous or semi-autonomous sensor systems will replace manual Antarctic Sea-ice Processes and Climate (ASPeCt)/Arctic Shipborne Sea-Ice Standardization Tool (ASSIST) sea-ice observations. • Increased transit in the polar regions will allow for timely ice observations. • Ship observations will be able to be assimilated into the production of routine operational ice charts for daily sea-ice type and concentration validation. • The use of a standardized sea-ice protocol from ASPeCt and ASSIST will allow for easier use of sea-ice observations. Ships of opportunity can be involved in providing this information. • With the new generation of icebreakers, there will be scope for a standardized automated or semi-automated underway system for sea-ice and snow observations. • More ships will be equipped with instrumentation to measure dissolved CO_2 in ocean water and in the atmosphere at the same time in order to characterize atmosphere-ocean fluxes.

Buoy observations – moored and drifting	Surface pressure, air temperature, humidity, wind, visibility, sea-surface temperature, sea-surface salinity, directional and 2D wave spectra, near-surface velocity, surface radiation variables, precipitation, ocean currents, CO_2 concentration, pH, ocean colour	• Smart technology will be developed for adaptive sampling to address specific environmental conditions and to optimize the endurance of the buoys. • Renewable energy power sources will be exploited. • Drifters and moored buoys will be optimized, have more instruments and be equipped with global and near-real-time satellite data telecommunication technology, yet will allow data to be transmitted at a higher rate. • Data will be provided at higher temporal and spatial resolution. • A global fleet of wave and sea state drifters using GNSS and microelectromechanical system multiple degree of freedom technology will be deployed. • Acoustic sensors will be used to measure wind and precipitation. • Vandalism-prone moored buoy systems will be equipped with video and/or imagery capability in order to detect incidents and acts of vandalism; there will be increased enforcement of legal measures relating to vandalism of these systems. • More traceable wave observations will be gathered from wave rider buoys, and global wave observations will be gathered from drifters.
Ice buoy observations	Ice kinematics, surface pressure, temperature, wind, ice thickness, ice and upper-ocean temperature, snow depth, snow temperature, sea-ice motion and others Snow over sea ice and snow stratification, snow chemistry and isotopic content	• Sea-ice buoys will carry unified sensors and will be deployed in a sustainable grid (International Arctic Buoy Programme and International Programme for Antarctic Buoys). • There will be smaller, cheaper ice buoys, with more instruments, the cost of satellite data telecommunication will be reduced, and data will be transmitted at a higher rate. • Buoys will have improved technology and more sensors and will be air-deployable. • There will be automated delivery of basic sea-ice data via WIS. Additional data will be transmitted at a reduced cost to the Science Principal Investigator. • Sensors will be able to be added to ice buoys using plug and play technology (for example, to establish a video system for melt ponds) in order to support specific scientific (sea-ice) studies.
Sea level observations	Sea-surface height, surface air pressure, wind, salinity, water temperature, gravity measurements (for ocean geoid)	• The Global Navigation Satellite System will be used systematically for geo-positioning and real-time data transmission.

Autonomous ocean surface vehicles	Surface air pressure, temperature, humidity, wind, visibility, sea-surface temperature, directional and 2D wave spectra	• There will be more systematic use of autonomous ocean surface vehicles (for example, wave gliders, sailing drones) capable of using renewable energy sources for propulsion and capable of sailing over predefined or targeted routes.
Ice-mounted instrumentation	Fast-ice observations: ice and snow thickness, freeboard, ice draft, vertical temperature profile (atmosphere-snow-ice-ocean), sea-ice biomass	• Fast-ice observations will be made via Arctic and Antarctic fast-ice stations (AFIN type). AFIN sites will potentially be maintained in Antarctica thanks to an already existing infrastructure.
In situ ice floe observations	Ice and snow thickness, freeboard, ice and snow stratigraphy, chemical composition, upper and lower surface profiles, biomass, ecosystems and biological parameters	• There will be short to multi-week (even seasonal) sea-ice stations: Camp NorthPole, etc. in the Arctic, and there will be a tendency to conduct shorter but more intensive ice-sampling observations supported by ships. • The new generation of icebreakers should support more ice floe work.
	Icebergs: position, form, size, concentration, motion, height/width/length, iceberg draft, underwater 3D form	
Underwater ocean observations		
Profiling floats	Temperature, salinity, current, dissolved oxygen, CO_2 concentration, various bio-geochemical variables	• Floats will spend less time at the surface, allowing them to have a longer lifetime and provide a longer time series of measurements. • Measurements will be taken systematically in marginal seas and under the ice. • Ocean profiles will extend deeper (more than 6 000 m). • More multidisciplinary measurements will be made. • More high-resolution near-surface observations will be made. • There will be swarm deployments of profiling floats, for example, ahead of storms/hurricanes. Under certain circumstances, the profiling missions of swarms may be altered within the existing region.

Autonomous underwater vehicles (for example, gliders)	Temperature, salinity, current, dissolved oxygen, CO_2 concentration, various bio-geochemical variables, sea-ice draft	• It will be possible for autonomous underwater vehicles to collect ocean profiles and conduct surveys along predefined routes. • Acoustic communication technologies will be used to transfer data from remotely deployed equipment. Autonomous underwater vehicles will be able to operate under the ice and record measurements onboard. They will transmit these measurements once they have the capability to relay the data to ground. (In most instances, the data will only be available in delayed mode.) • There will be subsurface docking stations for underwater gliders, and remote operation of the gliders will be possible. • Cheaper, ready-to-deploy equipment and sensor packages will enable more countries to participate in ocean observations, and swarm deployments will allow high-resolution observations (in space and time) to be made. • New sensors will allow measurements to be taken of a greater number of variables, particularly variables relating to biogeochemistry and biology that are required for Earth system approaches.
Subsurface observations from drifting and moored buoys	Temperature, salinity, currents, CO_2 concentration, pH, sea-ice draft	• Optimized acoustic profiling current meters will be used. • Vandalism-prone moored buoy systems will be equipped with video and/or imagery capability in order to detect incidents and acts of vandalism; there will be increased enforcement of legal measures relating to vandalism of these systems.
Ships of opportunity	Temperature, salinity, ocean colour, currents	• Commercial ships will be better designed and equipped to facilitate the making of metocean observations (for example, installation of XBT/XCTD autolaunchers). • ADCPs (SADCPs, LADCPs) will be used more systematically for current profiles.
Observations from platforms hosted at submarine telecommunication cables	Bottom and subsurface multidisciplinary measurements, tsunami monitoring (earthquakes, tsunami waves)	• With higher data rates and reduced transmission costs, there will be no need to transmit data to a surface buoy (which is subject to vandalism and is expensive to deploy and maintain).
Ice-tethered platform observations	Temperature, salinity, current, fast-ice observations	• Higher data rates will be supported, with reduced transmission costs. • Ocean profiles will extend deeper (6 000 m). • There will be more multidisciplinary measurements. • An ice-moored AFIN sensor suite will be used.
Instrumented marine animals	Temperature, salinity, sea-ice draft	• There will be more systematic use of instrumented marine animals (sea mammals, some fish species being tracked, turtles).

Cryospheric observations: sea ice		
Ice buoy observations	Surface pressure, surface air temperature, wind, ice thickness, ice and upper-ocean temperature, snow depth, snow temperature, sea-ice motion, and others Snow over sea ice: snow stratification, snow chemistry and isotopic content	• There will be smaller, cheaper ice buoys, with more instruments, the cost of satellite data telecommunication will be reduced, and data will be transmitted at a higher rate. • Buoys will have improved technology and more sensors and will be air-deployable. • There will be automated delivery of basic sea-ice data via WIS. Additional data will be transmitted at a reduced cost of transmission to the Science Principal Investigator. • Sensors will be able to be added to ice buoys using plug and play technology (for example, to establish a video system for melt ponds) in order to support specific scientific (sea-ice) studies.
Ship-based observations	Sea-ice thickness, concentration, type, floe size, and topography	• Increased transit in the polar regions will allow for timely ice observations. • Ship-based observations can be incorporated into routine operational ice charts for daily sea-ice type and concentration validation. • The use of standardized sea-ice protocol from ASSIST or ASPeCt will allow sea-ice observations to be used more easily.
Coastal stations	Ice thickness, ice type, and topography	• Arctic: Coastal stations will potentially be established near fast ice and drifting sea ice. • Antarctic: AFIN sites will potentially be sustained thanks to an already existing infrastructure.

Cryospheric observations: ice sheets glaciers, permafrost		
	Surface accumulation and ablation, surface temperature, surface albedo, ice sheet boundaries, ice sheet thickness, ice velocity, ice/firn temperature profile, snow cover, snow profile Direct and indirect measurements of ice sheet motion, tracking of grounding line migration, meltwater runoff, water pressure due to the weight of the ice sheet, water transfer from the ice sheet to areas below the ice surface, and interactions between meltwater and the underlying groundwater systems Glaciers: mass balance (accumulation, ablation), equilibrium line altitude, glacier thickness, ice flow velocity, calving flux, glacier discharge, snow/firn/ice temperature profile, surface albedo, snow over glaciers (stratification, chemistry, and isotope content) Permafrost: ground temperature, active layer thickness, rock glacier creep velocity, rock glacier discharge, rock glacier spring temperature, seasonal frost heave/subsidence, surface elevation change, ground ice volume, coastal retreat, soil moisture	• Independently powered automatic weather stations operating at the ice sheet surface will measure all relevant parameters, including all radiation fluxes, with sufficient accuracy to close the surface energy balance. • Albedo variability will be determined via both optical satellite remote sensing and ground observations, with the appropriate error corrections. • UAVs with a small observing footprint may be deployed to fill the spatial scale gap with respect to in situ observations of albedo. • Snow radar will combine coverage with new, highly accurate digital elevation models of glacier surfaces (from airborne lidar or satellite platforms). • More systematic glacier and permafrost monitoring will be established in partnership with research and operational agencies at the national and regional levels, and the data will be standardized and exchanged internationally. • Long-term sustainability of research stations is required to facilitate the availability of climatological records.

Space weather observations		
Solar short-wave spectrum observations	White light, H-alpha and calcium K images, sunspots, flares, filaments, prominences, coronal holes	• New telescopes will be able to resolve more spatial details. • Higher observing frequencies will provide better time resolution of the dynamic behaviour of solar structures. • International dissemination of similar observations will provide 24-hour solar watch capabilities.
Solar radio observations – spectrograph and discrete frequencies	Coronal mass ejections, radio bursts, solar activity (10.7 cm flux)	• New telescopes will be able to resolve more spatial details. • Higher observing frequencies will provide better time resolution of the dynamic behaviour of solar structures. • International dissemination of similar observations will provide 24-hour solar watch capabilities.
Ionospheric observations – ionosonde	Measurements of the ionosphere’s ability to reflect high-frequency radio waves at various frequencies and heights	• Time resolution will be improved. • Ionogram analysis will be automated. • The ionosonde network will be expanded.
Ionospheric observations – riometer	Measurements of the "opacity" of the ionosphere to radio noise, absorption events	• Riometer networks will be expanded.
Ionospheric observations – GNSS	Total electron content of the ionosphere, ionospheric gradients, ionospheric scintillation	• Spatial resolution will be improved through extensive expansion of the ground-based network of GNSS receivers. • Time resolution will be improved.
Geomagnetic observations	Measurements of the Earth's magnetic field and geomagnetic disturbances	• Spatial resolution will be improved through extensive expansion of the ground-based network of magnetometers. • Time resolution will be improved. • Real-time data retrieval will be improved.
Cosmic ray observations	Radiation measurements, neutron and muon monitors	• New technology for cosmic ray observations will be available to address space weather requirements. • Real-time data quality will be improved.

Research and development and operational pathfinders: examples		
UAVs	Wind, temperature, humidity, atmospheric composition, snow depth, river channel morphology, trace gas and aerosol concentration	• Larger platforms will be needed. • Drones will be used to measure the lower atmosphere and impassable areas. • Atmospheric composition instruments will be made smaller so they can be used on UAVs to measure greenhouse gas and aerosol concentrations.
Aircraft-based observations	Thunderstorms, total water content, radiation in different spectral ranges and directions, dust/sand particles	• There will be wider use of private companies' fleets of UAVs. The fleets will be capable of flying long distances and powered by renewable energy. They will be semi-permanently deployed for research purposes, observing campaigns and operational applications (for example, to address the requirements concerning lightning detection, to study volcanic ash, for severe weather forecasting (forecasts relating to rainfall, space weather, etc.)). • Electromagnetic field and radio-frequency instruments will provide improved lightning detection. • The water vapour measurement system will be used more extensively.
Observations from gondolas	Wind, temperature, humidity	• Constant-pressure balloons will operate in the lower stratosphere.
Low-cost sensors	Aerosol, reactive gas and greenhouse gas concentrations	• Miniaturization and advancements in measurement technologies will allow observations of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2) and methane (CH_4) to be made using low-cost systems; the quality of the systems will improve with time.
Melding of surface-based and satellite-based remote sensing observations	Wind, temperature, humidity, aerosols, atmospheric chemistry	• Wind profiler, radar wind and cloud movement data will be combined to produce wind products. • Surface-based microwave and infrared radiometer data will be combined with satellite-based observations to resolve the entire vertical profiles for temperature and humidity. • Surfaced-based lidar, DOAS and TCCON will be combined with satellite-based observations to provide joint vertical profiles.

ANNEX A. OBSERVING NETWORK DESIGN PRINCIPLES

1. **Serving many application areas**

Observing networks should be designed to meet the requirements of multiple application areas within WMO and WMO co-sponsored programmes.

2. **Responding to user requirements**

Observing networks should be designed to address stated user requirements, in terms of the geophysical variables to be observed and the space-time resolution, uncertainty, timeliness and stability needed.

3. **Meeting national, regional and global requirements**

Observing networks designed to meet national needs should also take into account the needs of WMO at the regional and global levels.

4. **Designing appropriately spaced networks**

Where high-level user requirements imply a need for spatial and temporal uniformity of observations, network design should also take account of other user requirements, such as the representativeness and usefulness of the observations.

5. **Designing cost-effective networks**

Observing networks should be designed to make the most cost-effective use of available resources. This will include the use of composite observing networks.

6. **Achieving homogeneity in observational data**

Observing networks should be designed so that the level of homogeneity of the delivered observational data meets the needs of the intended applications.

7. **Designing through a tiered approach**

Observing network design should use a tiered structure, through which information from reference observations of high quality can be transferred to other observations and used to improve their quality and utility.

8. **Designing reliable and stable networks**

Observing networks should be designed to be reliable and stable.

9. Making observational data available

Observing networks should be designed and should evolve in such a way as to ensure that the observations are made available to other WMO Members, at space-time resolutions and with a timeliness that meet the needs of regional and global applications.

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