

**Vision for WIGOS 2040; update**  
In response to CGMS action A46.16  
HLPP reference: 1.1

WMO regularly reviews its Vision of future global observing systems to support weather, climate and related environmental applications. Over the past four years, a new draft “Vision for WIGOS in 2040” has been in preparation, with the intent of submitting such a document to the 18<sup>th</sup> World Meteorological Congress for approval. The new Vision has been developed in consultation with a diverse community of both users and observing system developers and operators, including the space agencies, and CGMS has played an active role in its development.

The current draft version 2.1 has been submitted to the 18<sup>th</sup> World Meteorological Congress and will be discussed in June 2018. It is presented here to CGMS for information.

Action/Recommendation proposed: CGMS Space Agencies to take note of new WMO *Vision for WIGOS in 2040* and consider incorporating it in the planning of their activities.

# Vision for WMO Integrated Global Observing System in 2040

*Draft 2.1, 7 May 2019*

## • PART I. 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 EC-61 in 2009<sup>1</sup>. 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 couple of decades, and an ambitious, but technically and economically feasible vision for an integrated observing system that will meet them. The purpose of this is two-fold: The first is to inform the planning efforts undertaken by National Meteorological and Hydrological Services (NMHSs), space agencies and other observing system developers of the WMO view of the evolving user requirements. WMO Members providing the funding are called upon to take appropriate decisions to implement the observing system. The second is to inform the users of weather, climate and water and other related observations about what to expect in the coming decades and to provide guidance for their planning of information technology and communication systems, research and development efforts, staffing, and education and training. These include the numerical modelling and prediction centres of WMO Members to help them plan the evolution of their systems. Finally, the document also intends to provide useful guidance for the Global Weather Enterprise, which involves relevant non-governmental and the private sectors.

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 operational satellite and radar replacement programmes. Although driven by the development cycle of specific components, the nature of WIGOS as an integrated system, in which the various space-based and surface-based components complement each other, means that the full value of the Vision will only be delivered by addressing all components, to the extent possible.

While considered to be part of an integrated system, the space-based and surface-based system components are treated separately due to the fundamentally different ways in which these two components tend to evolve. Operational satellite 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

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<sup>1</sup> Reference

other hand, some of the surface-based observing programmes – especially over the last decades - have been driven by a number of unanticipated technological innovations. Since contributions are made by a broader community of stakeholders with a correspondingly wide range of motivations, these programmes are less influenced by centralized planning or coordination efforts.

The 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 and trends in capabilities and requirements for service delivery. It then outlines the principles and design drivers for WIGOS. Part II then describes the space-based observing system components of the Vision for WIGOS in 2040, and part III its surface-based observing system components.

## • **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 and observing systems used to acquire them are typically driven by the end user requirements for service delivery. Backtracking this into observing system requirements 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 exceed 9 billion people by the year 2040. 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. The population growth is also likely to contribute to the 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, land-slides, etc.

Accompanying the population growth is the tendency toward increased urbanization. In 1900, some 10% of the world's population lived in cities. Today more than 50% live in urban areas, and by 2050, this figure will have increased to between 66%<sup>2</sup> and 75%<sup>3</sup>. This massive migration will require metropolitan areas to absorb an additional more than 3 billion people over the next 30 years. Large agglomerations – especially the so-called mega-cities with more than 10 million inhabitants – are inherently vulnerable, as is their infrastructure. Food, water and energy supplies will need to be secure, and advance planning for response to a wide range of potential natural or partly man-made disasters scenarios will provide very strong drivers for meteorological and environmental service delivery and for temporal and spatial resolution of the required data products.

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<sup>2</sup> <http://www.unfpa.org/world-population-trends> (accessed 1 January 2017)

<sup>3</sup> <https://www.sipri.org/events/2016/stockholm-security-conference-secure-cities/urbanization-trends> (cited from The Urban Age Project, London School of Economics, accessed 1 January 2017)

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, etc.) will continue. Guidance and policy-related decisions on resilience, adaptation and/or mitigation of climate change will drive requirements for improved understanding of climate processes and for long-range prediction capabilities. Increased frequency of extreme weather events will exacerbate human vulnerability to weather and will impose additional requirements also on traditional weather forecast and warning services. The growing recognition of the value of extended-range weather forecasts will lead to increasing demand for such 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. Some 20 million people are at risk from flooding, with the associated damage costing nearly \$80 billion; this could rise to 50 million people affected in just 15 years' time, according to the World Resources Institute. The effects of drought across the world cost up to \$8 billion a year from losses in agricultural and related businesses, according to the World Economic Forum. These challenges will intensify with future climate change and population growth. Water features heavily in the new United Nations Sustainable Development Goals, not only in the explicit aim to ensure availability and sustainable management of water and sanitation for all 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 demonstrated that seven million premature deaths annually are associated with exposure to air pollution. WIGOS must reinforce and strengthen its components related to the atmospheric chemical composition, including both ground-based and space-based observations.

### • **1.3 Trends in Capabilities and Requirements for Service Delivery**

As late as in the early 1990's weather forecasting still relied much more heavily than today 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 NWP centres were already issuing routine 10-day forecasts, relatively few users were making decisions of substantial economic impact based on weather forecasts ranging 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 ahead, and even warnings of high-impact, localized severe weather are often provided with sufficient lead time to avoid or limit 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. In reality a latent demand was already there, but it simply 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 are now routinely making 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 environmental information, they are also more demanding about how, when, where they receive it, and in what form.

All indications are that the trend toward increasing 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 an ever more demanding and ever more knowledgeable set of user communities.

Common to all observing system components is the drive toward new business models, especially as concerns the role of the private sector. As both demand for and appreciation of the economic value of meteorological and related environment information increase, the private sector is showing 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 evolution will continue along them.

#### • **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 tactical and strategic levels. Tactical level guidance for each individual application area can be found in the respective *WMO Statement of Guidance*, found on the RRR webpage. The present document represents the long-term strategic guidance.

Observing systems must be designed with adequate resilience to a variety of natural and man-made hazards. For instance, the near-universal reliance on electronics for sensing, telecommunication and data processing has significantly increased the vulnerability of the system to natural events such as solar storms. Space weather, which describes the

impact of solar activity on Earth’s environment, has thus become an officially recognized WMO application area. It is of dual interest to WIGOS, partly since there is a need for observational data – especially satellite data - to monitor space weather, partly because of the potential impact of space weather events 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, say, 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, this is the responsibility of the implementing organizations and agencies rather than of WMO. While the guidance material provided by the RRR does include reference 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 the users and those that are deemed essential must be made available to the users with the required timeliness. For this, the continued evolution of the WMO Information System, WIS, and the leadership of the NMHSs in its operation will be critically important to the success of WIGOS, and the two systems will need to evolve in parallel.

The widespread reliance on information technology also leads to vulnerability to malicious human activity in the form of “cyber-attacks”. The WMO Information System 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 Applications Area
1	<a href="#">Global NWP</a>
2	<a href="#">High Resolution NWP</a>
3	<a href="#">Nowcasting and Very Short-Range Forecasting</a> (see note 1 below)
4	<a href="#">Sub-seasonal to longer predictions</a>
5	<a href="#">Aeronautical Meteorology</a>
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	<a href="#">Ocean Applications</a>
10	<a href="#">Agricultural Meteorology</a>
11	<a href="#">Hydrology</a>
12	Climate Monitoring (GCOS) The following GCOS reports are considered as Statement of Guidance: Status of the Global Observing System for Climate - <a href="#">GCOS 195</a>

The Global Observing System for Climate: Implementation Needs - <a href="#">GCOS 200</a>	
13	<a href="#">Space Weather</a>
14	Climate Science
n/a	<a href="#">Climate Applications</a> (Other aspects, addressed by the Commission for Climatology) See note 3 below.

**Notes:**

1 - Synoptic Meteorology application area has now been merged into the Nowcasting and Very Short-Range Forecasting Application Area.

2 - Atmospheric Chemistry application area has been replaced, and split into three new application areas, i.e. (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. Meanwhile, the old version of the Statement of Guidance for Atmospheric Composition is available [here](#).

3 -IPET-OSDE-3 (Jan. 2018) decided to discontinue the Climate Applications (Other aspects, addressed by the Commission for Climatology) Application Area, but to keep the Statement of Guidance up to date and link it from this Webpage. CCI will keep the document updated and assure whether important requirements are missing from a CCI/climate applications view. However, there is no intention to submit quantitative observational user requirements since it is assumed that such requirements are mostly captured by the GCOS 'Climate Monitoring' application area as well as by 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 Resolutions 25 (Cg-XIII), 40 (Cg-XII), and 60 (Cg-XVII) and 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. However, it has recently been found to apply to other Earth science disciplines as well, and several case studies have shown the economic advantages of open data exchange also at the national level.

- **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 with a view not only to the requirements that they will meet, but also to what other WIGOS components will deliver and how to optimally complement the observations provided by those. 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, say, climate monitoring, nowcasting and numerical weather prediction, flood and drought forecasting, 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, or others. Especially in developing countries they may be non-profit organizations, or they may be commercial entities. It is in the interest of the 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 networks**

The fourth principle is integration across different levels of performance through the concept of WIGOS consisting of tiered networks. 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* networks. Users can base their decision on whether or not to use certain observations for a given application on the tier to which they belong. For instance, when monitoring the onset of active severe weather, timeliness and spatial and temporal resolution are more important than

the lowest uncertainty, 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.

As an illustration, the *comprehensive network* for weather may include crowd-sourced observations and data from mass-produced commoditized sensors such as those already now deployed on smartphones and in cars. This network is characterized by 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 as concerns the quality of the data. 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. At the highest level are the *reference networks*, providing sparse coverage in space and time, but for which calibration is required, uncertainty estimates are included as part of the observations, and the measurement traceability to the SI. Full compliance with the WIGOS standards for metadata is also required. These are for instance the reference networks operating under the Global Climate Observing System.

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

WIGOS treats the space-based and surface-based components as one overall system contributing to meeting the requirements of the application areas. Certain requirements are more readily met from space, for instance regarding 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 system is expected to provide global coverage of clear sky observations of greenhouse gas concentrations at high spatial resolution in cloud-free regions, while the ground-based system will also provide data in persistently cloudy regions and at night and provide additional information needed for a solid basis for attribution of 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 them can be maintained continuously throughout the lifetime of space missions. This also provides an opportunity for non-space-faring nations to become actively involved in the satellite programmes. In turn the surface networks also benefit from the satellite observations since these may be used as a vicarious reference’.

- **1.6 Conclusion**

The Vision for the WMO Integrated Global Observing System in 2040 contains specific and separate descriptions of the space-based and surface-based components. It is emphasized, that it is their complementarity and the mutual recognition of their

respective strengths and limitations that 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 that in combination will help meet as many requirements as effectively and efficiently as possible.

WIGOS is an essential component of the infrastructure that enables WMO and its Members accomplish their shared mission to help save lives, protect property and increase prosperity everywhere on the globe, and provide relevant data and information for policy- and decision making in support of sustainable development. The evolution of WIGOS as described in this document will ensure that the system will continue to meet the needs of users in the coming decades.

## PART II: SPACE-BASED OBSERVING SYSTEM COMPONENT

### • 2.1 Introduction

This part describes the space-based component of the WMO Integrated Global Observing System (WIGOS) in 2040. It responds to the 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 in part to Members who have or actively participate in space programmes, it is also important for those Members who do not. All Members rely on satellite data for providing critical services to their constituencies, and also those who do not directly take active part in flight programmes may contribute with ground-station services or with surface-based observations in support of calibration and validation. The information presented here may therefore also help inform the planning of the surface-based components of WIGOS.

### • 2.2 Trends and Issues

#### • 2.2.1 User requirements

Compared to the present, it is expected that users will require by 2040:

- Higher resolution observations, better temporal and spatial sampling/coverage;
- Improved data quality and consistent characterization of uncertainty;
- Novel data types, allowing insight into hitherto poorly understood Earth system processes, including space weather;
- Efficient and interoperable data representation and dissemination methodology, given 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. They include:

- Atmospheric composition: **Limb sounding** for upper troposphere and stratosphere/mesosphere; **Nadir sounding** using short-wave infra-red (SWIR) spectrometry; trace gas Lidar;
- Hydrology and cryosphere: **Laser and radar altimetry; visible multi-frequency Synthetic Aperture Radar (SAR) and passive microwave imagery;**
- Cloud phase detection for NWP: **Sub-mm imagery;**
- Aerosol and radiation budget: **Multi-angle, multi-polarization radiometry, lidar;**
- Wind: **Lidar and hyperspectral capabilities;**
- Solar wind/solar eruptions: **solar wind monitor, magnetometer, energetic particle sensor, solar EUV imagery, heliospheric imagery** (at L5 point) and **in-situ energetic particle flux** (at L1).

To monitor climate change and support mitigation efforts in support of the 2015 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

be comprised of several components, including ground-based observations, space-based observations and modelling tools to assimilate these data into atmospheric transport models to estimate greenhouse gas fluxes. In this system, the space-based observations carry the promise of global coverage greenhouse gas concentrations at high spatial resolution in cloud-free regions while ground based measurements will provide data in persistently cloudy regions and at night and provide additional insight into emissions attribution.

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, such as the monitoring of global precipitation and the growing importance of monitoring air pollution due to its impact on human health, 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 anticipated user needs outlined above, lead to a vision for the space-based component of WIGOS in 2040 that represents an ambitious, but at the same time realistic and cost-effective target.

#### **Sensor technology**

It is expected that rapid progress in remote sensing technology will lead to higher signal sensitivity of sensors, allowing potentially higher spatial, temporal, spectral and/or radiometric resolution. However, progress will not only result from a continuation of measurements with better performance, but also from an extended utilization of the electromagnetic signal in different ways.

Key sensor technology trends include:

- Sensors with improved geometric/radiometric performance;
- Spectrum better exploited: UV, far IR, MW;
- Hyperspectral sensors in UV, VIS, NIR, IR, MW, including from GEO;
- Lidar;
- Combination of active/passive techniques;
- Expanded polarimetric measurement capability (including SAR imagery);
- Polarisation or incidence-angle pairing;
- Diverse radio occultation techniques;
- Near-IR Measurements of molecular oxygen and water vapor to provide clear-sky surface pressure and cloud top height estimates with accuracies near 1 hectopascal (hPa) and column water vapor estimates with accuracies near 1 millimetre.

The information content and the coverage of satellite observations are constrained by observation techniques. For example, high resolution spectra of emitted radiation yield estimate of trace gas concentration in the middle troposphere and above on both the day and night sides of the planet but provide little information about near-surface concentrations. Meanwhile, 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 the illumination

and viewing geometries.

Rigorous instrument characterization and improved pre-flight calibration are prerequisites for an improved uncertainty characterization of the observations. SI-based reference standards, both on-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 will provide standards with adequate spatial and temporal coverage to tie disparate observations together.

Regarding climate observations it is expected that the operational meteorological satellite systems remain the core observing system. Therefore, satellite agencies are encouraged to develop new satellite instruments with climate applications in mind; especially calibration, instrument characterisation, and uncertainty, as well as consistency and homogeneity of long time series should be realised. The GCOS Climate Monitoring Principles must be followed. Essential Climate Variables (ECV) should be produced in fulfilment of established key requirements for climate monitoring. In view of the existing gaps in ECV monitoring, space agencies should develop research missions to address them.

Observing capabilities to monitor the Earth's energy, water and biogeochemical cycles and associated fluxes need to be enhanced, and new techniques to measure the relevant physical and chemical aspects need to be developed, as documented in the 2016 GCOS Implementation Plan<sup>4</sup>.

### **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 complementarity and interoperability of the individual satellite programmes as well as the robustness of the overall system.

While the future space-based observing system will rely on the proven geostationary and low-Earth orbit sun-synchronous constellations, it will also include:

- Highly elliptic orbits providing permanent coverage for the Polar regions;
- Low-Earth orbit satellites with low or high inclination for a comprehensive sampling of the global atmosphere; and
- Lower-flying platforms, for example with small satellites serving as gap fillers or for dedicated missions which are best realized that way;
- Constellations, including of low-cost CubeSats.

For example, measurements from a large constellation (e.g. 3-10 LEO satellites, at least one of which carrying CO<sub>2</sub> and CH<sub>4</sub> lidar, and three or more GEO satellites) would be needed in order to obtain robust, operational, full-column observations of CO<sub>2</sub> and CH<sub>4</sub> 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

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<sup>4</sup> GCOS 2016 Implementation Plan, GCOS-200 (GOOS-214), WMO 2016, pp. 325.

satellites with HEO satellites.

Manned space stations, such as the International Space Station (ISS), may be used for demonstration purposes and for cross-reference calibration/validation of geostationary satellite instruments, and, 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. Diversity of orbits will increase the overall robustness of the system but will require 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-time foundation, complemented with small satellite programmes with shorter life cycles, limited scope, experimental payloads, and with faster, more flexible decision processes.

Given continued pressure for use of 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 on 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 preparing the vision of WIGOS in 2040 for the space-based observing system component, the following assumption were made with regards to the evolution of satellite programmes:

- The space-based observing system will continue to rely on both operational and R&D missions, pursuing different objectives and having different priorities;
- 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 where required;
- International fora such as CGMS and CEOS 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 groups. Three of them fulfil the Vision for WIGOS in 2040. The fourth group includes additional capacities and capabilities that may emerge in the future.

Rather than prescribing every group, a balance has been struck between providing enough specificity to describe a robust and resilient system, while also accommodating potential new capabilities arising from unanticipated opportunities

**Group 1 Backbone system with specified orbital configuration and measurement approaches**

- Basis for Members' commitments, should respond to the vital data needs;
- Building on the current CGMS baseline<sup>5</sup>, but with fully deployed (global) coverage, and with addition of newly maturing capabilities.

**Group 2 Backbone system with open orbit configuration and flexibility to optimize the implementation**

- Basis for open contributions of WMO Members, responding to target data goals.

**Group 3 Operational pathfinders, and technology and science demonstrators**

- Responding to R&D needs.

**Group 4 Additional capabilities**

- Additional contributions by WMO Members, including from academic and commercial sectors.

The sub-division of observing capabilities into four groups does not imply sequential priorities, i.e. it is not expected that all Group 1 systems would necessarily be realized before addressing elements of other groups.

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

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<sup>5</sup> See „CGMS Baseline – Sustained contributions to the Global Observing System”, Endorsd by CGMS-46 in Bengaluru, June 2018, CGMS/DOC/18/1028862, v.1, 20 December 2018.

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

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
<b><i>Geostationary core constellation with a minimum of five satellites providing complete Earth coverage</i></b>	
Multi-spectral VIS/IR imagery with rapid repeat cycles	Cloud amount, type, top height/temperature; wind (through 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 storm; convective initiation (combining multispectral imagery with IR sounders data)
IR hyperspectral sounders	Atmospheric temperature, humidity; wind (through 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
<b><i>Sun-synchronous core constellation satellites in three orbital planes (morning, afternoon, early morning)</i></b>	
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; realisation of a Day/Night band	Cloud amount, type, top height/temperature; wind (high latitudes, through 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 SWE
<b><i>Sun-synchronous satellites at 3 additional Equatorial Crossing Times, for improved robustness and improved time sampling particularly for monitoring precipitation</i></b>	
<b><i>Instruments on other satellites in Low-Earth Orbit</i></b>	
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 on 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 snow water equivalent (SWE)
MW cross-track upper stratospheric and mesospheric sounders	Atmospheric temperature profiles in stratosphere and mesosphere
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 and amount and profiles, aerosol, dust,

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<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
	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 TSI and SSI radiometers	Broadband radiative flux; Earth radiation budget; total solar irradiance; spectral solar irradiance
GNSS radio occultation (basic constellation)	Atmospheric temperature and humidity; ionospheric electron density, zenith ionospheric total electron content and total precipitable water
Narrow-band or hyperspectral imagers	Ocean colour; vegetation (including burnt 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, seas-ice classification, ice-floe geometry, ice sheets, soil moisture, floods, permafrost
Gravimetry missions	Ground water, oceanography, ice and snow mass
<b><i>Other missions</i></b>	
Solar wind in situ plasma and energetic particles, 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, and energetic particle spectrometers and magnetometers at GEO and LEO, and magnetic field at GEO	Energetic particle flux and energy spectrum, geomagnetic field (Radiation storms, geomagnetic storms)
X-ray spectrograph on GEO orbit	Solar X-ray flux (Solar flare)
On-orbit measurement reference standards for VIS/NIR, IR, MW absolute calibration	

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

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
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, Snow Water Equivalent (SWE), soil moisture
Lidar (Doppler and dual/triple-frequency backscatter)	Wind and aerosol profiling
Lidar (single wavelength) (in addition to radar missions mentioned in Component 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, e.g. cloud phase
NIR/SWIR imaging spectroscopy	Spatially-resolved two-dimensional maps of CO <sub>2</sub> , CH <sub>4</sub> and CO over sunlit hemisphere
Trace gas lidars	CO <sub>2</sub> and CH <sub>4</sub> column at night and high latitude winter
Multi-angle, multi-polarization radiometers	Aerosol properties, radiation budget
Multi-polarization 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, reactivetrace 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 (through 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 the Earth-Sun line 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 and 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 the Earth-Sun line and off the Earth-Sun line (e.g. L5 point)	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)

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**Table 4 Operational pathfinders, and technology and science demonstrators (Group 3).**

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
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 and 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	Water quality
Solar coronal magnetic field imagery, solar wind beyond L1	Solar wind, geomagnetic activity
UV spectral imagery (e.g. GEO, HEO, MEO, 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 (Group 4).**

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
GNSS radio occultation	Atmospheric temperature and humidity; precipitation detection; ionospheric electron density, zenith ionospheric total electron

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<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
	content and total precipitable water

## • **PART III: SURFACE-BASED OBSERVING SYSTEM COMPONENT**

### • **3.1 Introduction**

This chapter addresses the surface-based components of WIGOS, here defined any observing system not flying in space. It complements the equivalent chapter for the space-based components of WIGOS to provide a "Vision for WIGOS in 2040".

### • **3.2 Trends and Issues**

There will be continued expansion in both the range of user applications and the geophysical variables observed; this will include new application areas such as space weather, and observations to support the monitoring of ECVs, according to the GCOS climate monitoring principles;

#### **Expansion**

- Sustainability of new components of WIGOS will be secured, with some mature R&D capabilities transferring to operational status;
- The range and volume of observations exchanged globally (rather than locally) will be substantially increased;
- Regional observing networks will be developed to improve forecasting of mesoscale phenomena;
- Some level of targeting of observations will be achieved, whereby additional observations are acquired or usual observations are not acquired, in response to the local meteorological or environmental situation;
- New information will become available through miniaturization of sensors, cloud technology, crowdsourcing, and the "Internet of Things". There will be enhanced interactions between observation providers and users, including feedback of information on observation quality from data assimilation centres.

#### **Automation and technology trends**

- The trend to develop fully automated observing systems, using new observing and information technologies will continue, where it can be shown to be cost-effective and consistent with user needs;
- Access to real-time and raw data will be improved;
- Observing system test-beds will be used to compare and evaluate new systems and to develop guidelines for integration of observing platforms and their implementation;
- Observational data will be collected and transmitted in digital form, highly compressed where necessary. Observation dissemination, storage and

processing will take advantage of advances in computing, satellite and wireless data telecommunication, and information technology;

- Efficient and interoperable technologies will be developed to manage and present observational data; products for users will be adapted to their needs;
- Traditional observing systems, providing observations of high quality, 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;
- Commodity sensors will be developed for a broader range of geophysical variables.

### **Consistency, continuity and homogeneity of basic and reference networks**

- There will be increased standardization of instrumentation and observing methods;
- There will be growing reliance on reference networks to develop and establish standards serving as reference baselines;
- There will be improvements in calibration and decreasing uncertainty of observations and the provision of metadata, to ensure data consistency and traceability to the SI;
- There will be improved methods of quality control and characterization of errors and uncertainty of all observations;
- There will be improvements in procedures to ensure continuity and robustness in the provision of observations, including management of transitions when technologies change;
- There will be increased interoperability, between existing observing systems and with newly implemented systems;
- There will be improved homogeneity of data formats and dissemination via the WIS;

### 3.3 Evolution of the Surface-based Observing System Component

Planning for surface-based observing systems differs substantially from the planning of space-based observing systems, which is more centralized and can be organized decade(s) in advance. While the development cycle of space-based observing systems allows for robust tiered approach, surface-based observing systems will adopt tiered approach on case by case basis for different types of instruments or observations (e.g. surface weather and climate observations). Table 6 below is providing information on the foreseen evolution and trends of surface-based observing systems in different domains (upper air, 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 Foreseen evolution and trends of instrument and observation types and the geophysical variables they measure.**

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
<b>Upper air observations</b>		
Upper-air weather and climate observations	Wind, temperature, humidity, pressure	<ul style="list-style-type: none"> <li>• Radiosonde networks will be optimized, particularly in terms of horizontal density, which will decrease in some data-dense areas, and taking account of the need for observations in the stratosphere and of the availability of observations from other profiling systems.</li> <li>• Profiles from all radiosondes will be delivered at higher vertical resolution and used by applications as required, and from descents after balloon burst.</li> <li>• The GUAN network will be fully supported as part of RBON.</li> <li>• The GRUAN network will be extended and will deliver observations of reference quality in support of climate and other applications.</li> <li>• There will be an increase in the number of automated radiosonde systems, in particular those deployed at remote locations.</li> <li>• Targeted dropsondes will continue to be used and may increase in use through the evolution of air-deployed UAVs.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
		<ul style="list-style-type: none"> <li>• Remote radiosondes stations will be retained and protected.</li> <li>• Support for small islands and developing states will include: improved communications, sustainable power supplies, and training in measurement methods and instrument maintenance.               <ul style="list-style-type: none"> <li>• Reference measurements of humidity will improve monitoring of the UTLS, e.g. through frost-point hygrometer and Lyman-alpha techniques.</li> <li>• Facilities for drone-based observations (land, coastal and ships) will be developed.</li> </ul> </li> </ul>
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)	<ul style="list-style-type: none"> <li>• A large variety of automated operational, cost-effective and optimized aircraft-based observing (ABO) systems will be part of a wider observing system providing global upper-air data of high quality and will be complementary to other operational upper-air observing systems.               <ul style="list-style-type: none"> <li>• The global aircraft-based observing system will be an integrated system, based on requirements defined by both the meteorological and aeronautical user communities, regulated by their respective international organisations and jointly managed by WMO and its international partners.                   <ul style="list-style-type: none"> <li>• Aircraft on-board weather radar data will be down-linked in ABO to supplement fixed site weather radars.</li> <li>• Profiles from ABO systems will be provided at high vertical resolution, geographically selectable and according to user requirements, by using a system optimized at the regional level in collaboration with the aviation industry.                       <ul style="list-style-type: none"> <li>• Extended profiles will be available since some aircraft will be able to fly at higher altitudes.</li> </ul> </li> <li>• The range of meteorological and atmospheric composition variables provided by ABO will be extended. For example, research programmes such as the In-service Aircraft for a Global Observing System (IAGOS), which is</li> </ul> </li> </ul> </li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
		<p>also providing humidity observations from aircraft will eventually transition from research to operational status.</p> <ul style="list-style-type: none"> <li>• ABO will deliver improved water vapour information with global coverage.</li> <li>• Standard turbulence information will increasingly be provided by ABO, in cooperation with the relevant international aviation organizations.</li> </ul>
Remote sensing upper-air observations	Wind, cloud base and top, cloud water, temperature, humidity, aerosols, fog, visibility	<ul style="list-style-type: none"> <li>• Radar wind profiler networks are well established in some Countries and will be extended.</li> <li>• Wind measurements from cost effective Doppler lidar systems will be increasingly used for measurements in the boundary layer.</li> <li>• Raman lidar systems will deliver aerosol properties, humidity and temperature profiles of high accuracy in an operational manner.</li> <li>• Differential Absorption Lidar (DIAL) systems will deliver high resolution aerosol properties and humidity profiles for operational use.</li> <li>• Microwave radiometers will deliver information on temperature and humidity (with limited vertical resolution), total column water vapour and cloud liquid water path.</li> <li>• Ceilometers will increasingly be used to provide information on cloud and aerosol profiles and may partly be replaced by low-cost DIAL systems.</li> <li>• Cloud radar (Ka-band or W-band) will be used for improved quantitative monitoring of the structure of fog, clouds and precipitation.</li> <li>• There will be increased use of video cameras (e.g. at airports) to support local forecasting, including nowcasting and aviation meteorology.</li> <li>• There will be increased use of infra-red video cameras to support cloud identification, cloud height, as well as supporting local forecasting, nowcasting and another source of downward infra-red measurements.</li> </ul>
Atmospheric composition upper-	Atmospheric composition variables (aerosol properties, ozone,	<ul style="list-style-type: none"> <li>• A full global network of operational ozone sondes will be restored, maintained and extended, through GAW and cooperation with international</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
air observations	greenhouse gases, precipitation chemistry variables, reactive gases)	<p>partners.</p> <ul style="list-style-type: none"> <li>• There will be expanded use of automated drones for making air quality measurements.</li> <li>• Atmospheric sampling systems to measure trace gas from the middle stratosphere to the ground will be used (AirCore is an example).</li> <li>• Ground-based Fourier Transform Spectrometer (FTS) retrieving column averaged abundances of greenhouse gases will be used (the Total Carbon Column Observing Network – TCCON – is an example).</li> <li>• More lidars will be used to retrieve profiles of the aerosol variables</li> <li>• Other remote sensing techniques (like DOAS) will be introduced to measure the profiles of the reactive gases in the troposphere and low stratosphere.</li> </ul>
GNSS receiver observations	Total column water vapour, humidity, snow depth, soil moisture, snow water equivalent	<ul style="list-style-type: none"> <li>• 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.</li> </ul>
Lightning detection systems	Lightning variables (location, density, rate of discharge, polarity, volumetric distribution)	<ul style="list-style-type: none"> <li>• Networks of ground-based lightning detection systems will evolve to be complementary to new space-based systems.</li> <li>• Long-range lightning detection systems will provide cost-effective, global data with an improved location accuracy, significantly improving coverage in data-sparse regions including oceanic and polar areas.</li> <li>• 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.</li> <li>• Common formats and lightning observation archives will be developed.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
Weather radars	Precipitation (hydrometeor size distribution, phase, type), wind, humidity (from refractivity), sand and dust storm variables, some biological variables (e.g. bird densities)	<ul style="list-style-type: none"> <li>• There will be 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.</li> <li>• 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.</li> <li>• A weather radar data exchange framework will serve all users and achieve homogeneous data formats for international exchange.</li> <li>• Exploitation of radar technology and data for various other purposes, e.g. urban weather, atmospheric environment, volcanic ash plume monitoring, etc.</li> </ul>
Automated Shipboard Aerological Platform (ASAP) observations	Wind, temperature, humidity, pressure	<ul style="list-style-type: none"> <li>• Commercial ships will be designed to facilitate the making of metocean observations, including installation and use of ASAP systems.</li> </ul>
<b>Near-surface observations over land</b>		
Surface weather and climate observations	Surface pressure, temperature, land surface temperature, humidity, wind; visibility; clouds; precipitation; precipitation type, surface radiation variables; soil temperature; soil moisture; snow depth, snowfall, snow density	<ul style="list-style-type: none"> <li>• Tiered networks will be established: climate reference networks, baseline networks (including RBON), and comprehensive networks including non-NMHS and volunteer observing networks/national mesonets.</li> <li>• Crowd-sourced near-surface observations will be collected and disseminated and integrated with NMHS and other observations.</li> <li>• Automated Climate Reference Network stations (temperature and precipitation) will be deployed in all WMO Regions to improve measurement of national variability and trends.</li> <li>• Climate quality daily, hourly and sub-hourly (to 5-minute) data will be collected and disseminated internationally.</li> <li>• Synergy will be maintained between manual and automated observations, especially for elements such as precipitation as needed to ensure sufficient spatial coverage.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
		<ul style="list-style-type: none"> <li>• There will be expanded use of automated networks to improve the temporal resolution of observations.</li> <li>• There will be expansion of wireless or satellite data transmission for real-time dissemination from station to central facility.</li> <li>• There will be expansion of non-NMHS networks, including volunteer and private sector networks, with automated dissemination/collection to national archive centres.</li> <li>• Maintenance of a measurement lifecycle will be introduced, to recognize the importance of the full requirement of data stewardship, from collection of data and their metadata to their archiving.</li> <li>• There will be increased use of video cameras (e.g. at airports) to support local forecasting.</li> <li>• Expanded use of GNSS surface networks for humidity, snow depth, and snow water equivalent information. For example, it is expected that there will be increased use of vehicles for making surface observations.</li> </ul>
Atmospheric composition surface observations	Atmospheric composition variables <sup>6</sup> (aerosol properties, greenhouse gases, ozone, total atmospheric deposition, reactive gases)	<ul style="list-style-type: none"> <li>• More regional networks will be integrated in the quality controlled observing network</li> <li>• Low-cost sensors will play more prominent role in delivery of air pollution data and more facilities will be developed for their characterization and calibration.</li> <li>• Meteorology/climate measurements will be collocated with air quality measurements.</li> <li>• There will be expansion of global and regional measurements,</li> </ul>

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<sup>6</sup> The full list of the atmospheric composition variables includes more than 80 variables listed in the GAW Implementation Plan 2016-2023. This list may be extended to reflect the needs for the new products and services, for example in relation to carbon or nitrogen cycle (NH3 is already under consideration why the tracer of the photosynthetic activities like COS may be added in the list of the measurement variables in the future).

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
		<p>including through GAW with a special focus on the data sparse regions and with a specific focus on the data provision for the applications with a high societal impact (like human health, food security and biodiversity loss).</p> <ul style="list-style-type: none"> <li>•</li> <li>• An atmospheric composition baseline reference network will be developed.</li> </ul>
Application specific observations (road weather, airport/heliport weather stations, agromet stations, urban meteorology, etc.)	Application specific variables and phenomena	<ul style="list-style-type: none"> <li>• Urban reference networks will be established to provide observations important for urban meteorology/climatology.</li> <li>• Road weather networks will transmit in near-real time, with data collected and archived at national archive centres.</li> <li>• Soil moisture/temperature measurements, from near-surface to 100cm, will be maintained and expanded at agricultural meteorological stations.</li> <li>• Aerodrome observing systems will be enhanced for aviation-specific observation such as windshear, wake turbulence, slant visibility.</li> </ul>
Land-based (fast-)ice observatories	(Fast-)Ice extent, - ridging, - motion, leads	<ul style="list-style-type: none"> <li>• Affordable autonomous radar and visual observing systems.</li> <li>• Deployed in a sustainable network, both in Arctic and Antarctic and marginal seas.</li> </ul>
Observations of the biosphere	Vegetation, carbon (above ground and soil)	<ul style="list-style-type: none"> <li>•</li> </ul>
<b><i>Near-surface observations over rivers and lakes</i></b>		
Hydrological and cryosphere observations	Precipitation, snow depth, snow cover, snow water equivalent and glaciers, evaporation and evapotranspiration,	<ul style="list-style-type: none"> <li>• Hydrological data exchange will be improved in support of operational water resource management, in particular at the basin scale, with a special focus on transboundary catchments.</li> <li>• Automated measurement of snowfall/snow-depth will further augment manual measurements.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	vapor pressure/relative humidity, lake and river ice thickness date of freezing and break-up, melt on-set, 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 on-set, 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	<ul style="list-style-type: none"> <li>• Existing snow monitoring sites will be maintained, with data exchanged internationally.</li> <li>• There will be expansion of automated soil moisture/temperature measurements by installing sensors at existing sites.</li> <li>• Volunteer observations of lake/river ice freeze/thaw dates will be disseminated internationally and archived.</li> <li>• Reference observing stations will be established and maintained.</li> <li>• Concurrent measurement of river channel geometry, water quality data (temperature, turbidity, algae, etc.), river discharge gauging stations, and bedload monitoring stations and turbidity meters will be installed</li> <li>• Crowd sourcing of information on flooding and river drying via the development of public observing networks and social media (including impact reporting).</li> <li>• Satellite data will augment high spatial and temporal resolution data in some key regions (e.g., forested areas).</li> <li>• Several satellite-based methods will be further improved to map the extent of flooding in floodplains or large riverine systems as well as the duration of flooding.</li> <li>• Improved digital elevation data will increase observations on surface water storages for wetlands, large floodplains and estuaries.</li> <li>• Information from satellites and the emerging precipitation network through virtual constellation networks will provide improved precipitation information that can be used flood forecasting.</li> <li>• Radar based rainfall information in real-time will improve its use in flash flood forecasting.</li> <li>• A global in-situ network for soil moisture measurements will be indentified, involving network enhancement by expansion and standardization, dedicated soil moisture missions, and improved coordination of soil moisture</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	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.	<p>data network planning, observing standards, and data exchange.</p> <ul style="list-style-type: none"> <li>• Establishments and maintenance of conventional terrestrial observation methods together with satellite-based systems will increase the information on snow cover, depth, and water equivalent and glaciers.</li> <li>• information on water use will be consolidated on a national and local basis improving management of water resources as well as the assessment of the potential natural flow of water in rivers.</li> </ul>
Ground water observations	Ground water level, Groundwater fluxes, Groundwater chemistry, Aquifer characteristics.	<ul style="list-style-type: none"> <li>• Ground water monitoring networks will be established at national level, and the data will be exchanged internationally.</li> <li>• Gravimetric observation techniques for large groundwater bodies will be proven in operational circumstances.</li> <li>• Crowd sourcing of information on water levels in wells and wells drying will be acquired and incorporated by water management agencies.</li> <li>• Results of aquifer monitoring will be made available online to support groundwater flow modelling and integrated surface-subsurface flow modelling.</li> </ul>
<b><i>Near-surface observations over ocean</i></b>		
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, ice type,	<ul style="list-style-type: none"> <li>• Higher data rate and cheaper satellite data telecommunication will be established for remote automated stations.</li> <li>• More coastal HF radars will be used, with better standardization of the instruments, and sharing of the data internationally.</li> <li>• Arctic: Potential for coastal stations near fast ice and drifting sea ice</li> <li>• Antarctic: Antarctic Fast Ice Network sites as a potential due to an already established infrastructure.</li> <li>• Coastal stations will provide measurements of the atmospheric composition constituents (like CO<sub>2</sub> and DMS) to help characterize atmosphere-ocean exchange of trace gases</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	<p>and topography, ice motion Atmospheric composition variables related to atmosphere-ocean exchange</p>	
Ship observations	<p>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, CO2 concentration, surface radiation variables Sea Ice thickness, concentration, type, floe size, and sea ice topography Iceberg observations</p>	<ul style="list-style-type: none"> <li>• Commercial ships will be designed and equipped to facilitate the making of metocean observations.</li> <li>• There will be increased use of X-Band radars for wave observations and sea-ice ridges.</li> <li>• More systematic infra-red radiometer measurements will be made from ships for satellite validation.</li> <li>• More systematic use will be made of thermosalinograph and of ADCPs (SADCP, LADCP) for near-surface current profiles from Research Vessels.</li> <li>• Use will be made of tourist ships sailing in data-sparse regions (e.g. polar regions, southern ocean).</li> <li>• Use will be made of fishing vessels, assuming proper data policy can be negotiated.</li> <li>• Ship security issue will be addressed (to remove ship identification masking to end users).</li> <li>• Autonomous AWS ships sailing predefined or targeted routes will be expanded.</li> <li>• Data of high resolution and high accuracy from research vessels will be distributed in real-time.</li> <li>• (Semi-)Autonomous sensor systems to replace manual ASPeCt/ASSIST sea-ice observations</li> <li>• Increased transit in the polar regions will allow for timely ice observations</li> <li>• Ship-observations can be ingested into routine operational ice charts for daily sea ice type and concentration validation</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
		<ul style="list-style-type: none"> <li>• Use of standardized sea ice protocol from ASPECT and ASSIST will allow for easier use of sea ice observations. Important: Ships of opportunity can be involved.</li> <li>• With new generation of icebreakers, there is scope for a standardized (semi-) automated underway system for sea-ice and snow observations.</li> <li>• More ships will be equipped with instrumentation to measure dissolved CO<sub>2</sub> in ocean water and in the atmosphere at the same time to characterize the atmosphere-ocean fluxes.</li> </ul>
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 <sub>2</sub> concentration, pH, ocean colour	<ul style="list-style-type: none"> <li>• Smart technology will be developed for adaptive sampling to address specific environment conditions and optimize endurance of the buoys.</li> <li>• Renewable energy power sources will be exploited.</li> <li>• There will be optimized drifters and moored buoys, with more instruments and global and near real-time satellite data telecommunication, yet allowing higher data rate transmission.</li> <li>• Data will be provided at higher temporal and spatial resolution data.</li> <li>• Global fleet of wave and sea state drifters based on GNSS and Micro-Electro Mechanical System (MEMS) multiple degree of freedom technology will be deployed. <ul style="list-style-type: none"> <li>• Acoustic sensors will be used for the measurement of wind and precipitation.</li> <li>• Vandalism-prone moored buoy systems will be equipped with video and/or imagery for detection of incidents and acts of vandalism, together with increased enforcement of legal measures.</li> <li>• More traceable wave observations from wave rider buoys, and global wave observations from drifters.</li> </ul> </li> </ul>
Ice buoy observations	Ice kinematics, surface pressure, temperature, wind, ice thickness, ice and upper-ocean temperature, snow	<ul style="list-style-type: none"> <li>• Sea-ice buoys will be carrying unified sensors, deployed in sustainable grid (IABP and IPAB)</li> <li>• Smaller, cheaper ice-buoys, with more instruments, reduced cost of satellite data telecommunication, and higher data rate transmission.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	depth, snow temperature, sea ice motion and others Snow over sea ice and snow stratification, snow chemistry and isotopic content.	<ul style="list-style-type: none"> <li>• Improved buoy technology with more sensor and air-deployable.</li> <li>• Automated delivery of basic sea-ice data via WIS. Additional data at reduced cost of transmission to science PI.</li> <li>• Plug- and play capability (including video system for melt ponds) to add sensors to support specific scientific (sea-ice) studies.</li> </ul>
Sea level observations	Sea surface height, surface air pressure, wind, salinity, water temperature, gravity measurements (for ocean geoid)	<ul style="list-style-type: none"> <li>• There will be systematic use of Global Navigation Satellite System (GNSS) geo-positioning, and real-time transmission of the data.</li> </ul>
Autonomous Ocean Surface Vehicles	Surface air pressure, temperature, humidity, wind, visibility, sea surface temperature directional and 2D wave spectra	<ul style="list-style-type: none"> <li>• There will be more systematic use of autonomous ocean surface vehicles (e.g. wave gliders, sailing drones) for example capable of using renewable energy sources for propulsion and sailing over predefined or targeted routes.</li> </ul>
Ice-mounted instrumentation	Fast-ice observations: Ice- and snow thickness, freeboard, ice draft, vertical temperature profile (atm-snow-ice-ocean), sea-ice biomass	<ul style="list-style-type: none"> <li>• Arctic fast-ice stations (some were closed over last decade(s)), AFIN stations</li> </ul>
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	<ul style="list-style-type: none"> <li>• Short to multi-week (even seasonal) sea-ice stations: Camp NorthPole etc in the Arctic, nowadays more short but intense ship-supported ice sampling.</li> <li>• New generation of icebreakers should support more ice-floe work.</li> </ul>

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	Icebergs: position, form, size, concentration, motion, height/width/length, iceberg draft, underwater 3D form	
<b><i>Ocean underwater observations</i></b>		
Profiling floats	Temperature, salinity, current, dissolved oxygen, CO <sub>2</sub> concentration, and various bio-geochemical variables	<ul style="list-style-type: none"> <li>• Float will spend less time at surface allowing longer life-time of the measurements.</li> <li>• There will be systematic measurements in marginal seas and under the ice.</li> <li>• Ocean profiles will extend deeper (6000m and over).</li> <li>• More multi-disciplinary measurements will be made.</li> <li>• More higher resolution near-surface observations will be made.</li> <li>• Swarm deployments of profiling floats e.g. ahead of storms/hurricanes, and/or altering the profiling mission of floats within the existing region.</li> </ul>
Autonomous Underwater Vehicles (e.g. gliders)	Temperature, salinity, current, dissolved oxygen, CO <sub>2</sub> concentration, and various bio-geochemical variables, sea-ice draft	<ul style="list-style-type: none"> <li>• There will be capability of undertaking ocean profiles and surveys along predefined routes.</li> <li>• Acoustic communications technologies to transfer data from remotely deployed equipment. There will be capability for operating under the ice, and for transmitting data in delayed mode once in reach of real-time data telecommunication system (acoustic, satellite).</li> <li>• Subsurface docking stations for underwater Gliders and related mission control.</li> <li>• Cheaper ready to deploy equipment and sensor packages enabling more countries to participate in ocean observations, and swarm deployments for high resolution observations (in space and time).</li> <li>• New sensors will allow measuring more variables, particularly biogeochemistry and biology required for 'Earth System Approaches'.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
Sub-surface observations from drifting and moored buoys	Temperature, salinity, currents, CO <sub>2</sub> concentration, pH, sea-ice draft	<ul style="list-style-type: none"> <li>• Optimized acoustic profiling current meters will be used.</li> <li>• Vandalism-prone moored buoy systems will be equipped with video and/or imagery for detection of incidents and acts of vandalism, together with increased enforcement of legal measures.</li> </ul>
Ships of opportunity	Temperature, salinity, ocean colour, currents	<ul style="list-style-type: none"> <li>• Commercial ships will be better designed and equipped to facilitate the making of metocean observations (e.g. installation of XBT/XCTD autolaunchers).</li> <li>• There will be more systematic use of ADCPs (SADCP, LADCP) for current profiles.</li> </ul>
Observations from platforms hosted at submarine telecommunication cables	Bottom and sub-surface multi-disciplinary measurements, Tsunami monitoring (earthquakes, Tsunami wave)	<ul style="list-style-type: none"> <li>• With higher data rates and reduced cost of transmission, there will be no need to transmit data to a surface buoy (which is subject to vandalism and is expensive to deploy and maintain).</li> </ul>
Ice tethered platform observations	Temperature, salinity, current, fast-ice observations	<ul style="list-style-type: none"> <li>• Higher data rates will be supported, with reduced cost of transmission.</li> <li>• Ocean profiles will extend deeper (6000m).</li> <li>• There will be more multi-disciplinary measurements.</li> <li>• ice-moored AFIN (Antarctic Fast-Ice Network) sensor suite</li> </ul>
Instrumented marine animals	Temperature, salinity, sea ice-draft	<ul style="list-style-type: none"> <li>• There will be more systematic use of instrumented marine animals (sea mammals, some fish species being tracked, turtles).</li> </ul>
<b><i>Cryospheric Observations: Sea-ice</i></b>		
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.	<ul style="list-style-type: none"> <li>• Smaller, cheaper ice-buoys, with more instruments and reduced cost of satellite data telecommunication, yet allowing higher data rate transmission.</li> <li>• Improved buoy technology with more sensors and air-deployable.</li> <li>• Automated delivery of basic sea-ice data via WIS. Additional data at reduced cost of transmission to science PI.</li> <li>• Plug- and play capability (incl video system for melt ponds) to add sensors to support specific scientific (sea-ice) studies.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	Snow over sea ice: snow stratification, snow chemistry and isotopic content.	
Ship-based observations	Ice thickness, concentration, type, floe size, and sea ice topography	<ul style="list-style-type: none"> <li>● Increased transit in the polar regions will allow for timely ice observations</li> <li>● Ship-observations can be ingested into routine operational ice charts for daily sea ice type and concentration validation</li> <li>● Use of standardized sea ice protocol from ASSIST or ASPECT will allow easier use of sea ice obs.</li> </ul>
Coastal Stations	Ice thickness, ice type, and topography	<ul style="list-style-type: none"> <li>● Arctic: Potential for coastal stations near fast ice and drifting sea ice</li> <li>● Antarctic: Antarctic Fast Ice Network sites as a potential due to an already established infrastructure.</li> </ul>
<b><i>Cryospheric observations : ice sheets glaciers, permafrost</i></b>		
	<p>Surface accumulation and ablation, surface temperature, surface albedo , ice sheet boundaries, ice sheet thickness, ice velocity, Ice/firn temperature profile, snow cover, snow profile</p> <p>Direct and indirect measurements of ice sheet motion, tracking of grounding line migration, meltwater runoff, water pressure</p>	<ul style="list-style-type: none"> <li>● independently powered automatic weather stations (AWS) operating at the ice sheet surface, measuring all relevant parameters, including all radiation fluxes, sufficiently accurately to close the surface energy balance</li> <li>● Albedo variability – both from optical satellite remote sensing and ground observations, with appropriate errors corrections</li> <li>● Unmanned airborne vehicles (UAV's) may be deployed to understand this spatial scale gap between the in situ observation of albedo with a small footprint</li> </ul>

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	<p>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.</p>	
	<p>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).</p> <p>Permafrost: ground temperature, active layer thickness, rock glacier creep velocity, rock glacier discharge, rock glacier spring temperature, seasonal</p>	<ul style="list-style-type: none"> <li>• Combining snow radar coverage with new, highly accurate digital elevation models of glacier surfaces (from airborne Lidar or satellite platforms)</li> <li>• More systematic glacier and permafrost monitoring will be established as partnership between research and operational agencies, at national and regional level, and the data will be standardized and exchanged internationally</li> <li>• Long term sustainability of research stations is required, to facilitate the availability of climatological records.</li> </ul>

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	frost heath/subsidence, surface elevation change, ground ice volume, coastal retreat, soil moisture	
<b><i>Space weather observations</i></b>		
Solar short wave spectrum observations	White light, H-alpha and calcium K images. Sunspots, flares, filaments, prominences, coronal holes	<ul style="list-style-type: none"> <li>• New telescopes will be able to resolve more spatial details.</li> <li>• Higher observing frequency will provide better time resolution of dynamic behaviour of solar structures.</li> <li>• International dissemination of similar observations will provide 24-hour solar watch capabilities.</li> </ul>
Solar radio observations – spectrograph and discrete frequencies	Coronal mass ejections, radio bursts, solar activity (10.7cm flux)	<ul style="list-style-type: none"> <li>• New telescopes will be able to resolve more spatial details.</li> <li>• Higher observing frequency will provide better time resolution of dynamic behaviour of solar structures.</li> <li>• International dissemination of similar observations will provide 24-hour solar watch capabilities.</li> </ul>
Ionospheric observations - ionosonde	Measurements of the of the ionospheres ability to reflect high frequency radio waves at various frequencies and heights.	<ul style="list-style-type: none"> <li>• There will be improved time resolution.</li> <li>• There will be automation of ionogram analysis.</li> <li>• There will be an expansion of ionosonde network.</li> </ul>
Ionospheric observations - riometer	Measures the "opacity" of the ionosphere to radio noise. Absorption events.	<ul style="list-style-type: none"> <li>• There will be an expansion of riometer networks.</li> </ul>
Ionospheric observations - GNSS	Total electron content of ionosphere, ionospheric	<ul style="list-style-type: none"> <li>• There will be improved spatial resolution through extensive expansion of the ground-based network of GNSS receivers.</li> <li>• There will be improved time resolution.</li> </ul>

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<b>Instrument / observation type:</b>	<b>Geophysical variables and phenomena:</b>	<b>Evolution and trends</b>
	gradients, ionospheric scintillation.	
Geomagnetic observations	Measurements of Earth's magnetic field and geomagnetic disturbances.	<ul style="list-style-type: none"> <li>• There will be improved spatial resolution through extensive expansion of the ground-based network of magnetometers.</li> <li>• There will be improved time resolution</li> <li>• Improved real-time data retrieval</li> </ul>
Cosmic ray observations	Radiation measurements Neutron and muon monitors	<ul style="list-style-type: none"> <li>• New technology for cosmic ray observations will be available to address the requirements of space weather requirements</li> <li>• There will be improved real-time data quality</li> </ul>
<b><i>R&amp;D and Operational pathfinders – examples</i></b>		
Unmanned Aerial Vehicles (UAVs)	Wind, temperature, humidity, atmospheric composition, snow depth, , river channel morphology, trace gas and aerosol concentration	<ul style="list-style-type: none"> <li>• Larger platforms needed.</li> <li>• Lower atmosphere and impassable area measurements using drones.</li> <li>• Miniaturization of the atmospheric composition instruments allows for their use on UAVs for greenhouse gas and aerosol concentration measurements</li> </ul>
Aircraft based observations	Thunderstorms, total water content, radiation in different spectral ranges and directions, dust/sand particles	<ul style="list-style-type: none"> <li>• Wider usage of _private companies fleets of UAVs, capable of flying long distances, powered by renewable energy and semi-permanently deployed, for research observing campaigns and operational applications (e.g. to address the requirements for lightning detection, volcanic ash, severe weather forecasting e.g. rainfall, space weather). <ul style="list-style-type: none"> <li>• Improved lightning detection using Electromagnetic Field &amp; Radio-Frequency instruments</li> </ul> </li> <li>• Extension usage of Water Vapor Measurement (WVM) system.</li> </ul>
Observations from gondolas	Wind, temperature, humidity	<ul style="list-style-type: none"> <li>• Constant pressure balloons will operate in the lower stratosphere.</li> </ul>

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Low -cost sensors	Aerosol, reactive gases and greenhouse concertation	<ul style="list-style-type: none"> <li>• Miniaturization and advancement in the measurement technologies allow for the observations of PM, CO, NO<sub>x</sub>, CO<sub>2</sub> and CH<sub>4</sub> to be made using low-cost systems and the quality of the systems in improving with time</li> </ul>
Melding of surface-base and satellite based remote sensing observations	Wind, temperature, humidity, aerosols, atmospheric chemistry	<ul style="list-style-type: none"> <li>• Combining wind profiler and radar winds with cloud movement wind estimates</li> <li>• Combining surface-based microwave and infra-red radiometers with satellite based observations to resolve the entire vertical profiles of temperature and humidity</li> <li>• Combining surfaced-based lidar, DOAS and TCCON with satellite based observations to provide joint vertical profiles</li> </ul>

## • **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**

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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.