

**Vision for WIGOS 2040; update**  
In response to CGMS action A44.01  
HLPP reference: 1.1

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 18<sup>th</sup> World Meteorological Congress in 2019.

The document is structured in three parts: An overarching “Vision for WIGOS in 2040” providing scope, context and background for the Vision, supplemented by two annexes, Annex I: “Vision for the WIGOS space-based component in 2040”, and Annex II: “Vision for the WIGOS Surface-based component in 2040”.

Preliminary drafts of all three components have been developed, and these are included below for information. The plan is to further develop and integrate the three elements in consultation with a broad group of stakeholders, and to present a solid draft of an integrated “Vision” document for discussion at the 7<sup>th</sup> Session of the Inter-commission Coordination Group on WIGOS (ICG-WIGOS) in early 2018.

Annex I, “Vision for the WIGOS space-based component in 2040” has been developed with very substantial involvement from the satellite community and the CGMS agencies, and it has undergone further modification and editing since CGMS-44.

CGMS is invited to provide comments to the current draft “Vision for WIGOS 2040” by the end of July 2017, prior to final development of a draft “Vision”.

Action/Recommendation proposed: CGMS Space Agencies to provide comments on draft *Vision for WIGOS in 2040 (Appendix I)* by 31/07/2017

## Vision for WIGOS in 2040; update



**World Meteorological Organization**  
**EXECUTIVE COUNCIL**  
**Sixty-Ninth Session**  
Geneva, 10 to 17 May 2017

**EC-69/INF. 5.1(1)**  
Submitted by:  
Secretary-General  
8.V.2017

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### 1.1 WMO INTEGRATED GLOBAL OBSERVING SYSTEM (WIGOS)

#### **Vision for WIGOS in 2040**

*(Draft version 0.7, 3 May 2017)*

*ICG-WIGOS Co-Chairpersons and WIGOS Project Office*

The Vision for WIGOS in 2040 is planned to consist of three elements:

An over-arching document: Vision for WIGOS in 2040

[Annex I](#): Vision for the space-based observing system components of WIGOS in 2040

[Annex II](#): Vision for the surface-based observing system components of WIGOS in 2040

Initial drafts of all three components have been developed under the auspices of ICG-WIGOS and these are currently undergoing review with the involvement of all WMO technical commissions and experts and stakeholders from WMO co-sponsored programmes and other external partners. Once the feedback resulting from this process has been incorporated, further editing will take place to ensure proper integration of the three components.

The current (2<sup>nd</sup> Q 2017) status of the draft Vision components included in this document are provided to EC-69 for information. ICG-WIGOS plans to submit a final draft to EC-70 for its approval.

## Introduction

The purpose of this “Vision for WIGOS in 2040” is to envision the potential and desirable developments in the observing systems that underpin the efforts of WMO and its Members in providing and delivering services in the general areas of weather, climate and water over the coming two decades. The “Vision”, intended to inform planning efforts of WMO Members in the context of the WMO Integrated Global Observing System (WIGOS), represents a substantial effort contributed by experts and agency representatives from both the satellite and surface-based observing communities as well as representatives from a diverse group of scientific and operational user communities.

The Vision has been developed under the auspices of the Inter-Commission Coordination Group on WIGOS, but it is important to point out that this is not a vision for a particular organizational framework or programmatic structure. It is a vision describing the likely evolution of user requirements within the WMO domain, along with realizable paths toward satisfying them through the implementation of an integrated set of observing systems, independent of specific programmatic vehicles.

The “Vision” replaces the current “Vision for the Global Observing System in 2025”, which was adopted by Congress-13 in 2007, with a view to influencing the development of emerging space programmes, in particular, with an informed view on the changing requirements for meteorological and oceanographic observations. In addition to merely updating and extending the time horizon, the new Vision is also significantly expanded in scope. WIGOS supports all application areas covering the activities of WMO and its Members in the general areas of weather, climate and water, whereas the GOS was implemented primarily to serve weather monitoring and prediction, and the scope of the observing systems put in place under the WIGOS umbrella is thus significantly broader.

In extending all the way to 2040, the Vision is ambitious, arguably perhaps excessively so. To a large extent the 20-25 year horizon is driven by the very long programme development and implementation cycles of the operational satellite programmes. A document with, say, a 10- or 15-year horizon would be a commentary on plans already approved and not a true vision as such. Although driven by the development cycle of the space programmes, the nature of WIGOS as an integrated system, in which space-based and surface-based components complement each other, means that the full value of the Vision will only be delivered by addressing both components, to the extent possible.

The goal is not to attempt to predict what the world will look like in 2040. In fact, the useful shelf life of this document will have ended more than a decade before that time. The aim is to present a likely scenario of how user requirements may evolve in the WMO domain over the next couple of decades, and an ambitious, but fundamentally technically and economically feasible vision for a system that will meet them. The purpose of this is two-fold: The first is to inform the current and ongoing planning efforts undertaken by NMHSs, space agencies and other observing system developers of the WMO view of this. It is meant to inform, not to prescribe, and any decision on actual implementation will clearly remain with the agencies and individual WMO Members

providing the funding for it. The second is to inform the users of meteorological observations about what may be coming their way 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 intended audience for this “Vision for WIGOS 2040” includes the national governments of WMO Members, in particular their NMHSs, space agencies and other agencies with activities in the broader areas of weather, climate and water. The Vision is also intended to be helpful to the international coordination efforts undertaken by structures such as CEOS, CGMS, GEO and GCOS. This document is also addressed to numerical modelling and prediction centres of WMO Members, who are significant demand drivers for observations and who need to plan for the evolution of their systems. Other, current and future, partners from the non-governmental and the private sector, and equipment suppliers may also find items of interest in this Vision.

The document consists of three parts:

- (i) An over-arching Vision document providing scenario and context (*this document*);
- (ii) Vision for the Space-based component of WIGOS in 2040 (*Appendix I*);
- (iii) Vision for the Surface-based component of WIGOS in 2040 (*Appendix II*).

The reason for structuring the document this way is the fundamentally different ways in which the satellite- versus the space-based components of WIGOS have been evolving and are expected to continue to evolve. Satellite programmes are characterized by a high degree of central planning, long-term development cycles and well-structured formal mechanism for engagement with the WMO user community. Surface-based observing programmes have on the other hand – especially over the last decade – spawned 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 system components have largely eluded any attempt at central planning.

Common to both sides is the drive toward new business models, especially as concerns the relationship between public and private sectors. As 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 develop or imply policy positions around this issue, nor does it speculate about 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.

### **Some key drivers for meteorological services**

In keeping with the WIGOS philosophy of user- or requirements-driven observing systems (*insert reference to CIMO Vision document*), the starting point in the formulation of the Vision is the expected evolution of user requirements. In this section an analysis of current trends in societal requirements for weather-, climate- and water-related services and their likely extension over the next two decades is presented.

In most of its programmes and working structures, WMO breaks down the meteorological value chain into four separate links: (i) Observations, (ii) Information exchange and data dissemination, (iii) Data processing, and (iv) Service delivery. It is important at this point to acknowledge that while the purpose of this document is to formulate a vision for the first link, that is, the observations and the observing systems used to acquire them, end user requirements are typically derived by focusing on the desired capabilities of the final link, service delivery. Backtracking this into observing system requirements depends on a number of assumptions made about the two intermediate links in the chain. Wherever possible we have tried to make these assumptions as explicit as possible.

Some of the drivers for meteorological service delivery are linked to human activity, while others are entirely natural. One of the main drivers of the former category is the fact that the global population will continue growing and is projected to reach 10 billion people by the year 2050. 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, climate and water 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 choose or be forced to live in areas exposed to phenomena such as coastal or river flooding, landslides, etc.

A second factor related to population is that its geographic distribution is likely to be very different from today. 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>1</sup> and 75%<sup>2</sup>. This massive migration requires metropolitan areas to absorb an additional more than 3 billion people over the next 30 years. Large urban agglomerations – especially the so-called mega-cities with more than 10 million inhabitants – are inherently vulnerable entities, as are major elements of their infrastructure. Food, water and energy supply and supply lines will need to be secure, and advance planning for response to a wide range of potential natural or partly man-made disaster scenarios unfolding at various time-scales will provide very strong drivers for meteorological service delivery.

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, irreversible 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-related 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.

While any detailed long-term extensions of each of these major trends have large uncertainties, the trends themselves are well established and largely undisputed. It is therefore reasonable to base a

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

<sup>2</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)

vision for future observational data requirements and future observing systems on the assumption that these trends will continue.

The second group of major drivers are entirely natural and include phenomena such as extreme volcanic activity, meteor strikes and major solar storms. These are not in and of themselves of a meteorological nature, but some of them may have substantial impact on weather patterns, and some may significantly strain or limit our observing or communication capabilities. They are inherently unpredictable, but what can be predicted and to some extent be mitigated, is the degree of human exposure and vulnerability to them. Depending on the degree of politically acceptable risk and willingness to invest, requirements for service delivery may also be established. To some extent this is already happening today, for instance in the area of space weather, where the risks posed by solar storms to communication systems, power grids and other essential infrastructure elements are increasingly recognized and taken into account in emergency planning efforts.

The observing systems under the WIGOS umbrella must evolve toward supporting these growing and changing societal needs as well as toward increased readiness to guide emergency responses.

### **Trends in capabilities and requirements for meteorological service delivery**

In order to calibrate the expectations for what may happen over the course of the next 25 years, it may be useful to start with a few observations regarding the state-of-the-art of meteorology some 25 years in the past, at the beginning of the 1990s.

The world of meteorological observations was very different in 1990: Surface measurements were still taken, encoded and transmitted manually, upper-air sounding using radiosondes was a long-standing practice but was still based on visual or radar tracking of the balloons. On-board tracking using satellite navigation systems such as the US Global Positioning System was not implemented until the early 2000s. Meteorological satellite systems had been deployed, but very few in the meteorological community would have considered them among the core observing systems – in fact significant positive impact on the skill of numerical weather prediction models would not be widely achieved until the turn of the millennium, nearly a decade later. Outside the sphere of meteorological observing systems, the technological differences between today and 25 years ago are even more striking. The Internet was still the exclusive domain of academia and military users – the world wide web was invented in 1990, and the code for the first web browser was not written until 1993. Wireless telephony was starting to become generally available, but today's ubiquitous GSM technology would not be invented until 1991.

Although based on the science of meteorology, weather forecasting still relied much more heavily than today on the experience and knowledge of human forecasters and their ability to produce, interpret and extrapolate hand-drawn analyses, which were essentially subjective estimates of the state of the atmosphere informed by relatively sparse observational datasets. The useful forecast range that could be achieved based on this approach was limited, and although a handful of global NWP centres were already issuing routine 10-day forecasts, relatively few users were habitually making decisions of substantial economic impact based on weather forecasts ranging beyond two to three days at the most.



In the years since that time, the expectations of the user community (both public and private sectors and private citizens) regarding environmental information have evolved dramatically. A wide range of users from all economic sectors and from national, regional and municipal governments are making decisions with very significant economic impacts based on weather forecast and climate outlook information on an every-day basis. Not only are users more demanding about the content and quality of environmental information, they are also more demanding about how, when, where and how often 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. A useful analogy from a different Earth science discipline is the area of earthquake prediction. An operational prediction capability here would clearly be extremely valuable to society, but without a solid scientific basis or path toward developing such a capability, there is little reason to expend time and energy on formulating specific requirements for it.

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 savvy set of user communities.

## **WIGOS principles and design drivers**

The development of WIGOS is focused on ensuring that the provision and delivery of meteorological services responding to the societal needs listed 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.

To that effect WIGOS aims to design, develop and implement observing systems in response to specific requirements. The primary guidance comes from the WMO Rolling Review of Requirements (RRR; *insert reference*), in which observational data requirements for all WMO application areas (of which there are 14 per April 2017; *insert list or reference*), are gathered, vetted and recorded, and reviewed against actual and planned observational capabilities. The resulting guidance is formulated at both tactical and strategic levels. This document represents the strategic level guidance.

A fundamental principle of the RRR is that requirements are gathered for geophysical variables rather than for measurands provided by a specific observing system. The guidance provided by the RRR thus generally remains neutral with respect to which particular measurement system or systems will be implemented to meet the requirements. For example, the RRR will cite requirements for measurements of atmospheric temperature in terms of horizontal, vertical and temporal resolution, domain of coverage, acceptable uncertainty, data latency etc., but it will not list specific system requirements for, say, infrared or microwave satellite radiance measurements,

GPSRO phase delays, radiosonde instrumentation, aircraft-borne temperature sensors, etc. Specific requirements for individual observing systems can and should be derived from the overall requirements listed in the RRR, but this task is ultimately the responsibility of the entities responsible for funding, developing and implementing those systems.

It is not enough to design a system providing the required coverage of observations at the required quality. In order to be useful, the observations from WIGOS also need to be discoverable by the users and those that are deemed relevant will need to be disseminated to the users with the required timeliness. Concerning discovery and dissemination, continued evolution of the WMO Information System, WIS, and continued leadership of NMHSs in its operation, will thus be critically important to the success of WIGOS, and the two systems will need to evolve in parallel. The steadily increasing dependence on high performance computing, high volume data exchange and high demand users points to ICT security as a critical issue also in the future, and WIS is expected to provide guidance on this issue. Even though WIS may play a leading role, it is important not to see this as an ICT issue in isolation, but rather an issue potentially impacting network resilience, and as such central to the operation of WIGOS. An important additional role of WIS will be to continue its work on protecting important parts of the spectrum in order to safeguard vital communications and sensing capabilities.

## Integration in WIGOS

The term integration in the WIGOS context refers to a number of different things, specifically: (i) integrated network design; (ii) the use of multi-purpose networks, integrated across application areas; (iii) integration across national and organizational boundaries; and (iv) integration across technological boundaries, e.g. between space- and surface-based components. In the following paragraphs each of these elements are briefly described.

The principle of integrated network design is central to WIGOS. When designing and deploying a new observing system, it is thus imperative to do so with a view to not only the requirements that it will meet, but also with a view to what other WIGOS components are targeting with the same requirements and how to optimally complement the observations provided by them. This has been captured in the WIGOS network design principles and has been adopted by the World Meteorological Congress as part of the Manual on WIGOS (*insert reference*).

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 avoid setting up separate networks for, say, climate monitoring, nowcasting and numerical weather prediction that all require the same variable albeit with somewhat different requirements, and to instead establish integrated, multi-purpose networks serving several application areas wherever possible.

Within most WMO Members, it is no longer the case that the NMHS is a sole provider of meteorological observations. Instead, typically a variety of organizations are now running observing systems of interest for 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. A third principle of WIGOS is to integrate these observations into one overall system to the extent possible. 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. In order to do this successfully, there are a number of technical issues related to data quality, data formats, communication lines and data repositories to sort out, and agreements regarding data policy need to 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 when it comes to maximizing the overall socioeconomic value of the data. The more widely data is shared, the larger the community that will be able to use them and benefit from them, and consequently the larger the overall economic return on the investment made by society 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 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. There are aspects of the requirements that are more readily met from space, for instance regarding global coverage and high spatial resolution over large areas. On the other hand there are certain geophysical variables that are difficult to measure from space, for instance surface pressure or the chemical composition of the lower troposphere, and where surface-based measurements will continue to play an important role. Even in areas where space-based observing capabilities are strong, there is an important role for surface-based observations to provide ground truth for calibration and validation. This issue is further discussed in *Annex (insert reference)*.

Today, not all Members participate directly in the development, deployment and operation of space-based systems. However, the Vision for the space-based system components is still important even for those Members who do not. First, they rely on satellite data for providing critical services to their constituencies, second they may be able to provide contributions via ground service or surface-based observations for calibration and validation as mentioned above, and thirdly it will help inform their planning of the surface-based components of WIGOS in general.

Finally, it should be emphasized that while the annexes to this document contain specific and separate visions for space-based and for surface-based components of WIGOS, it is their complementarity and the growing mutual recognition of their respective contributions, strengths and limitations that will shape the overall future implementation of the WIGOS components. WIGOS provides the global framework and the practical management and design tools so that all providers of meteorological and related observations can optimize their investment in user-driven measurement capabilities that in combination will help meet as many requirements as possible as effectively and as efficiently as possible.

## VISION FOR THE WIGOS SPACE-BASED COMPONENT IN 2040 DRAFT V1.1 (13 December 2016)

### Document Change Record

Date	Status
12 Nov 2015	ET-SAT-10 Working Paper 3.1
21 Dec 2015	Modifications based on input from ET-SAT-10 (17 Nov 2015), WIGOS Space 2040 Workshop (18-20 Nov 2015, Geneva) and ICTSW (18 Dec 2015)
11 Jan 2016	Revision based on comments by chairperson IPET-OSDE and WMO Secretariat (OBS/SAT)
13 Jan 2016	Corrections to mission tables for Component 1 and 2
19 Jan 2016	Additional comments by chairperson IPET-OSDE
4 May 2016	Revisions by chairperson ET-SAT and WMO Secretariat
29 Sept 2016	Review and revisions by Secretariat: Inter alia comments from CGMS-44 and comments from expert teams and fora included
29 Nov 2016	CBS-16 approved the document for sending to WMO Members, technical commissions and other entities to be selected by WMO

### 1. Introduction

This document describes a new vision of the space-based observing components contributing to the WMO Integrated Global Observing System (WIGOS) in 2040. This new vision (henceforth referred to as the “WIGOS Space Vision 2040” or simply “Vision”) is formulated in anticipation of user needs for satellite-based observations in the 14 application areas that are recognized and documented by WMO<sup>3</sup>, by 2040. This anticipation is guided by the expected evolution of space-based observing technology.

The initial draft of the Vision was provided by the WMO/CBS Expert Team on Satellite Systems (ET-SAT) composed of representatives of space agencies, in consultation with the Coordination Group for Meteorological Satellites (CGMS), building on the outcome of the WIGOS Space 2040 workshop<sup>4</sup>, Geneva, 18-20 November 2015 and additional input from the Inter-Programme Coordination Team on Space Weather (ICTSW). A revision was prepared based on feedback received from a series of consultations – the WMO Presidents of Technical Commissions Meeting (19-20 January 2016), the Consultative Meeting on High Level Policy on Satellite Matters (CM-13, 28-29 January 2016), the WMO CBS Inter-Programme Expert Team on Satellite Utilization and Products (IPET-SUP-2, 23-26 February 2016) and the 2016 meeting of the Coordination Group for Meteorological Satellites (CGMS).

This draft version 1.0 is submitted for consideration by the WMO Commission for Basic Systems at its sixteenth session. CBS is asked to agree to the use of draft v1.0 for wider consultation in 2017-2018 with space agencies, user communities and additional groups

<sup>3</sup> <http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html>

<sup>4</sup> <http://www.wmo.int/pages/prog/sat/meetings/WIGOSSpace2040.php> (Presentations);  
<http://www.wmo.int/pages/prog/sat/meetings/documents/ListofParticipants.pdf> (List of participants)

representing a variety of viewpoints, including the research community. Eventually, the Vision shall be endorsed by the World Meteorological Congress in 2019.

It should be first recalled that the current space-based observing system as described in the Manual on WIGOS includes a constellation of advanced geostationary satellites, a three-orbit constellation of polar-orbiting satellites supporting atmospheric sounding and other missions, other operational missions on various orbits suited e.g. for altimetry or radio-occultation, with a general principle of operational continuity and near real-time data availability. Although there remain gaps and scope for improvement, this system is a solid foundation underpinning the successful operation of the World Weather Watch and other major WMO Programmes.

The new Vision will thus be devised through an evolutionary approach, with mostly incremental changes over the current baseline. It investigates what should be added, reinforced or improved, and what could be performed differently in the future in order to best respond to and serve the changing needs.

The following main drivers of change are identified:

- Emerging user requirements from new applications that are not, or only partly captured in the current Vision for 2025. Today, these are mainly related to atmospheric composition, cryosphere, hydrology and space weather;
- An increased need for a resilient observing system, with more and enhanced applications and services routinely utilizing satellite data; this applies not only to weather but also for example to climate applications where the impact of potential gaps in the observing system on the continuity of climate time series is particularly severe;
- Recent or anticipated advances in remote sensing technology, satellite system design and satellite applications, which will enable to meet currently unfulfilled performance requirements, implementation of currently experimental or newly demonstrated techniques, and possibly alternative, more cost-effective approaches;
- Changes in the satellite providers' community that will involve more space-faring nations, an increased maturity and potential of satellite industry; there will be increasing pressure to demonstrate the benefit to societies of public investments into satellite programmes; the latter includes due considerations of commercial satellite initiatives;
- An increased number of satellites from different space-faring nations will lead to larger diversity of data sources and therefore require new ways to document, process and apply satellite data, including a near-real time delivery of the data to users.

This Vision addresses specifically the space-based components of WIGOS and takes a perspective until 2040, mainly because of the long lead times in space programme development cycles. The Vision also attempts to address the evolving interests of WMO Members beyond the traditional WMO focus on observations for weather and climate by taking on more of an Earth system viewpoint which includes other applications.

The space segment must be complemented by the surface-based components of WIGOS, for example to provide surface-based reference measurements using a multi-tiered approach (i.e., a smaller number of high quality ground sites that are part of a much larger network of stations that provide significant geographical coverage). This applies to the many applications where both satellite and surface-based data are required, and for measurements that cannot be achieved from space. The WMO Vision for the surface-based component of WIGOS 2040, currently under development and for eventual endorsement by Congress in 2019, will address these needs. Mutual complementarity and consistency of the surface-based and space-based components of the Vision is essential for the WMO user community and should be addressed in an iterative manner through relevant WMO fora.

With regard to applications, satellite ground segments are critical for an effective exploitation of satellite missions by the user community. This will require

- Sufficient and timely investments in application development;
- Dedicated user training;
- Maintenance of efficient data dissemination systems meeting user needs for timeliness and completeness;
- New approaches for data processing, storage, and access with due consideration of increasing data volumes;
- Effective user-provider feedback mechanisms;
- NRT access to operational and to R&D mission data when relevant.

Since data management is an area under rapid technological development, satellite ground segment design principles will evolve over time. Consideration will also need to be given to the availability of the radio frequency spectrum for satellite data downlink given the increasing pressure on spectrum usage associated with advances in telecommunications.

The Vision recognizes the need for flexibility to support unanticipated areas of research and application, in particular those cases where community members identify and demonstrate that observations useful for one purpose (or set of environmental parameters) can be applied to different areas of application.

This Vision does not provide guidance regarding data policy.

## **2. General trends in user requirements**

It is difficult to exactly predict requirements for satellite data in support of weather, water, climate and related environmental applications in 2040. Nevertheless for the purpose of developing the 2040 Vision, an attempt has been made to anticipate the evolution of user needs, based on broad consultation with users and general expected trends in the use of satellite data; 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 uncertainty characterization of the observations;
- Novel data types, allowing insight into Earth system processes hitherto poorly understood;

- Efficient and interoperable data representation, given the exponential growth of data volumes.

These trends are reinforced by the growing role of integrated numerical Earth system modelling that will serve many applications and cover a seamless range of forecast ranges. More data streams are expected to be assimilated in numerical modelling frameworks, and this more effectively due to improvements in Earth system process understanding, refined assimilation methods, and better handling of observation uncertainty. Simultaneous observations of several variables/phenomena, as well as multiple observations of the same phenomenon will be beneficial to numerical weather prediction, to atmosphere, ocean, land and coupled reanalyses, and to many other applications.

Sustained observations of the Essential Climate Variables (ECVs) will provide the baseline for global climate monitoring and related climate applications. Seasonal-to-decadal predictions will, among others, require higher-resolution ocean surface and sub-surface observations, such as of salinity, SST and sea ice parameters, as well as information on the stratospheric state, solar spectral irradiance, and soil moisture. Ocean applications will, inter alia, require sustained satellite-based observations of essential ocean variables that can be measured from satellites, including ocean surface topography, SST, ocean colour, sea ice, surface winds and sea state.

Nowcasting, severe weather forecasting, disaster risk reduction and climate adaptation will particularly require impact-related data, such as on precipitation, temperature, sea level rise, ice formation and distribution, and winds. Applications related to health and the environment will require all observations needed for a “chemical weather or air quality forecast”, with variables characterizing atmospheric composition at the forefront, such as ozone, aerosols, trace gases, and atmospheric pollutants. Satellites will also play an important role in supporting applications in the data-sparse Polar Regions providing better insight into changes in ice sheets, sea ice parameters, and glaciers.

Managing and monitoring climate change mitigation as follow-up to the 2015 Paris Agreement will need greenhouse gas and additional carbon budget-related observations. New and better information relevant for renewable energy generation such as on winds and solar irradiance will be required.

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

- Limb sounding for atmospheric composition in the stratosphere and mesosphere, for numerical modelling and for climate modelling;
- Lidar altimetry in support of cryosphere monitoring, needed to support polar activities; this complements SAR imagery and radar altimetry;
- With the increasing importance of water resource management and flood prevention, hydrological applications should benefit from lidar altimetry but should also and progressively rely on the exploitation of gravity field measurements for operational monitoring of groundwater;

- SAR imagery and high-resolution optical imagery should be more systematically exploited for applications in the cryosphere, for example for ice sheet and glacier monitoring, deriving refined sea ice parameters, snow properties and permafrost changes;
- Sub-mm imagery for cloud microphysical observations (e.g. phase detection) will be beneficial for cloud modelling and atmospheric water cycle modelling;
- Multi-angle, multi-polarization radiances will allow better and continuous observation of aerosols and clouds which is needed in many applications, notably in NWP; furthermore such measurements over different scene types will improve BRDFs (bi-directional reflectance distribution functions) for the derivation of the radiation budget at the top of the atmosphere which is a key climate variable;
- 3D fields of horizontal winds from Doppler lidar should be assessed, with a view to improve the atmospheric dynamics in NWP models;
- Finally, solar observations on and off the Earth-Sun line (e.g. at L1, and L5), in situ solar wind at Lagrange point L1, and magnetic field measurements at L1 and GEO, measurement of energetic particles at GEO, LEO and across the magnetosphere, will be needed on a fully operational basis to support the warning of major space weather events.

It will be very important to maintain the investment into further development of forward operators (for model-based simulation of observations) and, related to this, into improved radiative transfer models and spectroscopic databases. These are needed to improve the accuracy of forward modelling and hence the utility of observations in numerical models, e.g., for assimilation.

The following sections describe trends in satellite systems and programmes. These, together with anticipated user needs outlined above, have led to the formulation of the WIGOS Space Vision 2040 that represents an ambitious, but at the same time realistic and cost-effective target (section 5).

### **3. Trends in system capabilities**

It is anticipated that rapid progress in remote sensing technology will lead to higher signal sensitivity of sensors, which translates into a potential for higher spatial, temporal, spectral and/or radiometric resolution, respectively. 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 that:

- The remote sensing frequency spectrum used for optical measurements will expand in both directions, towards UV and far IR, and wider use will also be made of the MW spectrum, subject to adequate frequency protection;
- Hyperspectral sensors will be used not only in IR but also in the UV, VIS, NIR and MW ranges, providing a wealth of information, opening new fields for research and generating a dramatic increase in data volumes and processing demand;



- Polarization of radiation can be further exploited in many areas, for example in Synthetic Aperture Radar imagery;
- Combinations of active and passive measurements with formation-flying spacecraft provide novel insight into physical processes in the atmosphere: one could also expect that those measurements would help to better define atmospheric initial conditions for numerical modelling; better coverage in space and time with such measurements will be beneficial for capturing rapid hydrological processes such as the temporal evolution of water vapour fields and clouds;
- Radar scatterometry of the ocean could be utilized to derive scales of ocean circulations smaller than currently possible which will benefit mesoscale modelling and the study of ocean circulation in coastal regions; radar scatterometry can be supplemented by GNSS-based reflectometry;
- The radio-occultation technique can also be generalized, in using additional frequencies (beyond the current L1, L2 and L5 GPS frequencies) to maximize the sensitivity to atmospheric variables, and monitoring more systematically the ionosphere including ionospheric scintillation.

Satellite observations are also determined and constrained by the choice of orbit; more diversity will be possible in this respect, too, thanks to a wider community of space faring nations. The benefit of a larger number of space-faring nations and entities can be enhanced with a high level planning aiming at the complementarity of individual space observations. Clearly such an international and collaborative process could be pursued under the auspices of WMO. This planning aims to make the various satellite programmes complementary and interoperable to ensure and enhance the robustness of the overall system. The future space-based observing system should rely on the proven geostationary and low-Earth orbit sun-synchronous constellations, but also include:

- Highly elliptic orbits that would permanently cover the polar regions;
- Low-Earth orbit satellites with low or high inclination for a comprehensive sampling of the global atmosphere;
- Lower-flying platforms, for example with small satellites serving as gap fillers or for dedicated missions which are best realized that way.

Manned space stations (e.g. the ISS) could be used for demonstration of new sensors, and, in the overlap region of space-based and surface-based observing systems, sub-orbital flights of balloons or unmanned aerial vehicles will also contribute.

Rigorous instrument characterization and improved calibration are prerequisites for an improved error characterization of the observations. Reference standards (on-ground or in-orbit), will enhance the quality of data from the whole system. A reference system in space would have the advantage of providing a single reference for other satellites on a global scale. Measurement traceability will also be important for the use of future space-based observations for climate monitoring and modelling, which also puts priority on ensuring long-term performance stability, comparability of new sensors with heritage datasets, long-term continuity of Essential Climate Variables, and generation and long-term preservation of

Fundamental Climate Data Records. Accuracy requirements for reference standards should consider the full range of research and applications for space based Earth Observations. Generally speaking, calibration references should be an integral part of the system, including Earth surface targets, in-orbit reference standards, and lunar observatories to use the Moon as a transfer standard. Dedicated calibration reference missions will provide intercalibration standards with good spatial and temporal coverage.

Regarding climate observations, it is expected that the operational meteorological satellite systems remain the core of the space-based climate observing system. Therefore, satellite agencies are encouraged to develop new satellite instruments with climate applications in mind; especially calibration, instrument characterization, and accuracy as well as consistency and homogeneity of long time series should be realized. The GCOS Climate Monitoring Principles need to be adhered to. Essential Climate Variables should be produced in fulfilment of established key requirements for climate monitoring. In view of the existing gaps in ECV monitoring, research space agencies should develop missions that fill those gaps over and above a continuous improvement of the existing monitoring of ECVs.

Observation 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. The importance of the Earth cycles is reflected in the 2016 GCOS Implementation Plan and helps to identify gaps and where ECVs contribute to fundamental understanding of the cycles <sup>5</sup>.

As highlighted earlier, an important future aspect is a faster path toward a full exploitation of new observing systems. Experience has shown that the full utilization of satellite data for applications and services is often only achieved years after launch, and hence the full benefit to the user community is only realized with delay. Satellite agencies are encouraged to create measures which support the full use of satellite data as soon as possible during the utilization phase of a satellite programme. The established reference for best practices also provides some useful guidance <sup>6</sup>.

It will also be essential to regularly measure the performance and impact of all components of the space-based observing system. Such a framework does exist for the impact of satellite observations on NWP with the quadrennial 'WMO Workshops on the Impact of Various Observing Systems on Numerical Weather Prediction (NWP)'. Satellite agencies could complement those regular WMO workshops with additional systematic impact studies with NWP centres. The success of those established workshops calls for similar ways of assessing the impact and benefit of satellite data for other applications.

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<sup>5</sup> GCOS 2016 Implementation Plan, GCOS-200 (GOOS-214), WMO 2016, pp. 325.

<sup>6</sup>Best Practices for Achieving User Readiness to New Meteorological Satellites  
[http://www.wmo.int/pages/prog/sat/documents/SAT-GEN\\_ST-15-SATURN-Reference-User-Readiness-Project-March2016-Final.pdf](http://www.wmo.int/pages/prog/sat/documents/SAT-GEN_ST-15-SATURN-Reference-User-Readiness-Project-March2016-Final.pdf)

Using a diversity of orbits will improve sampling the Earth's environment and remove sampling biases that a single source of measurement can introduce. They will facilitate simultaneous observations of several variables/phenomena, as well as multiple observations of the same phenomenon, both with benefits to applications. Multiple orbits will also increase the overall robustness of the system, but require a special effort on interoperability (on the provider side) and agility (on the user side). The diversity of mission concepts goes along with a diversity in programmatic approaches: the overall system should be composed of, on the one hand, the classical series of recurrent large satellite programmes which provide a solid and stable foundation over two decades, and on the other hand, smaller satellite programmes with shorter life cycles, more limited scope, more experimental payloads, and with faster, more flexible decision processes. The latter are the natural way to demonstrate novel observing techniques.

Faster realization of new capabilities and, where applicable, transition of new observational capabilities into operational applications will be required.

The need to maintain continuous data records for real time and for reanalysis purposes calls for robustness of the whole data chain: contingency plans need to ensure continuity and regularly assess and thus minimize the risk of sensor gaps; data processing infrastructures require protection against damage or intrusion through appropriate IT security measures.

IT evolves at a fast pace and assumptions about its status in 2040 are not possible. It is however fair to presume that satellite data management and data access will remain a challenge over the coming decades, as progress in information technology is constantly challenged by the rapid growth of data volumes, and by the increasing timeliness of data delivery required by users. At the same time, for building the historical record, long-term data preservation of these data must be managed. Higher connectivity and more providers of satellite data raise the question of interoperability and IT security that must be addressed with very high attention. Handling the growth of data volumes requires continuing expansion of telecommunications capacity. Trade-offs need to be made between exchanging data and exchanging products derived from the data, which raises the question of where the processing is performed, and how it is controlled. The prospect of distributed processing using multiple data sources is critically dependent on consistent data representation, detailed quality information, and comprehensive, standardized metadata. WMO provides a framework in the area of data management, for developing best practices and fostering cooperation with the goal to achieve maximum overall efficiency and quality.

WIGOS comprises a number of components which make use of a wide range of different radio frequencies for observations and data distribution. The crucial dependency on radio-frequencies implies the urgent need for preservation and protection of relevant radio-frequency spectrum resources. Thus, the protection of frequencies used for meteorological purposes is of vital interest to the international meteorological community, and to this end, WMO partners with the International Telecommunications Union (ITU) through the framework of the World Radio Conference (WRC). It is a permanent task in view of the continuous threats arising from the pressure to use those frequency spectra for other, mostly

commercial applications with detrimental effects on the long-term usability of those frequencies by meteorological and their related systems.

#### **4. Evolution of satellite programmes**

The space-based observing system will continue to rely on both operational and R&D missions, which are pursuing different objectives and are optimized along different priorities. This is a good basis for complementary international cooperation: operational users are encouraged to make use of R&D mission data, and R&D missions may benefit from flight opportunities on operational programmes. Moreover, the transition process from mature research programmes to operational missions should be systematically supported and reviewed while considering the technological maturity (robustness, availability, affordability), the operational maturity (possible long-term and real-time service continuity), the user maturity (evidence of a user community and applications with demonstrated benefit), and organizational maturity (established structures and mechanisms for user-provider interaction on requirements, system specifications, feedback, assessment of benefits, and funding schemes).

As the number of space-faring nations increases, there are growing opportunities to aim at a wider distribution of the space-based observation effort among WMO Members. This opportunity has associated challenges, for example the need for increasingly strong international cooperation required to avoid duplication of efforts and to ensure the interoperability of all components. To ensure operational continuity and avoid any gaps in addressing user needs, it is important that the space-based observing system be comprehensive and resilient to unexpected losses of instruments. The necessary redundancy in the system could be achieved with missions from emerging space-faring nations. While the WMO Space Programme, supported by the Coordination Group for Meteorological Satellites (CGMS), is an overall framework for global coordination, different models will be pursued to implement truly international satellite programmes: bilateral cooperation between agencies, intergovernmental regional programmes such as those of EUMETSAT and ESA, new regional initiatives (e.g. a potential future African Space Programme) or consortia under private law with governmental stakeholders (like e.g. the current DMC constellation or CLS-Argos).

Another evolution to be considered with attention is the role of the commercial sector. While satellite industry has so far most often assumed a role of contractor delivering a system to the governmental customer, industry might act in different ways in the future: for instance as implementing agent of the government to deliver data rather than systems; by sharing financial and technical risks in a different manner, e.g. through public/private partnerships; by implementing satellite missions on a purely commercial basis. These approaches could open opportunities to enhance the observing system. For WMO and user communities, there are also risks associated with a changing role of industry which should be anticipated and addressed carefully, in the following areas:

- Limitations to the exchange of data due to its commercialization, resulting overall in a lower availability of data;
- Lack of publicly-available information on the detailed technical specifications of the system, lack of visibility of processing software, resulting in loss of traceability, reliability and credibility of the science behind the data. This could undermine user uptake and readiness;
- Risk that potential benefits of commercial initiatives in the short-term undermine decision processes, funding mechanisms and sustainability of long-term national or regional programmes which are essential to meet national, regional or global requirements.

Given the opportunities and risks, it is important to identify the conditions under which commercial initiatives could make a successful contribution to the global space-based observing system such that it serves the requirements of WMO. There is a continuing need for governmental commitments by WMO Members, implemented by governmental agencies or any other government-designated agent, to preserve the possibility of coordinated, global optimization of the system, including gap assessments and contingency planning, international data exchange and interoperability under WMO auspices. International exchange of observational data in due time among Members has been critical for the excellent advances over the past decades witnessed in meteorology, climate and related sciences, having led to improved skill of global prediction models and improved warnings. This has been achieved thanks to global cooperation, duly considering the global nature of the discipline. WMO Resolution 40 (Cg-XII) provides a framework for the international exchange of data. It is expected that global data exchange will remain a key requirement to inform global and regional applications, and data policies should facilitate such exchange.

Without assuming to coordinate private sector initiatives, the WMO Vision can have a beneficial influence on the provision of observations by commercial operators through setting overall system aims and priorities, highlighting the importance of data quality and interoperability standards, and advocating full visibility of the science behind the data. The latter is an essential element to verify the quality of data and products. The success of weather forecasting and warnings relies on the near-real-time availability of global data because they are a prerequisite for weather forecasting with numerical models. Many studies on the benefit of observations – notably on satellite observations – have demonstrated how much modern societies gain from good weather forecasting and continuous weather awareness, e.g. for risk reduction and planning of many weather dependent businesses.

It will be important that WMO Members continue to have governmental control over the elements of a WMO-coordinated backbone observing system that keeps responding to evolving critical requirements, while acknowledging that initiatives from the private sector could enhance the system and increase its resilience in providing additional capacities or other capabilities.

## 5. The Vision

Trying to outline the space-based observing system envisioned for 2040, the first difficulty for space agencies is to anticipate and understand the user needs 25 years ahead, and for users to anticipate the potential future capabilities. Below, an outline is given of a possible configuration of the Vision. Rather than prescribing every component, a balance has been struck between being specific enough to provide clear guidance on how to achieve a robust and resilient system, while also acknowledging and welcoming additional capacities or new capabilities which could arise from opportunities and initiatives that can currently not be anticipated.

The proposed Vision consists of 4 components. Three of them describe components of a system that would fulfil the Vision 2040. The fourth one refers to additional capacities and capabilities which could emerge in the future:

1. A detailed specified backbone system, the basis for Members' commitments, addressing the vital needs for data critical to satellite applications with pre-determined orbital configuration and measurement approach. This specified backbone should as a minimum include all the elements of the 2025 Vision and of the current CGMS baseline with a few necessary additions and improvements; it would ensure the long-term stability of the system; the elements are listed in Table 1 as Component 1;
2. An equally important component to provide other critical data is defined in a more open way, i.e. without predetermining the final orbital configuration or measurement approach, in order to preserve the flexibility necessary to optimize the system based on latest demonstrated technologies and impact studies; those are listed in Table 2 as Component 2 of the backbone system;
3. Operational pathfinders, and technology or science demonstrators should be planned, to pave the way for future evolution of the system until and beyond 2040; they could inform user requirements beyond those currently recognized through their successful demonstration; the currently envisaged observations are listed in Table 3 as Component 3; this category of missions should include process study missions, for which the content and duration would have to be determined on a case by case basis, depending on process cycles considered. Such missions could rely on a diverse range of platforms. For instance, nanosatellites may be used for demonstration or science missions, and also for contingency planning as gap fillers, without excluding the use of nanosatellites also in Component 2 missions; at the other end of the platform size spectrum, the use of orbiting platforms (comparable to the International Space Station) can also be an option for demonstration or science missions;
4. Component 4 consists of additional capacities and other capabilities contributed by WMO Members and third parties including governmental, academic or commercial initiatives that could augment the backbone elements and thus enhance the global observing system and its robustness. Complementarity to what already exists as well as enhancing resilience should be the guiding principles. WMO could support these contributions without necessarily being involved in their coordination. WMO could



recommend standards and best practices that the operators may consider to comply with in order to maximize the benefits of their contributions to the community.

It is worth noting that the grouping of observations into four components does not imply sequential priorities, i.e. it is not the idea that all Component 1 observations should be realized before elements of other Components should be addressed. The major difference between the Components is the current consensus about the optimal measurement approach and especially the demonstrated maturity of that approach (there is stronger consensus for Component 1 than for Component 2). It is likely that the boundaries between the Components will not be rigid: it is possible that over the years between now and 2040, some observations currently identified as being in Component 2 could become part of Component 1. It is expected that this Vision will be revisited well before 2040, therefore there should be ample opportunity to reassess the assignment of observations to Components well before 2040.

Table 1:  
**Component 1: Backbone system with specified orbits and measurement approaches**

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

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
<b><i>Geostationary ring</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; aerosols; snow cover; vegetation cover; albedo; atmospheric stability; fires; volcanic ash
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
<b><i>Low-Earth orbiting sun-synchronous core constellation in 3 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; aerosols; snow and ice cover; vegetation cover; albedo; atmospheric stability
MW imagery	Sea ice parameters; total column water vapour; precipitation; sea surface wind speed [and direction]; cloud liquid water; sea/land surface temperature; soil moisture
Scatterometers	Sea surface wind speed and direction; surface stress; sea ice; soil moisture
<b><i>Low-Earth orbit sun-synchronous satellites at 3 additional Equatorial Crossing Times, for improved robustness and improved time sampling particularly for monitoring precipitation</i></b>	
<b><i>Other Low-Earth orbit satellites</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 topography
IR dual-angle view imagers	Sea surface temperature (of climate monitoring quality); aerosols; cloud properties
MW imagery with 6.7 GHz	Sea surface temperature (all-weather)
Low-frequency MW imagery	Soil moisture, ocean salinity, sea surface wind, sea-ice thickness
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/ top height/ particle distribution/ amount, 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
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; snow and ice parameters; permafrost
SAR imagery and altimeters	Sea state, sea ice parameters, ice sheets, soil moisture, floods, permafrost
Gravimetry missions	Ground water, oceanography
<b><i>Other missions</i></b>	
Solar wind in situ plasma and energetic particles, magnetic field, at L1	Energetic particle flux and energy spectrum (Radiation storms, geomagnetic storms )

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
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:

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

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
GNSS reflectometry missions, passive MW, SAR	Surface wind and sea state, permafrost changes/melting
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
Interferometric radar altimetry	Sea ice parameters, freeboard/sea ice thickness
Sub-mm imagery	Cloud microphysical parameters, e.g. cloud phase
NIR imagery	CO <sub>2</sub> , CH <sub>4</sub>
Multi-angle, multi-polarization radiometers	Aerosols, radiation budget
Multi-polarization SAR, hyperspectral VIS	High-resolution land and ocean observation
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 parameters; 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)
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
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:

**Component 3: Operational pathfinders, and technology and science demonstrators**

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
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;

<b>Instruments:</b>	<b>Geophysical variables and phenomena:</b>
	cloud amount, water content and top height/temperature; atmospheric composition (aerosols, ozone, greenhouse gases, trace gases)
Solar coronal magnetic field imagery, solar wind beyond L1	Solar wind, geomagnetic activity
Ionosphere/ thermosphere spectral imagery (e.g. GEO, HEO, MEO, LEO)	
Ionospheric electron and major ion density	
Thermospheric neutral density and constituents	

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**DRAFT REVIEW SCHEDULE**  
**Vision for the WIGOS Space-based Components in 2040**

<b>Version used</b>	<b>Review body</b>	<b>Comment Period</b>	<b>Remarks</b>
V.20160119	PTC-2016	19-20 Jan 2016	Comments received
	CM-13	21-29 Jan 2016	Comments received
	EUMETSAT	29 Jan- 5 Feb 2016	No response
V.20160119	IPET-SUP-2	23-27 Feb 2016	Comments received
V.20160119	Space weather task team of CGMS	12 Feb – 15 May 2016	E-mail by Secretariat on 12 Feb 2016
V.20160119	WMO CBS IPET-OSDE-2	11-14 Apr 2016	
	WMO CBS ICT-IOS-9	18-21 Apr 2016	Secretariat to subsequently generate V0.2 , using all comments received thus far
V0.2	CGMS -44	20 May – 8 Jul 2016	Open for comments by CGMS before and after CGMS-44; Secretariat to subsequently generate V1.0
V1.0	CBS-16 (23-29 Nov 2016)	1 Sep – 1 Dec 2016	Secretariat to subsequently generate V1.1
V1.1	WMO Members, technical commissions, other user communities, ICTSW, CEOS and CGMS Agencies	Q1-Q2/2017	Letter by WMO Secretary-General in Q1 2017
	Joint ET-SAT-11 / IPET-SUP-3 Meeting	3-7 Apr 2017	To discuss status of Vision
	70 <sup>th</sup> WMO Executive Council	May/June 2018	To endorse final draft, for submission to Cg-18
	18 <sup>th</sup> World Meteorological Congress	May/June 2019	To endorse Vision

**Annex II****VISION FOR THE SURFACE-BASED COMPONENTS OF WIGOS IN 2040**  
**Draft version 7.1, 12 October 2016****PREAMBLE**

This Vision provides high-level goals to guide the evolution of the WMO Integrated Global Observing System (WIGOS) in the coming decades. These goals are intended to be challenging but achievable. The Vision addresses an important area within the WMO Strategic Plan<sup>7</sup>.

The future WIGOS will build upon existing sub-systems, both surface- and space-based, and capitalize on existing, new and emerging observing technologies not presently incorporated or fully exploited. Incremental additions to the WIGOS will be reflected in better data, products and services from the National Meteorological and Hydrological Services (NMHSs).

WIGOS will be a comprehensive “system of systems” interfaced with WMO co-sponsored and other non-WMO observing systems, making major contributions to the Global Earth Observation System of Systems (GEOSS); and will be delivered through enhanced involvement of WMO Members, Regions and technical commissions. The space-based component will rely on enhanced collaboration through partnerships such as the Coordination Group for Meteorological Satellites (CGMS) and the Committee on Earth Observation Satellites (CEOS). Portions of the surface- and space-based sub-systems will rely on WMO partner organizations: the Global Terrestrial Observing System (GTOS), the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and others.

The scope of these changes to the WIGOS will be major and will involve new approaches in science, data handling, product development and utilization, and training.

The Vision addresses the observational needs for all application areas supporting the activities of WMO and the WMO Members. The respective roles of traditional NMHSs, research organisations, other government agencies and entities from the private sector in acquiring, processing and disseminating meteorological information are undergoing very rapid change, and it is impossible to predict future evolutions in this area. The Vision therefore does not prescribe the specific implementation agents. However, it is based on the general WMO principle that meteorological services - in particular weather forecasts, watches and warnings, and guidance on climate change, adaptation and mitigation - is a public good and should be provided to the citizens of all nations free of charge.

This Vision supersedes the “Vision for global observing systems in 2025”<sup>8</sup>, which has been an important WMO guidance document but is now becoming less useful for guiding long-term strategy and planning. Also, the new Vision embraces the broadened scope of WIGOS, in terms of application areas supported and their anticipated evolution, and reflects updated information on observing technologies and their expected development.

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<sup>7</sup> WMO Strategic Plan (date), Expected Result no.xx: “Improved observations and data exchange: Enhanced capabilities of Members to access, develop, implement and use integrated and interoperable Earth- and space-based observation systems for weather, climate and hydrological observations, as well as related environmental and space weather observations, based on world standards set by WMO”

<sup>8</sup> Footnote ref to Vision 2025.



This document addresses only the surface-based components of WIGOS. It will be merged with the equivalent document for the space-based components of WIGOS to provide a “Vision for WIGOS in 2040”.

## 1. GENERAL TRENDS AND ISSUES

User requirements for observations, to meet the needs of WMO Programmes and co-sponsored Programmes, will be documented through the Rolling Review of Requirements (RRR) process<sup>9</sup> in the “OSCAR/Requirements” database<sup>10</sup>. This Vision responds to the currently-stated requirements of WMO Applications Areas and attempts to anticipate the major evolutions of these requirements.

The Observing Network Design (OND) Principles of WIGOS now form part of the Manual on WIGOS<sup>11</sup>. The evolution of the observing system components of WIGOS will be guided by these Principles, which are copied as Annex A of this Vision, and will be influenced by the following general tendencies.

### Response to user needs

WIGOS will:

- Provide observations when and where they are needed in a reliable, stable, sustained and cost-effective manner;
- Respond to users’ requirements for observations with improved spatial and temporal resolutions and timeliness;
- Reflect the need for observations of high quality and for improved levels of quality control, including user feedback mechanisms;
- Evolve in response to a rapidly changing user and technological environment, based on improved scientific understanding and advances in observational and data-processing technologies.

### Integration

- WIGOS will provide observations to support the full range of WMO Programmes and co-sponsored Programmes. This include operational weather forecasting, and also other applications within climate monitoring, ocean applications, atmospheric composition, hydrology, space weather, weather and climate research, and other application areas within WMO Programmes as they emerge;
- Integration will be developed through the analysis of requirements and, where appropriate, through sharing observational infrastructure, platforms and sensors, across systems and with WMO Members and other partners;
- Surface- and space-based observing systems will be planned in a coordinated manner to serve, in a cost-effective way, a variety of user needs. Surface- and space-based systems will increasingly complement each other, both in terms of data coverage and for calibration and quality control;
- As far as is possible, non-NMHS observations will be integrated into WIGOS, consistently with WIGOS principles and technical regulations;

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<sup>9</sup> Footnote ref to RRR process

<sup>10</sup> Footnote ref to OSCAR/Requirements

<sup>11</sup> Footnote ref to Manual on WIGOS, section on OND Principles

- WIGOS metadata will be collected, exchanged, recorded, standardized and quality monitoring will be implemented across all WIGOS component observing systems.

### **Expansion**

- There will be an expansion in both the user applications served and the geophysical variables observed;
- This will include observations to support the monitoring of Essential Climate Variables, adhering to the GCOS climate monitoring principles;
- Sustainability of new components of the WIGOS will be secured, with some mature R&D systems integrated as operational systems;
- 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 targeted 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 be made 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 automatic 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 forms, 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;
- Similarly, small inexpensive sensors will be developed to measure a broader range of geophysical variables.

### **Consistency, continuity and homogeneity**

- There will be increased standardization of instruments 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;

## 2. THE SURFACE-BASED COMPONENT

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 spacing which will increase in data-dense areas, and taking account of observations available from other profiling systems.</li> <li>• Profiles from radiosondes will be delivered at higher vertical resolution, as required by applications.</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>• Automated sonde systems will be deployed at remote locations.</li> <li>• Targeted dropsondes will continue to be used and may evolved into air-deployed UAVs.</li> <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.</li> </ul>
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)	<ul style="list-style-type: none"> <li>• Global coverage from several regional aircraft-based observing (ABO) programmes - expansion of current (regional) programmes, development of new (regional) programmes covering data sparse regions.</li> <li>• The ABO Programme achieves 500,000 vertical profiles per day, with humidity measurements, and almost evenly distributed among all WMO Regions.</li> <li>• ABO systems expected to be among the basic aircraft systems in newly manufactured commercial aircraft to maximize aviation safety and efficiency, for modernized navigation systems and Air Traffic Management (ATM) and to provide high resolution data. Activation on request.</li> <li>• ABO-generated observations transmitted in real-time during flight, to be received by ATM and aircraft flying in neighbouring air space, displayed in cockpit.</li> <li>• Aircraft fly at higher altitudes (environment, separation) providing profiles with data higher in the atmosphere.</li> <li>• Globally integrated NMHS- and non-NMHS ABO system ABO observations (semi-)online distributed on internet for general public information via dedicated apps.</li> <li>• Flexible adaptation of ABO systems to user requirements by the use of geographically distributed optimization systems for optimal and cost-effective global coverage.</li> <li>• Aircraft-to-ground communication to be two-way broadband allowing cheap and constant communication and transfer of ABO data at 3 seconds interval and other flight operations information, throughout flight.</li> <li>• Optimized data communication protocol and message format.</li> <li>• Aircraft onboard weather radar data is down-linked in ABO to supplement fixed site weather radars.</li> <li>• AMDAR (-equivalent) Onboard Software (AOS) adapted to latest development in avionics and aircraft-to-ground communication and ready for new aircraft generations (digital systems, navigation).</li> <li>• Sensors newly developed and mounted on (commercially applied) Unmanned Aerial Vehicles (UAVs) providing</li> </ul>

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
		<p>vertical profiles in oceanic regions where commercial aircraft do not provide ascents/descents.</p> <ul style="list-style-type: none"> <li>● Large commercial aircraft fleet equipped to conduct operationally long-term near real-time in-situ observations of atmospheric composition and cloud particles on a global scale, integrated with ABO data.</li> <li>● Verified and quantified benefits of using water vapour data in on-board anti-icing protection, avoidance of high-altitude ice crystals, and aircraft engine performance optimization.</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 and will be extended.</li> <li>● Wind measurements from cost effective Doppler-Lidar will be increasingly used for measurements in the boundary layer.</li> <li>● Raman-Lidar deliver humidity and temperature profiles of high accuracy, operational reliable systems will be available.</li> <li>● Differential Absorption Lidar deliver high resolution humidity profiles, first systems for operational use will be available in near future.</li> <li>● Microwave Radiometers have been proven to deliver information on temperature and humidity, but with limited vertical resolution.</li> <li>● Enhanced automated cloud detection technology to heights above 6000m.</li> <li>● Cloud radar (Ka-band or W-band) will be used for improved measurements of thunderstorm and strong precipitation.</li> <li>● Data from automated profile systems nationally disseminated/centrally archived.</li> <li>● Establish/maintain training programs for sound manual observations to augment automated and remotely sensed observations for cloud observations.</li> <li>● Improved methods for combining surface and space-based cloud observations.</li> <li>● Increased use of video cameras (e.g. at airports) to support local forecasting, including nowcasting and aviation meteorology.</li> </ul>
Atmospheric composition upper-air observations	Atmospheric composition variables (aerosol variables, ozone, greenhouse gases, precipitation chemistry variables, reactive gases)	<ul style="list-style-type: none"> <li>● Restore and maintain full global network of operational ozonesondes through GAW and cooperation with international partners.</li> <li>● Expanded use of automated drones for making air quality measurements.</li> <li>● Ozone and PM2.5 measurements extended to more developing nations.</li> <li>● Aircraft in ABO Programme begin to be equipped to measure these variables – see above.</li> </ul>
GNSS receiver observations	Humidity	<ul style="list-style-type: none"> <li>● Networks of ground-based GNSS receivers extended across all land areas to provide global coverage of total column water vapour observations, and the data exchanged globally.</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 a high location accuracy, significantly improving coverage in data sparse regions including oceanic and polar areas.</li> <li>● High-resolution lightning detection systems with a higher location accuracy, cloud-to-cloud and cloud-to-ground</li> </ul>

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
		<p>discrimination will support nowcasting and other applications.</p> <ul style="list-style-type: none"> <li>• Common formats and lightning observation archives will be developed.</li> </ul>
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>• 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.</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> </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>
Drone-based observations	Wind, temperature, humidity, pressure	<ul style="list-style-type: none"> <li>• Facilities for drone-based observations (land, coastal, ships) will be developed.</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; surface radiation variables; soil temperature; soil moisture	<ul style="list-style-type: none"> <li>• Tiered networks established; climate reference networks, baseline networks (including RBON), and comprehensive (which include non-NMHS and volunteer observing networks/national mesonets).</li> <li>• Collect, archive, and provide access to crowd-sourced near-surface observations; integrate with NMHS and other observations as part of tiered network design.</li> <li>• Automated Climate Reference Network stations (temperature and precipitation) 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 collected and globally disseminated.</li> <li>• Synergy maintained between manual and automated observations, especially for elements such as precipitation as needed to ensure sufficient spatial coverage.</li> <li>• Expanded use of automated networks to improve high temporal resolution observations.</li> <li>• Expansion of wireless or satellite data transmission for real-time dissemination from station to central facility.</li> <li>• Expansion of non-NHMS networks, including volunteer and private sector networks; automated dissemination/collection to national archive centers.</li> <li>• Maintenance of a measurement lifecycle that recognizes the importance of the full requirement of data stewardship; from data collection, metadata, and archive.</li> <li>• Increased use of video cameras (e.g. at airports) to support local forecasting.</li> </ul>
Atmospheric composition surface observations	Atmospheric composition variables (aerosol variables, greenhouse gases, ozone, precipitation chemistry variables, reactive gases)	<ul style="list-style-type: none"> <li>• Meteorology/climate measurements collocated with air quality measurements.</li> <li>• Expand global and regional measurements including through GAW.</li> </ul>
Application specific observations (road weather,	Application specific variables and phenomena	<ul style="list-style-type: none"> <li>• Urban reference networks established to measure urban meteorology/climatology.</li> <li>• Road weather networks transmit in near-real time; data collected and archived at national archive centres.</li> <li>• Soil moisture/temperature measurements at agricultural meteorological stations from near-surface to 100cm.</li> </ul>



Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
airport/heliport weather stations, agromet stations, urban meteorology, etc.)		
<b><i>Near-surface observations over rivers and lakes</i></b>		
Hydrological observing stations	Precipitation, snow depth, snow water content, lake and river ice thickness/date of freezing and break-up, water level, water flow, water quality, soil moisture, soil temperature, sediment loads	<ul style="list-style-type: none"> <li>• Automated measurement of snowfall/snow-depth further augments manual measurements.</li> <li>• Maintain existing snow monitoring sites, exchange data internationally, and provide global monitoring of that data on the GTS.</li> <li>• Expansion of automated soil moisture/temperature measurements by installing sensors at existing sites.</li> <li>• Volunteer observations of lake/river ice freeze/thaw dates globally disseminated and archived.</li> <li>• Establish and maintain reference observing stations.</li> </ul>
Ground water observations	Ground water measurements	
<b><i>Near-surface observations over ocean</i></b>		
Ground-based observing stations at sea (ocean, island, coastal and fixed platform/station locations)	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	<ul style="list-style-type: none"> <li>• Higher data rate and cheaper satellite data telecommunication for remote automated stations.</li> <li>• More coastal HF radars being used; better standardization of the instruments, and sharing of the data across borders for combining products from different sources and HF radar sources.</li> </ul>
Ship observations	Surface pressure, temperature, humidity, wind, visibility, cloud amount, type and base-height, precipitation, weather, sea surface temperature, wave direction, period and height, sea ice, salinity, currents, bathymetry, CO2 concentration, surface radiation variables	<ul style="list-style-type: none"> <li>• Commercial ships designed to facilitate the making of meteocean observations.</li> <li>• Increased use of X-Band radars for wave observations.</li> <li>• More systematic infra-red measurements from ships for satellite validation.</li> <li>• High resolution, high accurate data from Research Vessels distributed in real-time.</li> <li>• More systematic use of underway Thermosalinograph and of ADCPs (SADCP, LADCP) for near-surface current profiles from Research Vessels.</li> <li>• Use of tourist ships sailing in data sparse regions (e.g. polar regions, southern ocean).</li> <li>• Use of fishing vessels, assuming proper data policy can be negotiated.</li> <li>• Ship security issue addressed (no ship identification masking to end users).</li> </ul>

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
		<ul style="list-style-type: none"> <li>Autonomous AWS ships sailing predefined or targeted routes.</li> <li>High resolution, high accurate data from Research Vessels distributed in real-time.</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>Development of smart technology for adaptive sampling to address specific environment conditions and optimize endurance of the buoys.</li> <li>Exploitation of renewable energy power sources.</li> <li>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>Provision of high temporal and spatial resolution data.</li> <li>Global fleet of wave &amp; sea state drifters based on GNSS and Micro-Electro Mechanical System (MEMS) multiple degree of freedom technology.</li> <li>Use of acoustic sensors for the measurement of wind and precipitation.</li> <li>Vandalism prone moored buoy systems with video and/or imagery and detection of incidents and acts of vandalism; enforcement of legal measures.</li> <li>Better understanding of wave measurements from buoys through inter-comparisons in the laboratory and in the field.</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>Systematic use of 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>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>
<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>Less time at surface allowing longer life-time of the measurements.</li> <li>Systematic measurements in marginal seas.</li> <li>Deeper ocean profiles (6000m and over).</li> <li>More multi-disciplinary measurements.</li> <li>More higher resolution near-surface observations.</li> </ul>
Autonomous Underwater Vehicles (e.g. gliders)	Temperature, salinity, current, dissolved	<ul style="list-style-type: none"> <li>Capability of undertaking ocean profiles, and surveys along predefined routes.</li> <li>Capability of operating under the ice, and to transmit data in delayed mode once in reach of real-time data telecommunication system (acoustic, satellite).</li> </ul>

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
	oxygen, CO <sub>2</sub> concentration, and various bio-geochemical variables	
Sub-surface observations from drifting and moored buoys	Temperature, salinity, currents, CO <sub>2</sub> concentration, pH	<ul style="list-style-type: none"> <li>• Use of optimized acoustic profiling current meters.</li> <li>• Vandalism prone moored buoy systems with video and/or imagery and detection of incidents and acts of vandalism; enforcement of legal measures.</li> </ul>
Ships of opportunity	Temperature, salinity, ocean colour, currents	<ul style="list-style-type: none"> <li>• Commercial ships designed to facilitate the making of metocean observations (e.g. installation of XBT/XCTD autolaunchers).</li> <li>• 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>• Higher data rates, reduced cost of transmission, no need to transmit data to a surface buoy which is subject to vandalism and expensive to deploy and maintain (cost of ship time).</li> </ul>
Ice tethered platform observations	Temperature, salinity, current	<ul style="list-style-type: none"> <li>• Higher data rates, reduced cost of transmission.</li> <li>• Deeper ocean profiles (6000m).</li> <li>• More multi-disciplinary measurements.</li> </ul>
Instrumented marine animals	Temperature, salinity	<ul style="list-style-type: none"> <li>• More systematic use of instrumented marine animals (sea mammals, some fish species being tracked, turtles).</li> </ul>
<b><i>Cryospheric Observations over Sea-ice</i></b>		
Ice buoy observations	Surface pressure, temperature, wind, ice thickness	<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> </ul>
<b><i>Cryospheric observations over ice sheets</i></b>		
<ul style="list-style-type: none"> <li>•</li> </ul>		
<b><i>Other Cryospheric observations (glaciers, permafrost, frozen lakes and rivers)</i></b>		
<ul style="list-style-type: none"> <li>•</li> </ul>		
<ul style="list-style-type: none"> <li>•</li> </ul>		
<b><i>Space weather observations</i></b>		
Solar Optical observations	White light, H-alpha and Calcium K images. Sunspots, flares, filaments, prominences, coronal holes	<ul style="list-style-type: none"> <li>•</li> </ul>
Solar Radio	Coronal Mass Ejections, radio	<ul style="list-style-type: none"> <li>•</li> </ul>

Instrument / observation type:	Geophysical variables and phenomena:	Evolution and trends
Observations – Spectrograph and discrete frequencies	fadeouts, solar activity (10.7cm flux)	
Ionospheric Observations - ionosonde	Measurements of the of the ionospheres ability to reflect high frequency radio waves at various frequencies and heights.	•
Ionospheric observations - riometer	Measures the "opacity" of the ionosphere to radio noise. Absorption events.	•
Ionospheric Observations - GNSS	Total electron content of ionosphere. Ionospheric gradients, ionospheric scintillation.	•
Geomagnetic Observations	Measurements of earth's magnetic field. Geomagnetic disturbances.	•
Cosmic ray observations	Neutron monitors. Radiation measurements.	•
<b><i>R&amp;D and Operational pathfinders – examples</i></b>		
Unmanned Aerial Vehicles (UAVs)	Wind, temperature, humidity, atmospheric composition	
Aircraft based observations	Thunderstorms, total water content, radiation in different spectral ranges and directions, dust/sand particles	<ul style="list-style-type: none"> <li>• Lightning detection (EM Field &amp; RF).</li> <li>• Avoidance of fuselage/engine damage, similar to volcanic ash detection.</li> <li>• Extension usage WVM system, severe weather forecasting (rainfall).</li> </ul>
Observations from gondolas	Wind, temperature, humidity	• Constant pressure balloons operating in the lower stratosphere.
Chemistry, aerosol, wind (lidar), clouds (rain, Doppler radar)	Chemistry, aerosol, wind (lidar), clouds (rain, Doppler radar)	• Chemistry, aerosol, wind (lidar), clouds (rain, Doppler radar).



### 3. APPLICATION-SPECIFIC AND SYSTEM-SPECIFIC TRENDS AND ISSUES

[This is draft material only – the intention is to have here sub-sections covering all/most of the key Application Areas and to make generic statements about major evolutions in these Areas which will affect requirements for observations.]

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#### [Some possible items – taken from Vision 2040 Space]

- Growing role of integrated numerical Earth system modeling, which will serve many applications and cover a seamless range of forecast ranges;
- More data streams are expected to be assimilated in numerical modeling frameworks, as a result of improvements in Earth system process understanding, refined assimilation methods, and better handling of observation uncertainty;
- Sustained observations of the GCOS ECVs will provide the baseline for global climate monitoring and related climate applications;
- Seasonal-to-decadal predictions will, among others, require higher-resolution ocean sub-surface observations;
- Nowcasting, severe weather forecasting, disaster risk reduction and climate adaptation will particularly require ... [Specifics?];
- Managing and monitoring climate change mitigation as follow-up to the 2015 Paris Agreement will need ... [Specifics?];
- The integrity of the radio frequency spectrum, which is critical for remote sensing and telecommunications, needs to be preserved;
- Data processing infrastructures require protection against damage or intrusion through appropriate IT security measures.

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Potential new application areas may require special new observing systems: road meteorology, urban meteorology, chemical weather, space weather, renewable energies.

Increase in spatial and temporal resolutions towards mesoscale resolution. Networks of weather radars will be used to generate regional radar composites in near-real time in order to obtain a full ‘global’ picture of the ‘present weather’.

Observations in the PBL will be greatly improved, denser in horizontal, vertical and temporal space.

National regulations will prevent frequency interferences with illegal sources.

#### **The surface-based WIGOS components will provide:**

- Improved detection (e.g. earlier or more detailed) of mesoscale phenomena;
- High vertical resolution profiles world-wide to represent the atmospheric structure;

#### **Building resilient systems**

High quality information requires that the knowledge about the design and specification of the observing systems, and installation and maintenance of the observing networks will continue to lie with the NMHSs and partner organizations.

## **Data generation and delivery**

For better understanding of the data, more information about the surface-based observing systems and the instrument, including opensource software for data processing will be encouraged and increasingly used.

## **Other?**

### **Application specific topics:**

#### **Aerosol, atmospheric pollution, atmospheric chemical composition monitoring**

By 2040 the surface observing component of WIGOS will serve a number of new application areas (e.g. chemical weather).

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## **Annex A Observing Network Design Principles (from Manual on WIGOS)**

[To be added]

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