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Vision for WIGOS 2040; update

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WMO regularly reviews its Vision of future global observing systems to support weather, climate and related environmental applications. Currently, a "Vision for WIGOS in 2040" is in preparation, with the aim of submitting it for approval to the 18th World Meteorological Congress in 2019.

The Vision draws on input from a diverse community of both users and observing system developers and operators and has been in development since 2015. Since CGMS-45 an integrated document has been edited, incorporating the respective contributions from the drafting groups that provided the initial component vision documents.

This integrated document will be presented at the WMO Executive Council Session in June 2018, and it is expected that the CGMS agencies will have a final opportunity to review and comment on the draft during the second half of 2018, prior to the preparation of a document for WMO Congress in 2019.

Action/Recommendation proposed: CGMS Space Agencies to provide comments on the integrated draft *Vision for WIGOS in 2040* when invited to do so by WMO, tentatively during the second half of 2018.

Vision for WIGOS in 2040

(Draft 1.5, May 31, 2018)

CHAPTER I. INTRODUCTION, PURPOSE AND SCOPE

This document provides high-level targets to guide the evolution of the WMO Integrated Global Observing System (WIGOS) in the coming decades. This new vision (henceforth referred to as the "Vision for WIGOS in 2040" or simply the "Vision") replaces the current "Vision for the Global Observing System in 2025", which was adopted by EC-61 in 2009. In many ways the 2025 Vision foreshadowed the development of WIGOS, whereas the current document anticipates a fully developed and implemented WIGOS framework that supports all activities of WMO and its Members within the general areas of weather, climate and water.

The aim with the 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 system that will meet them. The purpose of this is two-fold: The first is to inform the planning efforts undertaken by NMHSs, space agencies and other observing system developers of the WMO view of the evolving user requirements. Decisions on implementation will clearly remain with the agencies, international structures and individual WMO Members providing the funding for it. The second is to inform the users of meteorological observations about what to expect over the coming decades, to be used in their planning of IT and communication systems, research and development efforts, staffing, and education and training. The document is also addressed to numerical modelling and prediction centres of WMO Members to help hem plan the evolution of their systems. Other partners from the non-governmental and the private sector may also find items of interest in this Vision.

In extending all the way to 2040, the Vision takes a very long-term view. To a large extent this 20-25 year time horizon is driven by the long programme development and implementation cycles of the operational satellite programmes and radar replacement programmes. Although driven by the development cycle of certain 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.

The document is divided into three Chapters:

Chapter I: Introduction, purpose and scope*;*
Chapter II: The space-based observing system components of WIGOS in 2040*;*
Chapter III: The surface-based observing system components of WIGOS in 2040*.*

The reason for treating space-based and surface-based systems separately is the fundamentally different ways in which the 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. Surface-based observing programmes have on the other hand – especially over the last decade – been driven by a number of unanticipated technological innovations, and since contributions are made by a broader community of stakeholders driven by a correspondingly broad range of motivations, these systems are less influenced by centralized planning or coordination efforts.

Common to both 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 information increase, the private sector is showing increasing 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.

1.1 Key drivers for meteorological 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. While this document is about the vision for the first link, the observations and the observing systems used to acquire them, end user requirements are typically driven by the final link, 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 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 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%[1] and 75%[2]. This

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

2 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)

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 service delivery and for temporal and spatial resolution of the required meteorological data products.

Another major driver linked to human activities is climate change; overwhelming scientific evidence suggests that global warming (and with it, consequences such as sea level rise, increased frequency of various extreme weather and climate events, geographic shifts in major agricultural growing zones, etc.) will continue. Guidance and policy-related decisions on 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 prediction 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.

Managing and monitoring climate change mitigation and adaptation as follow-up to the 2015 Paris agreement will require observations of greenhouse gas concentrations as well as additional measurements related to global carbon. WIGOS must therefore become and integral part of a global carbon monitoring system, that include both ground-based and space-based observations as well as data assimilation and modeling.

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.

1.2 Trends in capabilities and requirements for meteorological 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, 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 private citizens) has evolved dramatically. 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 and climate 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.

One of the major drivers behind the demand for meteorological services thus seems to stem from the steadily increasing prediction capability. In reality a latent demand was already there, but it simply was not explicitly articulated until the capabilities to satisfy it began to materialize. All indications are that the trend toward increasing demand for meteorological information will continue into the future. As prediction capabilities continue to improve, new application areas will emerge and new markets for meteorological 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.

1.3 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, in which observational requirements for all WMO application areas (14, as of Feb 2018), are gathered, vetted and recorded, and reviewed against observational capabilities. The resulting guidance is formulated at both tactical and strategic levels. This document represents the strategic level guidance.

Commented [L1]: List of application areas to be included in a separate box

A fundamental principle of the RRR is that requirements are gathered for geophysical variables rather than for specific measurands For example, the RRR will cite requirements for measurements of atmospheric temperature, but it will not provide system requirements for, say, satellite radiometers or in situ temperature sensors. Specific requirements for such observing systems should be derived from the overall requirements listed in the RRR, but this is the responsibility of the implementing agencies. While the guidance material provided by the RRR does include reference to available technologies, it nevertheless strives to remain impartial with respect to which particular measurements will be implemented 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. Concerning discovery and availability of observational data, continued evolution of the WMO Information System, WIS, and continued leadership of the Member NMHSs in its operation, will thus be critically important to the success of WIGOS, and the two systems will need to evolve in parallel.

In addition to meeting the observational data requirements, 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 both sensing, telecommunication and data processing has significantly increased the vulnerability of the system to natural events such as solar storms. So-called "space weather" – the variability of the Earth's outer environment due to solar activity – has thus become an officially recognized WMO application area, and 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 other WIGOS components.

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 IT security. An additional 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.

1.4 Integration in WIGOS

In the context of WIGOS, the term integration refers to the observing networks, not to the observations. Integration of the observations themselves, e.g. through data assimilation or generation of end-user products, remains outside the scope of WIGOS. Five specific aspects of WIGOS integration are highlighted in the following paragraphs.

First, the principle of **integrated network design** is central to WIGOS. When designing observing networks, it is thus 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.

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

A third principle of WIGOS is 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, etc. 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.

The final decision on data policy resides with the originator and owner of the data. 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.

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 absolute accuracy, 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 absolute calibration is required, with traceability to SI standards. 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.

The fifth and final integration principle is to treat 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 important role. Fine-scale vertical resolution is also generally better achieved via in situ observations, as evidenced by the continued high impact of aircraft and radiosonde observations in spite of their relative sparsity.

In the carbon monitoring system mentioned in Section 1.1, the space-based system will provide global coverage of clear sky observations of greenhouse gases at high spatial resolution, while the ground-based system will provide data in persistently cloudy regions and at night to provide a solid basis for attribution of 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 'traveling calibration reference'.

Finally, it should be emphasized that while the following two chapters contain specific and separate visions for space-based and for surface-based components of WIGOS, it is their complementarity and the mutual recognition of their respective strengths and limitations that will shape the overall future implementation of the WIGOS components. 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 possible as effectively and efficiently as possible.

CHAPTER II: THE SPACE-BASED OBSERVING SYSTEM COMPONENTS OF WIGOS IN 2040

Introduction

This chapter describes the space-based components of the WMO Integrated Global Observing System (WIGOS) in 2040. It responds to the evolving user needs for observations in all 14 WMO application areas and is guided by the expected evolution of space-based observing technology.

While this chapter is addressed in part to Members who have or actively participate in space programs, it is equally important for those Members who do not. First, all Members rely on satellite data for providing critical services to their constituencies, second they may make important contributions via ground service or surface-based observations for calibration and validation, and thirdly the information presented here may help inform their planning of the surface-based components of WIGOS in general.

2.1 General trends and issues

2.1.1 General trends in user requirements

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

- higher resolution observations, better temporal and spatial sampling/coverage;
- improved data quality and consistent characterization of uncertainty;
- novel data types, allowing insight into Earth system processes, including space weather, previously poorly understood,
- efficient and interoperable data representation, given continued growth in data volumes.

Already in the near term, certain additional observations are required to address immediate needs and gaps in several specific application areas. Examples include:

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

It should be noted that emerging needs, e.g for monitoring precipitation, carbon dioxide (CO_2) and methane (CH_4) anthropogenic emissions from various source sectors, may require significant augmentations to the operational meteorological constellation. For example, measurements from a large constellation (e.g. minimum 10 LEO systems, at least one of which carrying CO_2 and CH_4 lidar, and three or more GEO satellites) would be needed in order to obtainrobust, operational, full-column observations of CO_2 and CH_4 at daily to weekly intervals in persistently cloudy regions.

The following sections describe trends in satellite systems and programmes relevant to WMO. These trends, together with anticipated user needs outlined above, leads 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.

2.1.2 Trends in system capabilities

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 trends include:

- Sensors with improved geometric/radiometric performance
- Spectrum better exploited: UV, far IR, MW
- Hyperspectral sensors in UV, VIS, NIR, IR, MW
- Combination of active/passive techniques
- Expanded polarimetric measurement capability (including Synthetic Aperture Radar imagery)
- Polarisation or incidence-angle pairing
- Diverse radio occultation techniques
- NEAR-IR Measurements of molecular oxygen and water vapor i to provide clear-sky surface pressure and cloud top height estimates with accuracies near 1 hecto-Pascal (hPa) and column water vapor estimates with accuracies near 1 millimeter

Orbital scenarios

Satellite observations are also constrained by the choice of orbit. The growing number of space-faring nations may lead to additional diversity in this regard, especially for geostationary orbits, inclined orbits and highly elliptical orbits. This will require a high-level planning and coordination effort undertaken by CEOS and 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 of low-cost CubeSats

Manned space stations (e.g. the ISS) may be used for demonstration purposes, 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 information content and the coverage of satellite observations is constrained by observation techniques. For example high resolution spectra of emitted radiation yields estimates 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 provides 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 calibration are prerequisites for an improved error characterization of the observations. Reference standards (both on-ground and in-orbit), will enhance the quality of data from the whole system. Measurement traceability will be important for the use of observations for climate monitoring. Dedicated calibration 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 accuracy, as well as consistency and homogeneity of long time series should be realised. The GCOS Climate Monitoring Principles must be followed. Essential Climate Variables 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[3].

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 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

3 GCOS 2016 Implementation Plan, GCOS-200 (GOOS-214), WMO 2016, pp. 325.

capabilities on all contributing space-faring nations are needed in order to ensure continuity and thus minimize the risk of gaps in data records.

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 and cooperation issues.

2.2 Approach to developing the space-based component of the Vision

Below, an outline is given of a possible configuration of the space-based components of WIGOS in 2040. Rather than prescribing every tier, a balance has been struck between providing enough specificity to outline a robust and resilient system, while also accommodating potential new capabilities arising from unanticipated opportunities.

The proposed space-based component consists of four groups or systems. Three of them would fulfil the Vision for 2040. The fourth includes additional capacities and capabilities that may emerge in the future:

1. **Backbone system with specified orbital configuration and measurement approaches**
   - Basis for Members' commitments, should respond to the vital data needs
   - Similar to the current CGMS baseline with addition of newly mature capabilities
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
3. **Operational pathfinders, and technology and science demonstrators**
   - Responding to R&D needs
4. **Additional capabilities** contributed by WMO Members and third parties including governmental, academic or commercial initiatives.

The sub-division of observing capabilities into four groups does not imply sequential priorities, i.e. it is not the idea that all group 1 systems should be realized before addressing elements of other groups. The main difference between the 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 than for 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.

Table 1:

Tier 1: Backbone system with specified orbits and measurement approaches

The backbone system, building on/enhancing current vision of the observing system should include:

Instruments:	**Geophysical variables and phenomena:**
Geostationary ring	
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; aerosols; snow cover; vegetation cover; albedo; atmospheric stability; fires; 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	Lightning (in particular cloud to cloud), location of intense convection, life cycle of convective systems
UV/VIS/NIR sounders	Ozone , trace gases, aerosol, humidity, cloud top height
Low-Earth orbiting sun-synchronous core constellation in three orbital planes (morning, afternoon, early morning)	
IR hyperspectral sounders MW 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)
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; aerosols; snow and (sea) ice cover; ice-floe distribution; vegetation cover; albedo; atmospheric stability; 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 (5 to 18 GHz)
Low-Earth orbit sun-synchronous satellites at 3 additional Equatorial Crossing Times, *for improved robustness and improved time sampling particularly for monitoring precipitation*	

Other Low-Earth orbit satellites	
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 SWE (1.4 to 37 GHz)
MW cross-track upper stratospheric and mesospheric sounders	Atmospheric temperature profiles in stratosphere and mesosphere
UV/VIS/NIR sounders, nadir and limb	Atmospheric composition and aerosol
Precipitation radars and cloud radars	Precipitation (liquid and solid), cloud phase, cloud top height, cloud particle distribution and amount and profiles, aerosol, dust, volcanic ash
MW sounder and imagery in inclined orbits	Total column water vapour; precipitation; sea surface wind speed [and direction]; cloud liquid water; sea/land surface temperature; soil moisture
Absolutely calibrated broadband radiometers, and 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; ice sheet altimetry)
Narrow-band or hyperspectral imagers	Ocean colour; vegetation (including burnt areas); aerosols; 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 imagery 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

Other missions	
Solar wind in situ plasma and energetic particles, magnetic field, at L1	Energetic particle flux and energy spectrum (Radiation storms, geomagnetic storms)
Solar coronagraph and radio-spectrograph, at L1	Solar imagery (detection of coronal mass ejections and solar activity monitoring)
In-situ plasma probes and energetic particle spectrometers at GEO and LEO, and magnetic field at GEO	Energetic particle flux and energy spectrum (Radiation storms, geomagnetic storms)
Magnetometers on GEO orbit	Geomagnetic field at GEO altitude (geomagnetic storms)
On-orbit measurement reference standards for VIS/NIR, IR, MW absolute calibration	

Table 2:

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

Instruments:	**Geophysical variables and phenomena:**
GNSS reflectrometry 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 imagery/radiometry	CO_2, CH_4
Multi-angle, multi-polarization radiometers	Aerosols, radiation budget
Multi-polarization SAR, hyperspectral VIS	High-resolution land, ocean, and sea ice extent, sea ice types
GEO or LEO 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, greenhouse gases, trace gases)
UV/VIS/NIR/IR/MW limb sounders	Ozone, trace gases, aerosol, humidity, cloud top height
HEO VIS/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); 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 (e.g. L1, GEO) and off the Earth-Sun line (e.g. L5, L4)	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 (e.g. L5)	Solar wind; energetic particles; interplanetary magnetic field; geomagnetic activity
Solar coronagraph and heliospheric imagery off the Earth-Sun line (e.g. L4, L5)	Solar heliospheric imagery (Detection and monitoring of coronal mass ejections travelling to the Earth)
Magnetospheric energetic particles	Energetic particle flux and energy spectrum (geomagnetic storms)

Table 3:
Tier 3: Operational pathfinders, and technology and science demonstrators

Instruments:	**Geophysical variables and phenomena:**
GNSS RO additional constellation for enhanced atmospheric/ionospheric soundings, including additional frequencies optimized for atmospheric sounding	Atmospheric temperature and humidity; ionospheric electron density
NIR spectrometer	Surface pressure
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, greenhouse gases, 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
Micro satellites	

CHAPTER III: THE SURFACE-BASED OBSERVING SYSTEM COMPONENTS OF WIGOS IN 2040

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".

3.1. General 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 Essential Climate Variables, 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

- 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 of observations and the provision of metadata, to ensure data consistency and traceability to absolute standards;
- There will be improved methods of quality control and characterization of errors 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;

3.2 The Surface-based component: evolution and trends

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

Aircraft-based observations	Wind, temperature, pressure, humidity, turbulence, icing, precipitation, volcanic ash and gases, and atmospheric composition variables (aerosol variables, ozone, greenhouse gases, precipitation chemistry variables, reactive gases)	• A large variety of automated operational, cost-effective and optimized aircraft-based observing (ABO) systems will be part of a wider observing system providing global upper-air data of high quality and will be complementary to other operational upper-air observing systems. • The global aircraft-based observing system will be an integrated system, based on requirements defined by both the meteorological and aeronautical user communities and regulated by their respective international organisations. • Aircraft on-board weather radar data will be down-linked in ABO to supplement fixed site weather radars. • Profiles from ABO systems will be provided at high vertical resolution, geographically selectable and according to user requirements, by using a global optimization system. • Targeted ABO will be available for specific applications. • Extended profiles will be available since some aircraft will be able to fly at higher altitudes. • The range of meteorological and atmospheric composition variables provided by ABO will be extended. • ABO will deliver improved water vapour information with global coverage.
Remote sensing upper-air observations	Wind, cloud base and top, cloud water, temperature, humidity, aerosols, fog, visibility	• Radar wind profiler networks are well established and will be extended. • Wind measurements from cost effective Doppler lidar systems will be increasingly used for measurements in the boundary layer. • Raman lidar systems will deliver aerosol, humidity and temperature profiles of high accuracy in an operational manner. • Differential Absorption Lidar (DIAL) systems will deliver high resolution aerosol and humidity profiles for operational use. • Microwave radiometers will deliver information on temperature (with limited vertical resolution), total column water vapour and cloud liquid water path. • Ceilometers will increasingly be used to provide information on cloud and aerosol profiles and may partly be replaced by low-cost DIAL systems. • Cloud radar (Ka-band or W-band) will be used for improved quantitative monitoring of the structure of clouds and precipitation. • There will be increased use of video cameras (e.g. at airports) to support local forecasting, including nowcasting and aviation meteorology.

Atmospheric composition upper-air observations	Atmospheric composition variables (aerosol variables, ozone, greenhouse gases, precipitation chemistry variables, reactive gases)	• A full global network of operational ozonesondes will be restored and maintained, through GAW and cooperation with international partners. • There will be expanded use of automated drones for making air quality measurements. • Ozone and PM2.5 measurements will be extended to more developing nations. • Aircraft in Atmosphere Monitoring Programmes will begin to be equipped to measure these variables operationally. • An atmospheric composition baseline reference network will be developed
GNSS receiver observations	Total column water vapour, humidity, snow depth, soil moisture, snow water equivalent	• Networks of ground-based GNSS receivers will be extended across all land areas to provide global coverage of total column water vapour observations and other variables, and the data will be exchanged internationally. .
Lightning detection systems	Lightning variables (location, density, rate of discharge, polarity, volumetric distribution)	• Networks of ground-based lightning detection systems will evolve to be complementary to new space-based systems. • Long-range lightning detection systems will provide cost-effective, global data with an improved location accuracy, significantly improving coverage in data-sparse regions including oceanic and polar areas. • Lightning detection systems with a higher location accuracy and with cloud-to-cloud and cloud-to-ground discrimination will support nowcasting and other applications in selected areas. • Common formats and lightning observation archives will be developed.
Weather radars	Precipitation (hydrometeor size distribution, phase, type), wind, humidity (from refractivity), sand and dust storm variables, some biological variables (e.g. bird densities)	• There will be expansion of Doppler and polarimetric weather radars to developing nations, including training on processing and interpretation, and capacity development to handle the extremely large amounts of data. • Emerging technologies will gain widespread use: electronically-scanning (phased-array) adaptive radars will acquire data in unconventional ways, necessitating adaptation by data exchange and processing infrastructure. • A weather radar data exchange framework will serve all users and achieve homogeneous data formats for international exchange.
Automated Shipboard Aerological Platform (ASAP) observations	Wind, temperature, humidity, pressure	• Commercial ships will be designed to facilitate the making of metocean observations, including installation and use of ASAP systems.
Near-surface observations over land		

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	• Tiered networks will be established: climate reference networks, baseline networks (including RBON), and comprehensive networks including non-NMHS and volunteer observing networks/national mesonets. • Crowd-sourced near-surface observations will be collected and disseminated and integrated with NMHS and other observations. • Automated Climate Reference Network stations (temperature and precipitation) will be deployed in all WMO Regions to improve measurement of national variability and trends. • Climate quality daily, hourly and sub-hourly (to 5-minute) data will be collected and disseminated internationally. • Synergy will be maintained between manual and automated observations, especially for elements such as precipitation as needed to ensure sufficient spatial coverage. • There will be expanded use of automated networks to improve the temporal resolution of observations. • There will be expansion of wireless or satellite data transmission for real-time dissemination from station to central facility. • There will be expansion of non-NHMS networks, including volunteer and private sector networks, with automated dissemination/collection to national archive centres. • 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. • There will be increased use of video cameras (e.g. at airports) to support local forecasting. • Expanded use of GNSS surface networks for humidity, snow depth, and snow water equivalent information
Atmospheric composition surface observations	Atmospheric composition variables (aerosol variables, greenhouse gases, ozone, precipitation chemistry variables, reactive gases)	• Meteorology/climate measurements will be collocated with air quality measurements. • There will be expansion of global and regional measurements, including through GAW. • An atmospheric composition baseline reference network will be developed.

Application specific observations (road weather, airport/heliport weather stations, agromet stations, urban meteorology, etc.)	Application specific variables and phenomena	• Urban reference networks will be established to provide observations important for urban meteorology/climatology. • Road weather networks will transmit in near-real time, with data collected and archived at national archive centres. • Soil moisture/temperature measurements, from near-surface to 100cm, will be maintained and expanded at agricultural meteorological stations.
Land-based (fast-)ice observatories	(Fast-)Ice extent, -ridging, - motion, leads	• Affordable autonomous radar and visual observing systems. • Deployed in a sustainable network, both in Arctic and Antarctic and marginal seas.
Observations of the biosphere	Vegetation, carbon (above ground and soil)	• INPUT NEEDED
Near-surface observations over rivers and lakes		

Hydrological and cryosphere observation s	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 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,	• Automated measurement of snowfall/snow-depth will further augment manual measurements. • Existing snow monitoring sites will be maintained, with data exchanged internationally. • There will be expansion of automated soil moisture/temperature measurements by installing sensors at existing sites. • Volunteer observations of lake/river ice freeze/thaw dates will be disseminated internationally and archived. • Reference observing stations will be established and maintained. • Concurrent measurement of water quality data (temperature, sediment load, algae, etc.) and river discharge gauging stations will be installed • Crowd sourcing of information on flooding and river drying via the development of public observing networks and social media (including impact reporting)
Ground water borehole observations	Ground water level	• Ground water monitoring networks will be established at national level, and the data will be exchanged internationally • Crowd sourcing of information on water levels in wells and wells drying will be acquired and incorporated by water management agencies
Near-surface observations over ocean		

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, sea ice, surface radiation variables, surface currents Ice thickness, ice type, and topography, ice motion	• Higher data rate and cheaper satellite data telecommunication will be established for remote automated stations. • More coastal HF radars will be used, with better standardization of the instruments, and sharing of the data internationally. • Arctic: Potential for coastal stations near fast ice and drifting sea ice • Antarctic: Antarctic Fast Ice Network sites as a potential due to an already established infrastructure.
Ship observations	Surface pressure, temperature, humidity, wind, visibility, cloud amount, type and base-height, precipitation, weather, sea surface temperature, wave direction, period and height, salinity, currents, bathymetry, CO2 concentration, surface radiation variables Sea Ice thickness, concentration, type, floe size, and sea ice topography Iceberg observations	• Commercial ships will be designed and equipped to facilitate the making of metocean observations. • There will be increased use of X-Band radars for wave observations and sea-ice ridges. • More systematic infra-red radiometer measurements will be made from ships for satellite validation. • More systematic use will be made of thermosalinograph and of ADCPs (SADCP, LADCP) for near-surface current profiles from Research Vessels. • Use will be made of tourist ships sailing in data-sparse regions (e.g. polar regions, southern ocean). • Use will be made of fishing vessels, assuming proper data policy can be negotiated. • Ship security issue will be addressed (to remove ship identification masking to end users). • Autonomous AWS ships sailing predefined or targeted routes will be expanded. • Data of high resolution and high accuracy from research vessels will be distributed in real-time. • (Semi-)Autonmous sensor systems to replace manual ASPeCt/ASSIST sea-ice observations • Increased transit in the polar regions will allow for timely ice observations • Ship-observations can be ingested into routine operational ice charts for daily sea ice type and concentration validation • 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. • With new generation of icebreakers, there is scope for a standardized (semi-) automated underway system for sea-ice and snow observations.

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, CO2 concentration, pH, ocean colour	• Smart technology will be developed for adaptive sampling to address specific environment conditions and optimize endurance of the buoys. • Renewable energy power sources will be exploited. • 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. • Data will be provided at higher temporal and spatial resolution data. • 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. • Acoustic sensors will be used for the measurement of wind and precipitation. • 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.
Ice buoy observations	Ice kinematics, surface pressure, temperature, wind, ice thickness, ice and upper-ocean temperature, snow depth, snow temperature, sea ice motion and others Snow over sea ice and snow stratification, snow chemistry and isotopic content.	• Sea-ice buoys will be carrying unified sensors, deployed in sustainable grid (IABP and IPAB • Smaller, less expensive ice-buoys, with more instruments and reduced cost of satellite data telecommunication, yet allowing higher data rate transmission. • Improved buoy technology with more sensor and air-deployable. • Automated delivery of basic sea-ice data via GTS. Additional data at reduced cost of transmission to science PI. • Plug- and play capability (incl video system for melt ponds) to add sensors to support specific scientific (sea-ice) studies.
Sea level observations	Sea surface height, surface air pressure, wind, salinity, water temperature, gravity measurements (for ocean geoid)	• There will be systematic use of GNSS geo-positioning, and real-time transmission of the data • Tide gauge network ….
Autonomous Ocean Surface Vehicles	Surface air pressure, temperature, humidity, wind, visibility, sea surface temperature directional and 2D wave spectra	• There will be more systematic use of autonomous ocean surface vehicles (e.g. wave gliders, sailing drones) for example capable of using renewable energy sources for propulsion and sailing over predefined or targeted routes.

Ice-mounted instrumentation	Fast-ice observations: Ice- and snow thickness, freeboard, ice draft, vertical temperature profile (atm-snow-ice-ocean), sea-ice biomass	• Arctic fast-ice stations (some were closed over last decade(s)), AFIN stations
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	• Short to multi-week (even seasonal) sea-ice stations: Camp NorthPole etc in the Arctic, nowadays more short but intense ship-supported ice sampling. • New generation of icebreakers should support more ice-floe work.
	Icebergs: position, form, size, concentration, motion, height/width/length, iceberg draft, underwater 3D form	
Ocean underwater observations		
Profiling floats	Temperature, salinity, current, dissolved oxygen, CO_2 concentration, and various bio-geochemical variables	• Float will spend less time at surface allowing longer life-time of the measurements. • There will be systematic measurements in marginal seas. • Ocean profiles will extend deeper (6000m and over). • More multi-disciplinary measurements will be made. • More higher resolution near-surface observations will be made.
Autonomous Underwater Vehicles (e.g. gliders)	Temperature, salinity, current, dissolved oxygen, CO_2 concentration, and various bio-geochemical variables, sea-ice draft	• There will be capability of undertaking ocean profiles and surveys along predefined routes. • 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).

Sub-surface observations from drifting and moored buoys	Temperature, salinity, currents, CO_2 concentration, pH, sea-ice draft	• Optimized acoustic profiling current meters will be used. • Vandalism-prone moored buoy systems will be equipped with video and/or imagery for detection of incidents and acts of vandalism, together with increased enforcement of legal measures.
Ships of opportunity	Temperature, salinity, ocean colour, currents	• Commercial ships will be better designed and equipped to facilitate the making of metocean observations (e.g. installation of XBT/XCTD autolaunchers). • There will be more systematic use of ADCPs (SADCP, LADCP) for current profiles.
Observations from platforms hosted at submarine telecommunication cables	Bottom and sub-surface multi-disciplinary measurements, Tsunami monitoring (earthquakes, Tsunami wave)	• 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).
Ice tethered platform observations	Temperature, salinity, current, fast-ice observations	• Higher data rates will be supported, with reduced cost of transmission. • Ocean profiles will extend deeper (6000m). • There will be more multi-disciplinary measurements. • ice-moored AFIN (Antarctic Fast-Ice Network) sensor suite
Instrumented marine animals	Temperature, salinity, sea ice-draft	• There will be more systematic use of instrumented marine animals (sea mammals, some fish species being tracked, turtles).
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Cryospheric observations : ice sheets glaciers, permafrost		
	Ice sheets: surface accumulation and ablation, ice sheets thickness, ice velocity, Ice/firn temperature profile, snow cover, snow profile	•

	Glaciers: mass balance (accumulation, ablation), Equilibrium Line Altitude, Glacier thickness, Ice flow velocity, calving flux, Glacier discharge, Snow/firn/ice temperature profile, Surface albedo Snow over glaciers (stratification, chemistry, and isotope content). Permafrost: ground temperature, active layer thickness, rock glacier creep velocity, rock glacier discharge, rock glacier spring temperature, seasonal frost heath/subsidence, surface elevation change, ground ice volume, coastal retreat, soil moisture	• Combining snow radar coverage with new, highly accurate digital elevation models of glacier surfaces (from airborne Lidar or satellite platforms) • More systematic glacier and permafrost monitoring will be established as partnership between research and operational agencies, at national and regional level, and the data will be standardized and exchanged internationally • Long term sustainability of research stations is required, to facilitate the availability of climatological records.
		•
Space weather observations		
Solar optical observations	White light, H-alpha and calcium K images. Sunspots, flares, filaments, prominences, coronal holes	• New telescopes will be able to resolve more spatial details. • Higher observing frequency will provide better time resolution of dynamic behaviour of solar structures. • International dissemination of similar observations will provide 24-hour solar watch capabilities.

Solar radio observations – spectrograph and discrete frequencies	Coronal mass ejections, radio fadeouts, solar activity (10.7cm flux)	• New telescopes will be able to resolve more spatial details. • Higher observing frequency will provide better time resolution of dynamic behaviour of solar structures. • International dissemination of similar observations will provide 24-hour solar watch capabilities.
Ionospheric observations - ionosonde	Measurements of the of the ionospheres ability to reflect high frequency radio waves at various frequencies and heights.	• There will be improved time resolution. • There will be automation of ionogram analysis. • There will be an expansion of ionosonde network.
Ionospheric observations - riometer	Measures the "opacity" of the ionosphere to radio noise. Absorption events.	• There will be an expansion of riometer networks.
Ionospheric observations - GNSS	Total electron content of ionosphere, ionospheric gradients, ionospheric scintillation.	• There will be improved spatial resolution through extensive expansion of the ground-based network of GNSS receivers. • There will be improved time resolution.
Geomagnetic observations	Measurements of Earth's magnetic field and geomagnetic disturbances.	• There will be improved spatial resolution through extensive expansion of the ground-based network of magnetometers. • There will be improved time resolution • Improved real-time data retrieval
Cosmic ray observations	Radiation measurements Neutron and muon monitors	• New SW services • There will be improved real-time data quality
R&D and Operational pathfinders – examples		
Unmanned Aerial Vehicles (UAVs)	Wind, temperature, humidity, atmospheric composition, snow depth	• Larger platforms needed • Lower atmosphere • Valuable in impassable areas
Aircraft based observations	Thunderstorms, total water content, radiation in different spectral ranges and directions, dust/sand particles	• Lightning detection (EM Field & RF). • Avoidance of fuselage/engine damage, similar to volcanic ash detection. • Extension usage WVM system, severe weather forecasting (rainfall). • Ionised radiation at aircraft latitudes for space weather services.
Observations from gondolas	Wind, temperature, humidity	• Constant pressure balloons will operate in the lower stratosphere.

Chemistry, aerosol, wind (lidar), clouds (rain, Doppler radar)		•

Hydrology – observation requirements (from Christel Prudhomme, head of the European Flood Awareness System, EFAS)
GRACE – gravimetric measurements – ground water on continental scales, snow and ice mass
Flood extent, Lake extent, wetlands – (radar?)
River height as a proxy for discharge (altimeter)
Lake height (altimeter)
Soil-moisture (L-band)
Snow cover fraction,, snow water equivalent (if possible).
Detection of irrigated areas.
Water content in vegetation. Phenology
Lightening detection (and flash count) as a proxy for flash flood risk
Mud slides (from change detection in altimeters and radar).
High-definition river networks, static, and with seasonal updates.
Glacier extent.
Albedo of snow and glaciers (for snow modelling of freezing and melting)

ANNEX A OBSERVING NETWORK DESIGN PRINCIPLES

1. Serving many application areas

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

2. **Responding to user requirements**

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

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

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

4. **Designing appropriately spaced networks**

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

5. **Designing cost-effective networks**

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

6. **Achieving homogeneity in observational data**

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

7. **Designing through a tiered approach**

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

8. **Designing reliable and stable networks**

Observing networks should be designed to be reliable and stable.

9. **Making observational data available**

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