



HIGH LEVEL GUIDANCE ON THE EVOLUTION OF GLOBAL OBSERVING SYSTEMS DURING THE PERIOD 2023–2027 IN RESPONSE TO THE VISION FOR WIGOS IN 2040

(Draft document compiled by JET-EOSDE Working Group, supported by a consultant and experts from WMO and GCOS Secretariat, SC-MINT, GAW, SG-GBON and OceanPredict Evaluation Task Team)

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1. PURPOSE AND SCOPE

1.1 The need to respond to the Vision for WIGOS in 2040

This document provides guidance to WMO Members on the envisaged evolution of observing systems, nationally and regionally, as components of the WMO Integrated Global Observing System (WIGOS) through to 2040. The guidance primarily consists of principles of general nature that should be considered for the development of Implementation Plans by Members and other operators of observing networks. In addition, the guidance identifies urgent specific actions that arise in response to the priorities of WIGOS, WMO programmes, and our knowledge of current data gaps. The document gives a structured overview about documents relevant to the Vision for WIGOS in 2040 ([AR](#), [EN](#), [ES](#), [FR](#), [RU](#), [ZH](#)) and sets priorities for the next five years (2023–2027) to implement the scenario of the Vision for WIGOS in 2040. It is assumed that the reader of this document is aware of the content of the Vision for WIGOS in 2040.

During the development and pre-operational phase of WIGOS, a number of documents have been developed aimed at maintaining and developing all WMO component observing systems. [Annex 1](#) lists the relevant WIGOS documents, tools and regulatory material and illustrates how they are connected. This document draws information from many of these underlying documents.

The “Vision for the Global Observing System (GOS) in 2025”, approved by EC-LXI (Geneva, 2009), provided high-level goals to guide the evolution of global observing systems. The “Rolling Review of Requirements” (RRR) provides “Statements of Guidance” (SoGs) that identify key gaps in the observing systems for WMO Application Areas. The “Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP), available in WMO languages ([EN](#), [ES](#), [FR](#), [RU](#), [ZH](#)), accompanies the GOS Vision. The objectives of the EGOS-IP were to address the observational requirements of WMO weather, climate and water applications in the most cost-effective way. The implementation plan contains specific actions for the development of the space-based and surface-based WMO observing system components which were regularly reviewed. In 2018, a subset of 10 such actions were adopted by the eighteenth session of the World Meteorological Congress (Cg-18) (see [Annex 3](#)), and the EGOS-IP action list was reviewed during the preparation of this High Level Guidance document and those that remained relevant have been included in the recommendations given in [Section 2.5](#).

The progress made with the WIGOS implementation called for an update of the Vision to take into account current challenges and opportunities. With this information, National Meteorological and Hydrological Services (NMHSs), space agencies and other observing system developers will be able to adapt their planning efforts accordingly to maximize synergies and value-for-money. In extending all the way to 2040, the Vision for WIGOS takes a long-term view. To a large extent, this time horizon is driven by the long programme development and implementation cycles of specific components such as operational satellites or radar replacement programmes.

The WIGOS initial operational phase, commencing in 2020, is a response to the increased demand for meteorological, hydrological and climatological services from Members being more resilient to the socioeconomic consequences of extreme weather,

climate, water and other environmental events. WMO's Earth System approach¹, aligned with evolving user requirements and advancement of observing technology together with a foreseen increased role of the private sector and third parties, was considered in the Vision for WIGOS in 2040. Now there is a need to realign observing strategies to realize the Vision.

In accordance with [Resolution 37 \(Cg-18\)](#) on the WIGOS transition to operational status commencing in 2020, the Annex to this Resolution describes the main activities that are planned to take place from 2020 and beyond in order to develop further the system during this next period. Global Earth System observations will provide the foundation for meeting the demand for increasing seamless prediction capability from weather to climate scales based on unified modelling approaches. Furthermore [Resolution 38 \(Cg-18\)](#) requests the Infrastructure Commission to undertake the necessary planning activities that will help Members and partner organizations respond to the Vision for WIGOS in 2040. It further requests Members to take into account the Vision for WIGOS in 2040 when planning the evolution of their observing networks.

At its first session the Commission for Observations, Infrastructure and Information Systems (INFCOM) endorsed a plan for the WIGOS Initial Operational Phase (2020–2023) (WIOP). In this plan, which was then adopted by the Executive Council (EC-73/Doc. 4.2(1)), high priority has been given to those activities that will assist Members in developing and implementing WIGOS at national, regional and global level. But it also requests Members to foster a culture of compliance with the WIGOS Technical Regulations. In addition, the WIOP proposes an approach to guide Members to evolve their observing systems during the period 2020–2023 towards achieving the Vision for WIGOS 2040 (see [Annex 1](#) for more details). The WIOP includes specific activities supporting the national WIGOS implementation and the development of Regional Associations, which will not be part of the considerations of this document but will complement them.

1.2 Aim of the document

The Vision for WIGOS in 2040 presents a likely scenario of how user requirements for observational data may evolve in the WMO domain over the next several decades and an ambitious but technically and economically feasible vision for an integrated observing system that will meet them. With this information, NMHSs, space agencies and other observing system developers will be able to adapt their planning efforts accordingly and will be able to make the decisions necessary to implement this integrated system. The Vision also informs users of weather, climate, water, atmospheric composition and other related observations about what to expect over this time frame and provides guidance relating to the planning of information technology and communication systems, research and development efforts, staffing, and education and training.

The plan for the WIGOS Initial Operational Phase (2020–2023) describes the main activities that are planned to take place in the near term. Among others, a guidance document for the evolution of global observing capabilities in response to the Vision for WIGOS in 2040 will be developed (section 5.7 of the plan).

¹ WMO Strategic Plan 2020–2023 introduces WMO's Earth System approach whereby the key driver of serving implementation of the the centrepieces for national and international policymaking and action such as the 2030 Agenda for Sustainable Development, the Paris Agreement on climate change, and the Sendai Framework for Disaster Risk Reduction will increasingly demand actionable, accessible and authoritative information and services on the changing states of the entire Earth System. In this context, the Earth is being considered as an integrated system of atmosphere, ocean, cryosphere, hydrosphere, biosphere and geosphere, which informs policies and decisions based on a deeper understanding of the physical, chemical, biological and human interactions that determine the past, current and future states of the Earth.

This is the purpose of the current document: it provides High Level Guidance to help Members evolve their observing systems in the next five years (2023–2027) in a manner that is simple and easy to use by all actors, with special emphasis on Least Developing Countries, Landlocked Developing Countries and Small Island Developing States. The current guidance document identifies several areas of high priority where concrete and effective improvements of observing system capabilities can be realized and progress can be demonstrated over the next five years. The recommended actions are written in such manner as to inform decision makers and strategic planners at upper management level.

The document focusses on some key priorities, while adopting a more dynamic approach than the one adopted with the former Vision for the GOS in 2025, the Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP) and its 115 focused actions. This new approach will allow the implementation actions to be adjusted according to evolving requirements, technology and opportunities. In [Chapter 2](#) a summary of findings and recommendations from a series of international workshops on the impact of various observing systems on numerical weather prediction (NWP), as well as a synthesis of key observational gaps from the Rolling Review of Requirements Statements of Guidance, with some recommendations on what mix of technologies to use to address these gaps are provided. Thereby, priorities will be set according to the Earth System approach, with global NWP and Climate Monitoring regarded as foundational² applications, as well as to areas where substantial socioeconomic benefits can be derived, including Disaster Risk Reduction (DRR).

[Chapter 2](#) also includes guidance and obligations to implement and manage the Global Basic Observing Network (GBON) network as well as commitments of Members to broaden and enhance free and unrestricted data exchange. Other evolutionary aspects when responding to the Vision for WIGOS in 2040 are given as well in this chapter. [Chapter 3](#) suggests actions for developing a national strategy to implement the WIGOS Vision 2040. [Chapter 4](#) is on capacity development opportunities and [Chapter 5](#) presents details for a communication plan.

2. GUIDANCE ON THE EVOLUTION OF THE GLOBAL OBSERVING CAPABILITIES IN RESPONSE TO THE VISION FOR WIGOS IN 2040

WIGOS provides the global framework and the management and design tools for all contributing observing systems, in order to optimize user-driven investments for sustainable developments to deliver the environmental services related to weather, water, atmospheric composition, and climate. The main components of WIGOS comprise the Global Observing System (GOS) networks, the observing component of Global Atmospheric Watch (GAW), the observing components of Global Cryosphere Watch (GCW), and WMO Hydrological Observing System (WHOS). In addition, WMO is working with partner organizations to complement these networks in the WIGOS framework for climate monitoring and ocean observing via the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS), respectively.

The Vision for WIGOS in 2040 is a scenario for how space-based and surface-based observing systems might evolve over the next two decades to respond to evolving user requirements for observations. In addition, it addresses evolving user needs and the expected evolution of space-based and surface-based observing technologies. It is an ambitious, but technically and economically feasible plan. The Vision considers that future observing systems will build upon existing sub-systems, both surface- and space-based, while making use of existing, new and emerging observing technologies not

² foundational with the meaning of global NWP providing outputs to other WMO applications allowing WMO Members to address a wide variety of socio economic benefits.

presently incorporated or fully exploited. The Vision incorporates observations acquired from commercial operators and other third parties and considers their importance as well as the challenges involved in ensuring the free and open exchange of such data between NMHSs and other national and international partners.

The High-Level Guidance given in this document summarizes gaps identified in the current observing networks, lists specific priorities for actions over the next five years (2023–2027), and provides recommendations regarding specific developments which should be considered when implementing the Vision for 2040.

Some topics to be discussed in this chapter, such as the gap analysis in [Section 2.1](#), recommendations from NWP impact studies ([Section 2.2](#)), information on the status and procedures to expand GBON ([Section 2.4.1](#)), and new activities on data policy ([Section 2.4.1](#) and [Section 2.6](#)), give rise to specific actions for Members to develop a strategy to implement the Vision for WIGOS in 2040. Other topics covered in this chapter, such as information about cost-effectiveness of observing systems and opportunities to combine activities on the global and regional levels, will help network managers to run their networks more effectively.

2.1 Synthesis of key observational gaps from Statements of Guidance with some recommendations

To develop a consensus view on user requirements for observational data and the design and implementation of WMO integrated observing systems, WMO runs the RRR process.

The RRR process jointly reviews Members' evolving requirements for observations and the capabilities of existing and planned observing systems. As a result, through so-called "Statements of Guidance", experts in each application area consider the extent to which the capabilities meet the requirements, and they produce gap analyses with recommendations on how these gaps could be addressed. For each application area, the process consists of four stages:

- (a) Technology-free review of Members' requirements for observations, within an area of application covered by WMO programmes and co-sponsored programmes;
- (b) Review of the observing capabilities of existing and planned observing systems, both surface- and space-based;
- (c) "Critical Review" of the extent to which the capabilities (b) meet the requirements (a); and
- (d) Statement of Guidance (SoG) based on (c).

This process is repeated on an approximately 2-years cycle. The SoGs also serve as a useful resource for dialogue with observing system agencies on whether existing systems should be continued, modified or discontinued, whether new systems should be planned and implemented, and whether research and development is needed to meet unfulfilled user requirements.

A WMO Application Area describes a homogeneous activity for which it is possible to compile a consistent set of observational user requirements agreed by community experts working operationally in this area. The Application Areas currently identified are ([SoG](#), [Application Areas](#)):

- (a) Global NWP;

- (b) High Resolution NWP;
- (c) Nowcasting and Very Short-Range Forecasting;
- (d) Sub-Seasonal to Longer timescale Predictions;
- (e) Aeronautical Meteorology;
- (f) Forecasting Atmospheric Composition;
- (g) Monitoring Atmospheric Composition;
- (h) Providing Atmospheric Composition information to support services in urban and populated areas;
- (i) Ocean Applications;
- (j) Climate Monitoring (GCOS);
- (k) Agricultural Meteorology;
- (l) Hydrology;
- (m) Space weather.

The status of the observational user requirements is recorded in [OSCAR/Requirements](#) and the status of SoGs for WMO Application Areas is provided under the following link: [SoG, Application Areas. There is some variability with regard to the level of maturity of the SoGs of the various Application Areas.](#) SoGs of Global NWP, High Resolution NWP, Nowcasting and Very Short Range Forecasting, Sub-Seasonal to Longer Predictions, Aeronautical Meteorology and Space Weather are up to date. The SoG for Ocean Applications is a few years old but arrangements to obtain updates have been taken. GCW, GAW, GCOS and WHOS are working towards high level statements to be included in this document as soon as they are available.

The Strategic Plan of WMO for the period 2020–2023, adopted by Cg-18, sets overarching priorities, which must be respected when identifying key observational gaps from the SoGs. These are:

- (a) the “Earth System” approach;
- (b) priorities on socioeconomic benefits; and
- (c) reduction of disaster risk in relation to high impact weather.

As part of WMO’s Earth System approach, the Earth is being considered as an integrated system of atmosphere, ocean, cryosphere, inland hydrology, biosphere and geosphere. This informs policies and decision makers based on a deeper understanding of the physical, chemical, biological and human interactions that determine the past, current and future states of the Earth. In this regard, the Application Area of Global NWP is regarded as foundational, with its models needing data from various components of the Earth System. It is therefore given key priority. Thereby interfaces between Earth System domains have been incorporated. Improved monitoring and forecasting activities assist to reduce disaster impacts in relation to high risk weather and improve societal and socioeconomic benefits.

Priorities should also be given to monitoring and prediction on sub-seasonal to longer time spatial scales for: climate applications and services, hydrology, and chemical weather/air quality and greenhouse gas (GHGs) distribution and variability. Many of these requirements overlap with and are synergistic to common NWP variables, although there is often a need for additional summary reports (daily and monthly). There are also needs for monitoring and prediction of terrestrial, atmospheric composition (e.g., pollution), and ocean variables not typically utilized by NWP.

To summarize, the following key drivers and priorities considered in this document are:

Key drivers³:

- (a) Better protection of life & property, disaster risk and impact reduction
 - (i) High impact weather
 - (ii) Other application areas like Integrated Urban Services or ocean applications will come more into focus if the future Strategic Plan of WMO sets priorities accordingly.
 - (iii) Heat waves, drought and water scarcity;
 - (iv) Floods, Inundations (pluvial, fluvial, coastal);
 - (v) Extreme pollution
- (b) Improving societal and socioeconomic benefits
 - (i) Transportation services (Aviation, Road and Rail, Marine, inland navigation);
 - (ii) Availability and quality of water resources;
 - (iii) Climate services for mitigation and adaptation;
 - (iv) Agriculture, aquaculture services;
 - (v) Energy production support;
 - (vi) Tourism and recreation services;
 - (vii) Support to ecosystems and biodiversity;
 - (viii) Health services

Application Areas with high priority:

- (a) Global NWP, regarded as foundational application area in WMO's Earth System approach with particular attention given to GBON requirements (see [Annex 4](#) for details) and interfaces between Earth System domains:
 - (i) Atmosphere – Ocean, including sea-ice,
 - (ii) Atmosphere – Land;
 - (iii) Atmosphere – Cryosphere;
 - (iv) Atmosphere – Hydrosphere.
- (b) Climate monitoring, applications and services;
- (c) Sub-seasonal to longer range prediction;

³ These key drivers have been identified as key for this document during a JET-EOSDE meeting, this is not an exhaustive list.

- (d) Greenhouse Gas monitoring and information services for greenhouse gas emissions management,
- (e) Hydrological monitoring and Services for Water management.

The Application Areas have been selected due to the current priorities in the WMO Strategic Plan and those Earth System domains where WMO programmes have set priorities within the next five years. Other applications including Ocean and urban applications will gain more importance in the future.

In the remainder of this chapter, a synthesis of key observational gaps will be given together with recommendations on how to fill them, taking the above stated priorities into account. For the complete SoGs of the respective Application Area, see the link given above.

2.1.1 Global NWP

Global NWP systems produce short- and medium-range weather forecasts up to 10–15 days of the state of the atmosphere, with a horizontal resolution of typically 10–25 km and a vertical resolution of 10–30 m near the surface increasing to 500–1000 m in the stratosphere. Large multi-member ensembles of such forecasts provide estimates of uncertainty. Forecasters use NWP model outputs as guidance to issue forecasts of important weather variables for their area of interest. Ensemble model output is used to predict the risk for extreme or severe and damaging weather events in terms of probabilities. Such ensembles require good knowledge of the uncertainty in the NWP model and all input data including the observations. Global NWP models are also used to provide boundary conditions for regional NWP, for high-resolution models, for systems predicting air quality and atmospheric composition, and for operational oceanography and hydrology. Recent developments on coupled forecasting systems indicate the benefits of coupling ocean and sea-ice models with the atmosphere for the NWP forecasts, following the Earth System approach. Both surface-based observations and satellite observations contribute significantly to the accuracy of NWP. Satellite sounding data provide very good horizontal resolution and coverage but limited vertical resolution.

NWP models have shown strong positive impact from advanced microwave sounding instruments such as AMSU-A⁴, MHS and ATMS, and also from high spectral resolution sounders with improved vertical resolution (AIRS, IASI, and CrIS). Bias-free radio occultation measurements now complement other systems through high accuracy and vertical resolution with demonstrated significant NWP impact. Research data from the Aeolus Doppler wind lidar has demonstrated benefit in operational systems, confirming the requirement for an operational mission providing high vertical resolution wind information.

The modern data assimilation components of NWP systems are able to make effective use of both synoptic and asynoptic observations. These methods have facilitated the extraction of information from time series from low-earth-orbit and geostationary satellites, aircraft, and automated surface stations, and from measurements of cloud, precipitation, ozone, etc. Highest benefit is derived from observations available in near-real-time. Several types of in situ measurement and radar rainfall data are currently not disseminated globally. The near-real-time exchange of these observations would deliver additional information to NWP models, in particular on soil moisture, snow depth or water equivalent (SWE) of snow cover, wind gusts, precipitation (from rain gauges and radar) and ground-based GPS data.

⁴ Detailed information on satellite programmes and instruments can be found under <https://space.oscar.wmo.int/spacecapabilities>

The accurate characterization of the land and cryosphere surfaces poses specific challenges: (a) the model representation of small-scale processes affecting sea-ice, snow, solid precipitation, mixed-phase clouds and stable boundary layers, including mountain boundary layers, and their uncertainties, (b) the limited availability, maintenance/quality and real time exchange of snow and ice observations, (c) the suboptimal assimilation (typically over snow and ice-covered surfaces) of the large data volumes from polar orbiting satellites due to ambiguous signal properties and larger systematic model errors than at lower latitudes, and (d) a lack of satellite products measuring accurately in high mountain regions solid precipitation, snow depth or SWE of snow cover, glacier mass change, and permafrost at all latitudes and (e) continued coordination maximizing the benefits of cryosphere observations from space using Synthetic Aperture Radar.

The NWP community has identified the following significant priorities for improvements in the observing systems and their global transmission:

- (a) Vertical profiles of the horizontal wind vector (u,v) at all levels outside the main populated areas, particularly in the tropics, for ocean regions and in the stratosphere;
- (b) Temperature and humidity profiles of adequate vertical resolution in cloudy areas, particularly over the poles and sparsely populated land areas where satellite data utilization remains challenging;
- (c) More timely availability and wider distribution of several types of surface-based measurements, and radar data that are made but not currently disseminated globally;
- (d) Further increased coverage of aircraft data, particularly from ascent/descent profiles in the tropics;
- (e) Global dissemination of high-resolution BUFR radiosonde measurements with detailed time-space information from all radiosonde sites;
- (f) More sea-ice thickness observations, as well observations from the Arctic and the cryosphere in general on snow depth and water equivalent of snow cover;
- (g) More ocean observations (sea-surface temperature, sea-surface salinity and profile measurements) and ocean near-surface measurements are needed;
- (h) Increased spatial and temporal (target sampling period of 1 hour) coverage of certain satellite observations e.g. microwave and hyperspectral infrared sounding.

2.1.2 Sub-Seasonal to Longer Predictions

In order to provide predictions at sub-seasonal to decadal timescales in the order of two weeks to 10 years, fully coupled ocean-land-atmosphere models are generally used. Just as in weather prediction, ensemble forecasts using these coupled models give probabilistic risk forecasts of climate events. In some parts the requirements for Sub-Seasonal to Longer Predictions (SSLP) are essentially the same as for global NWP. Therefore, the SoG of SSLP focuses on elements that are important for initialization, validation, and calibration of the sub-seasonal to longer timescale predictions.

Observational capabilities in polar and mountain regions are necessary to support improved parametrization of polar and mountain processes, e.g. new observational

techniques, remote-sensing products for applications, and new strategies for network design and data assimilation in complex terrain, to address the needs of coupled land-atmosphere-ocean-sea ice prediction systems, including the initialization of coupled predictions across the interfaces. For example, the uptake of sea-ice/ocean observations in data assimilation systems for initialization is challenged by the large model and observational uncertainties (e.g. sea-ice thickness) and complex multiscale interactions between sea-ice variables.

Key opportunities summarized in the Statements of Guidance for improvements of SSLP models are:

- (a) Sea-Surface Temperature (SST) products of high quality and rapid delivery are very important for the progress of sub-seasonal to seasonal predictions. Currently the accuracy and spatial scale of such diurnal SST products are only marginally adequate. Ships and moored and drifting buoys provide surface-based observations with acceptable accuracy, but coverage and frequency are poor or marginal over large areas.
- (b) Improved estimation of precipitation over the oceans.
- (c) Accurate estimation of initial land surface conditions, such as soil moisture and snow characteristics, for predictions at sub-seasonal scale.
- (d) Stratospheric sulphate aerosol injected by large explosive volcanic eruptions have a significant impact on the global climate. Therefore, sub-seasonal to decadal predictions require geographic distribution of aerosol loading with 1–2 km vertical and monthly time resolutions.

2.1.3 High-Resolution NWP

High-Resolution (HR) NWP models produce forecasts of meteorological events with a 1–5 km horizontal resolution. Such forecasts are more detailed due to more realistic descriptions of atmospheric phenomena such as clouds and precipitation. The added detail is made possible by a finer computational grid, more detailed specification of terrain and more accurate prescription of physical processes. The models need denser and more frequent observations to specify appropriately detailed initial conditions. The data assimilation schemes for HR NWP systems often require frequent analysis, every 6, 3 or 1 hour, and therefore frequent observations with a shorter delivery delay.

HR NWP models make use of the same observations as global NWP, plus some local surface-based observing systems, mostly located over land such as weather radars. In particular, HR NWP outputs would benefit from:

- (a) Better use of cloud and precipitation observations from Doppler weather radar, including precipitation types deduced from polarimetric measurements;
- (b) Increased coverage of profile measurements of temperature and humidity in the boundary layer since this is where the model vertical resolution is highest;
- (c) Increased coverage of aircraft data, particularly from ascent and descent profiles including humidity;
- (d) More measurements of variables describing the land surface, such as soil moisture and snow depth;

- (e) Surface-based temporal and spatial high-resolution observations in urban areas, over sea or over the areas prone to high impact weather events;
- (f) Ground-based Global Navigation Satellite System (GNSS) observations giving information on total column water vapour;
- (g) Full use of high spatial resolution satellite observations, both from GEO and LEO orbits;
- (h) High-frequency Hyperspectral infrared sounder data from Geostationary orbit;
- (i) High-resolution and high-frequency Sea-Surface Temperature including representation of strong fronts and gradients induced by ocean meso and sub-mesoscale processes in coastal areas, in river plume, in upwelling, in high energetic and turbulent areas during nowcast and forecast.

2.1.4 Nowcasting and Very Short-Range Forecasting

Forecasts for the next 0–2 hours are called Nowcasting (NWC), from 2–12 hours Very Short-Range Forecasting (VSRF), and Short-Range Forecasting beyond that. Nowcasting techniques use extrapolation of observations, applying heuristic rules to modify these observations into the future, such as displacing thunderstorm cells by tracking derived vectors. With increasing lead time synoptic rules and NWP data take over. Depending on the phenomena, nowcasting and VSRF cover spatial scales from the micro-alpha (hundreds of metres to 2 km) to the meso-alpha (200–2000 km). Temporal scales are from a few minutes to 12 or more hours.

Nowcasting and VSRF techniques can be applied to many phenomena. They are most frequently used to forecast convective storms with attendant phenomena; mesoscale features associated with extratropical and tropical storms; fog and low clouds; locally forced precipitation events; wintertime weather (snow, ice, glazed frost, blizzards, avalanches); wildfires and contaminated areas by air pollution, chemical or radioactive accidents. The horizontal resolution of observations to forecast these phenomena is acceptable in some populated areas but marginal to absent in sparsely populated areas and above seas. Only a subset of all available surface observations arrives in useful time to the NMHSs. Data from weather radar networks have high temporal and spatial resolutions and deliver important information about the internal structure and movement of severe storms and are essential for detection of high impact weather in real time, but radar sites are only in populated areas and the cross-border exchange of data must be improved.

VSRFs are now more commonly being generated with high-resolution local area and regional NWP models, some of them with rapid update cycles. In recent years, nowcasting and VSRF rely more and more on blending techniques combining several data sources (both in situ and remote-sensing observation, NWP, model output statistics (MOS) data, high resolution topography, heuristic rules) in a seamless way using lead-time-dependent weights, both deterministic or probabilistic. The exploitation of modern data-driven methods (AI, deep learning) and the use of non-conventional, crowdsourcing data (e.g., smartphone data) have gained attraction to nowcasting applications. Human forecasters also play an invaluable (currently irreplaceable) role in the required VSRF time frames. Such time frames are also where the data from the “comprehensive” networks and even poor-quality data come into play to help support the human judgement.

The key observational gaps discussed here concentrate on uses other than via data assimilation and NWP, which are already covered in the previous sections. Proposals for addressing gaps for Nowcasting and VSRF are:

- (a) Additional data from many local meso-networks could be used, if the data are made widely available. (Crowdsourcing data and images for identification and nowcasting of weather-related impact);
- (b) More weather radar should be installed near, but not immediately at, sensitive areas such as airports, harbours and cities;
- (c) Radar wind profilers providing profiles with high vertical resolution at sub-hourly intervals – their geographical coverage is restricted to a few regions of the world;
- (d) New lidar systems for temperature and water vapour profiling provide accurate high-resolution vertical profiles, but currently very few instruments are operational worldwide;
- (e) ground-based lightning detection networks with good detection efficiency are available mostly only in developed countries – space-based lightning detection instruments potentially filling the gaps are in operation on recently launched GEO satellites like GOES and FY (and soon also MTG), but not yet having full global lightning detection coverage on GEO;
- (f) aircraft-based observations: accurate Aircraft Meteorological Data Relay (AMDAR) profiles are available from ascent and descent from the vicinity of airports with good spatial and temporal coverage, and flight level AMDAR observations are available from major flight routes; AMDAR observations are increasingly complemented by aircraft data from ICAO and ATM regulated systems (ADS-C and ADS-B/Mode-S);
- (g) satellite data: rapid imaging aboard geostationary satellites sampling the Earth's surface at a frame 2 ms rate is critical for nowcasting, but not fully available for all geostationary satellites. The new generation geostationary satellites are also providing lightning observations which combined with imagery data can potentially mitigate lack of radar observations. This potential should be fully explored.

2.1.5 Aeronautical Meteorology

Aeronautical Meteorological services support air traffic safety, efficiency and capacity worldwide resulting in economic and environmental benefits. The basic requirements are expressed in Annex 3 to the ICAO Convention on International Civil Aviation, Meteorological Service for International Air Navigation. Aeronautical Meteorology has a global role, where its users range from pilots, air traffic control and management to airline dispatch offices as well as airport authorities. The ICAO World Area Forecast System (WAFS) is one of a multitude of facilities and services required under ICAO Annex 3. The WAFS defines forecasts to be issued in multiple formats by two ICAO-designated World Area Forecast Centres (WAFCs), London and Washington. The global WAFS forecasts produced by the WAFCs are derived using a combination of ground-based and satellite-based observations as well as NWP models. Other types of facilities and services required under ICAO Annex 3 include (but are not limited to) the provision of meteorological observations, reports, forecasts, warnings and alerts at aerodromes and the provision of information on the occurrence or expected occurrence of hazardous meteorological conditions in en-route airspace (known as SIGMET). In some countries

these facilities and services are supplemented by nowcasting and very short range forecasting methods. The user requirements are given in the Observing Systems Capability Analysis and Review (OSCAR) WMO database.

For forecasts and warnings in the wider terminal area, surface-based measurements and ground-based remote-sensing technology has the potential to meet the requirements. These are met for large hubs in developed countries, but its high costs hamper general, global availability. Capacity development mechanisms as explained in [Chapter 4](#) of this document might improve the situation in developing countries.

At large international airports users require for new terminal forecasts and warnings for the larger approach and departure areas. Challenges in observations and thus forecasting and warning specific to aviation include observation of windshear/microbursts, turbulence, volcanic ash and SO₂ concentration and low visibility. Meso-networks, including lightning detection, LIDAR and Doppler radar with dual polarization functionality coupled with nowcasting algorithms will be requested for these airports.

Evolving user needs and changing operational environment is resulting in a progressive migration from human-made observations to fully automated observations at aerodromes.

In some countries, the production of routine and special aerodrome meteorological reports (METAR and SPECI), via human observations or fully automated observations, may be the only source of regular, reliable, high-quality surface (ground-based) observations, i.e. they may not be supplemental to the availability of SYNOP reports. Prevailing policy requires that meteorological services comprising all observations, reports, forecasts, warnings and alerts supporting international air navigation and controlled under the auspices of the ICAO Convention, that may be subject to national or multinational cost recovery, are made available only on the ICAO Aeronautical Fixed Service (AFS). As a consequence, METAR/SPECI and other types of meteorological observations/reports such as special air-reports (AIREP) are not included in the WIGOS.

2.1.6 Space Weather

Space Weather is the physical and phenomenological state of the natural space environment including the Sun, the solar wind, the magnetosphere, the ionosphere and the thermosphere, and its interaction with the earth. Originating from the Sun, the space weather disturbances evolve during their propagation through the interplanetary media before reaching the near-Earth space, disturbing the magnetosphere and ionosphere and impacting the Earth's magnetic field. Space weather events can adversely affect critical infrastructure and technologies operating in space and on earth.

Multiple types of modern technological infrastructure are affected by Space Weather. Among these vulnerable technologies are satellites, navigation and communication, electric power grid and pipeline operations, aviation and others. The start of the operational space weather service to ICAO in November 2019 has defined new high priority requirements for the continuous near-real-time data provision and for the event-based issuance of nowcast and forecast of impacts on some of these technologies and on aviation. The robustness and continuity of measurements are far from being sufficient for satisfying existing demands.

Space Weather services are provided as national efforts and by multinational consortia and organizations. The International Space Environment Service acts as the umbrella for Space Weather Centres located in different countries. Today, Space Weather services rely on both operational and research facilities, both ground-based and space-borne,

which are not fully integrated into coordinated observing networks capable of provision of near-real-time data for operational purposes. The gap analysis in the “Statements of Guidance for Space Weather Services” describes the operational requirements for six categories, i.e. Solar, Solar Wind and Heliosphere, Energetic Particles in the near-Earth Environment, Ionosphere, Thermosphere and Geomagnetic Field. See Section 2, Solar Observations, of the [Statement of Guidance](#) for recommendations on how to address the identified gaps.

2.1.7 Ocean Applications

These recommendations have been derived from a preliminary version of the SoG document prepared in 2016 and updated in 2021 by the Ocean Predict Observing System Evaluation Task Team. Main challenges are observation of ocean biogeochemistry at global scale, high resolution spatial observations and coastal observations.

- (a) Satellite provides essential information on the surface sea state to constrain ocean forecasting models of the “blue ocean” and in particular ocean physics including waves. Information on significant wave height, geostrophic currents, sea level height, temperature and since recently salinity. Mesoscale features are derived from satellite at global scale with an always increasing resolution. For satellite altimetry, to obtain a satisfactory spatial resolution (i.e. <100 km and even less for coastal areas) a combination of several instruments is required. Still the resolution for altimetry products in the coastal regions is too coarse. Next generation altimetry based on wide-swath observation (e.g., Surface Water and Ocean Topography (SWOT)) is promising for these purposes and will provide observation at higher resolution (<50 km).
- (b) In general, synergetic use of data from satellite missions and surface-based platforms are highly needed in order to develop accurate ocean products. For instance, measurements from drifters and tidal gauges, sea-surface salinity, temperature and radiometric data are needed to support the development of high-quality altimeter, ocean colour and salinity ocean products. This coordination is still insufficient. This is particularly critical in some regions like coastal areas and the polar ocean.
- (c) The dynamics of the coastal ocean is strongly governed by its lateral boundaries. The quality of ocean predictions can be adversely affected by a too coarse resolution forcing. A high-resolution information on the heat, water, nutrients fluxes from the atmosphere and land would improve the performances of coastal forecasting systems. For ocean wave calculation, the accuracy of the satellite surface wind data is insufficient, especially in the stormy wind speed range. Coastal dynamics can be observed by high frequency radar measuring surface current.
- (d) Assimilation of sea-ice concentration observed by satellite microwave radiometers such as SSMI/SSMIS or AMSR/AMSR2, etc. is often conducted in sub-seasonal to longer term prediction systems, and it has a crucial impact on accurate estimates of initial sea-ice state. The current observation capacity during the freezing season is sufficient if the current quality of sub-seasonal to longer prediction systems is considered. Some research indicates that assimilation of sea-ice thickness is effective to improve predictions of the sea-ice extent in ice-melting seasons.
- (e) 6-hourly sampling of scatterometer measurements for surface wind.

- (f) The quality of the sea-surface ocean prediction improves if ocean models assimilate surface and sub-surface data. The advent of autonomous platforms like Argos, gliders, buoys and moorings has improved the quality of ocean forecasts delivering observations in (N)RT mode. In particular, autonomous platforms with sea-ice detection are particularly useful in the polar ocean where the observational gap (in real-time) hinders the reliability of sea-ice forecasts with impact on NWP.
- (g) During the next decade, a boom of (sub-)surface-based (e.g. BGC Argo floats, gliders) and satellite biogeochemical observation is expected, enhancing the forecasting capabilities of the "green ocean" (biochemistry and ecosystem).

2.1.8 Climate Monitoring

A global system of climate observations, both surface- and satellite-based, provides many benefits to all countries and to society. They support the outputs of global models, forecasts and projections. Emergency warning systems use local models and observations that are embedded in a global modelling system and planning often uses models downscaled from global results. Climate-related policy is driven by data: the United Nations Framework Convention on Climate Change (UNFCCC) is a science-based process that uses IPCC assessments of the state of the climate based on the climate observations as well as observation-based reports on the state of the climate. Securing and extending the observing systems needed for the long-term monitoring of the Earth System requires substantial efforts and collaboration at all levels including international organizations, national agencies, and the scientific community.

Many of the key requirements for climate monitoring are similar to the ones identified for other applications (see above). However, the requirements for climate typically go well beyond those for weather forecasting as high levels of accuracy and consistency are needed to detect long-term changes embedded in diurnal, seasonal and multiannual variations. Historical observational data from sources well distributed across the globe are required to establish the long-term trends needed to understand and better plan for future changes in climate. Historical observations are also required for climate reanalysis, with multiple benefits for climate monitoring and applications, including adaptation. Finally, monitoring of climate requires a set of observations that comprise also terrestrial and ocean ones. GCOS currently specifies 54 Essential Climate Variables (ECV) that critically contribute to the characterization of Earth's climate.

Therefore, key requirements for climate monitoring include:

- (a) sustained long-term support for a global system of climate observations;
- (b) reference observations: GCOS has established the GCOS Reference Upper-Air Network (GRUAN) and is in the process of setting up, with WMO, a GCOS Surface Reference Network (GSRN); over recent years considerable progress has been made in the implementation of GRUAN – the network has expanded considerably to include several stations in regions that were previously under-represented including the first station in the tropics and in Antarctica;
- (c) data stewardship, archiving and access: to preserve the fundamental climate data record, adequate data stewardship, archiving and access is essential; data rescue from hard copy or archaic digital formats is essential to ensure the longest possible time series of the basic data record;

- (d) exchange of daily and monthly summaries (CLIMAT and DAILY-CLIMAT messages) and of both historical and NRT data collected by Members;
- (e) inclusion of observations of several additional terrestrial and oceanic ECVs not normally measured by NMHS.

The GCOS Status Report 2021 will be published in October 2021 and provides more specific information on existing gaps. Key findings on existing gaps of this report are:

- (a) There are still gaps in the global coverage of in situ observations: surface-based observations for almost all ECVs are consistently deficient over certain regions, most notably parts of Africa, South America, Southeast Asia, the Southern Ocean, and ice-covered regions.
- (b) On-ice in situ observations remain a challenge due to logistical difficulties.
- (c) Large gaps still exist in ocean observations, in particular along continental boundaries, the polar oceans and marginal seas. Ocean subsurface measurements are critical to monitor and forecast the climate system. The decision to expand the Argo programme (ocean profiling floats) to the full water column and under sea-ice, including biogeochemical variables addresses that challenge, but the effort needs to be sustained.
- (d) Gaps in the satellite-based observations include lower tropospheric ozone to supplement the limited coverage of surface observations and to determine trends, and an instrument that measures stratospheric CH₄ profiles globally.
- (e) Observations of many ECVs are not sustainably funded. Observations such as atmospheric composition, permafrost and deep ocean depend on short-term funding with no guarantee of long-term operation.

The GCOS panels, AOPC, OOPC and TOPC, will start discussion to propose actions to improve the Global Climate Observing System and address the gaps identified in the Status Report. The identified actions will be included into the next version of the GCOS Implementation plan, to be published in October 2022.

2.1.9 Atmospheric Composition

The observing component of the GAW Programme provides global information on the chemical composition and related physical characteristics of the atmosphere. These observations support multiple applications and are needed to reduce environmental risks to society, meet the requirements of environmental conventions, strengthen capabilities to predict air quality, climate, and weather and contribute to scientific assessments in support of environmental policy⁵. GAW assists Member countries in observing and sharing atmospheric composition data. Atmospheric composition and its changes have multiple impacts on our lives and our environment. Changing greenhouse gas concentrations are well documented through observations. Data from the global network of greenhouse gas observations are disseminated by the World Data Centre for Greenhouse Gases (WGCGG) hosted by Japan Meteorological Agency. This global network is supplemented by the data from the projects undertaken by the GAW [Integrated Global Greenhouse Gas Information System](#), that looks at the greenhouse gas distribution with higher spatial and temporal resolution to support emissions estimates in support of different objectives (from urban and facility scale to national). A

⁵ Including obligations specified in the [Paris Agreement to the United Framework Convention on Climate Change \(2015\)](#) and [The Vienna Convention for the Protection of the Ozone Layer \(1985\)](#).

comprehensive network design for the studies of the carbon cycles is provided in the Global Earth Observations (GEO) [Carbon Strategy](#). In addition, the Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Virtual Constellation developed a [white paper](#) describing how estimates of CO₂ and CH₄ from space-based sensors can be integrated into a global carbon monitoring system. Greenhouse gas observations enable to track changes in climate drivers, identify emission hotspots, set up emission reduction goals, and evaluate progress made or to take further migration actions under the Paris Agreement.

Ozone observations have demonstrated the success of the treaty and the start of the ozone layer recovery since 2000 ([2018 Scientific Assessment](#)⁶). Poor local and regional air quality due to high level of atmospheric pollutants has been estimated to cause seven million premature deaths every year (World Health Organization, 2016). Data on the abundance of aerosols and reactive gases are key to determine acute health threats and are used in the estimates of the Global Burden of Disease (Shaddick et al., 2021⁷). Delivering such data in near-real-time is crucial for improved forecast accuracy that may be used to issue warnings and to guide mitigation measures. Observations are also used to establish policy measures addressing atmospheric pollutants, to monitor compliance and to assess the impact of those measures (Maas, R., P. Grennfelt (eds), 2016⁸).

Although the GAW network of observations is growing, important gaps remain (Laj et al., WMO Bulletin Vol 68 (2) – 2019). There is no observational infrastructure in large areas of the globe. Further, some observations are not shared and consequently not available to the international community, either through GAW or through other mechanisms.

While data coverage and availability represent clear challenges, the quality of the observational data is another aspect that must be considered. Some observations do not have metadata describing the quality of the data that prevents their full utilization. Observational requirements apply not only to the quality of the raw observational data. They also define the quality of the final products and services that build on them, and to the timeliness with which they are made available.

Monitoring of Atmospheric Composition covers applications related to evaluating distributions of and analysing changes in atmospheric composition, temporally and spatially, on regional to global scales. Such applications support scientific assessments and process studies and require very small uncertainty of the data and global or regional data representativeness, while the delays in the data delivery can be rather substantial to ensure high quality of the observations. There are synergies with the [GCOS observing strategy](#) and its global monitoring ECVs.

For ozone, the 2021 Ozone Research Manager's Meeting noted the need to restore and expand regular, long-term monitoring where scientific needs are clearly identified. Key regions are those of troposphere-stratosphere exchange, such as Monsoon regions, Southeast Asia, the maritime continent, and mountainous regions. Ozone and UV measurements also should be targeted to data-sparse areas (e.g. South America, Africa, and Asia), and in the inter-tropical region for accurate detection of Brewer-Dobson Circulation changes and other transport phenomena.

⁶ WMO (World Meteorological Organization), Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, 588 pp., Geneva, Switzerland, 2018.

⁷ Shaddick, G.; Salter, J.M.; Peuch, V.-H.; Ruggeri, G.; Thomas, M.L.; Mudu, P.; Tarasova, O.; Baklanov, A.; Gumy, S. Global Air Quality: An Inter-Disciplinary Approach to Exposure Assessment for Burden of Disease Analyses. *Atmosphere* **2021**, *12*, 48. <https://doi.org/10.3390/atmos12010048>

⁸ Maas, R., P. Grennfelt (eds), 2016. Towards Cleaner Air. Scientific Assessment Report 2016. EMEP Steering Body and Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution, Oslo. xx+50pp.

The global coverage requirements to monitor a wide range of atmospheric composition variables requires the use of satellite platforms for comprehensive and consistent observations. The existing combination of ground-based monitoring stations and remote-sensing data are still not enough to precisely identify the sources of many atmospheric constituents and their transport in the atmosphere.

Global monitoring of atmospheric GHG, such as CO₂ and CH₄ in support of climate monitoring, has been developed leveraging the assets from NWP and GHG satellite data collected from recent GHG observing satellites (e.g. GOSAT, OCO-2, TROPOMI). The ability has become increasingly matured, and products are being produced by major modelling/data assimilation centres such as the European Centre for Medium-Range Weather Forecasts (CAMS) and the NASA Global Modelling and Assimilation Office (GEOS).

The implementation of the Paris Agreement will require countries and sub-national entities (e.g., megacities) to take actions to reduce emissions of greenhouse gases in an optimal way. To assist them in meeting their commitments WMO has initiated the development of an [Integrated Global Greenhouse Gas Information System \(IG³IS\)](#). IG³IS combines accurate atmospheric measurements with enhanced socioeconomic activity data and model analyses to provide information to inventory builders in support of their efforts to compile and report and reduce uncertainty of national emission inventory reporting to UNFCCC.

IG³IS is building upon, integrating, and improving existing and planned surface-based measurement networks, airborne and satellite observations, modelling frameworks, and data assimilation systems, to help fill key gaps in those systems. Working with CEOS and Coordination Group for Meteorological Satellites (CGMS), IG³IS will integrate surface and airborne measurements of CO₂ and CH₄ with those from available and planned space-based sensors to develop a prototype, global atmospheric CO₂ and CH₄ flux product in time to support inventory builders in their development of GHG emission inventories for the 2023 global stocktake.

Forecasting Atmospheric Composition Change and its induced environmental phenomena covers applications from global to regional scales, with horizontal resolutions similar to Global Numerical Weather Prediction (approx. 10 km and coarser), and with stringent timeliness requirements (near-real-time). The uncertainty of these observations can be higher than in the case of monitoring. These applications include support for operations such as air quality and chemical weather forecasts, sand and dust storm warnings, wildfires plume dispersion, and haze-fog prediction. There are clear connections and synergies with many of the numerical weather prediction applications.

The numerical prediction of aerosol particle properties has become an important activity at many research and operational weather centres. This is due to growing interest from a diverse set of stakeholders, such as air quality regulatory bodies, aviation and military authorities, solar energy plant managers, climate services providers, and health professionals. [Benedetti et al. \(2018\)](#) described outstanding aerosol observational gaps, including the need for improved aerosol speciation and aerosol size distributions for modelling and data assimilation and verification.

Forecasting atmospheric composition also requires model and product validation, data for research and development, data to qualify model improvements, and other needs to support of services like Copernicus Atmosphere Monitoring Service (CAMS). Operational forecasting gaps were described by [Peuch](#) at the 2020 WMO Data Conference. These gaps exist in large parts of Africa, South America and SE Asia. There is a need for improved aerosol composition and ultrafine fraction, high-precision greenhouse gas concentrations, high-precision nitrogen oxides, volatile organic compounds and stable

isotopes. The vertical domain remains challenging. There are very few sondes, balloons and commercial aircraft platforms.

The use of satellite observations for the troposphere and near-surface measurements of atmospheric chemical composition (only for some variables) are only emerging outside of the academic domain (e.g., the recently launched South Korean Geostationary Environment Monitoring Spectrometer (GEMS) instrument). While geostationary platforms will improve our ability to monitor, forecast, and manage air quality, the current plans for the future WIGOS lack the constellation of dedicated GEO missions needed for ongoing monitoring of air quality.

Providing Atmospheric Composition information to support services in urban and populated areas leads to a very specific set of observation requirements that target megacities and large urban complexes (with horizontal resolution of a few km or smaller, e.g., city block) and, in some cases, with stringent timeliness requirements. A distinguishing feature of this category of applications is their emphasis on research in support of operational services, such as air quality forecasting, which use approaches such as pilot projects and feasibility demonstrations such as the development of a new air quality forecasting service in several Latin American cities. Comprehensive forecasting systems at the urban scale have the potential to help build resilience for these urban centres and provide early warning systems for a full suite of weather and environmental conditions.

The GAW Urban Research Meteorology and Environment (GURME) plays an important role in the development of these urban scale models which need to tightly couple meteorology, atmospheric composition, hydrology, and climate processes. In step with the development of urban systems, GURME will work with others to define the observation systems that can support the evaluation and eventually assimilation at these scales.

An important observational requirement is to determine anthropogenic emission in major urban cities. To account for sources realistically, emission inventories on human activities at relatively higher resolution are also required. The establishment of local stations to enable and enhance research and services in areas impacted by nearby emission sources will contribute to filling this gap. Local stations complement air pollution data collected by local regulatory authorities and/or may form a nucleus for building up such networks in regions which have no operational air quality monitoring in place.

IG³IS is providing large urban source regions with timely and quantified information on the amounts, trends and attribution by sector of their greenhouse gas (GHG) emissions to evaluate and guide progress towards emission reduction goals. IG³IS determines the expectations and needs of stakeholders through direct connection with city authorities and through creation of an advisory group of interested stakeholders and pilot cities. Through a number of demonstration projects, these interactions are facilitating improved measurement network design and are supporting improvements of the inventory and identity of emission anomalies.

2.1.10 Emerging Cryospheric Services

The cryosphere is the part of the Earth's climate system that includes solid precipitation, snow, sea-ice, lake and river ice, icebergs, glaciers and ice caps, ice sheets and ice shelves, and permafrost and seasonally frozen ground. It is an important component of the Earth climate system, and it affects the energy budget by exchange of heat, moisture, and via albedo-temperature feedback. The increased variability of snow cover, widespread glacier retreat, decline in sea-ice, and thawing permafrost at all latitudes and

elevations have major consequences on economies, societies and environments. Practical mitigation and adaptation strategies require accurate predictions of anticipated changes in the cryosphere, on timescales relevant to applications such as ocean and atmosphere predictions and climate monitoring. Despite major progress in recent years, currently, accurate predictions are hampered by insufficient cryosphere observations, process understanding, and modelling capacities⁹. Observations spanning several decades are required to quantify trends understanding climatic behaviour and identify changes, as different components of the cryosphere have different timescales.

In polar and mountainous regions producing accurate and reliable predictions from hours to seasons ahead is more difficult than in other regions due to specific challenges related to understanding processes, modelling and observation gaps of the cryosphere. In seasons and areas with snow and sea-ice, there is not an optimal use of available surface and satellite-based observations for weather and hydrological prediction and climate monitoring. Most existing cryosphere observations, e.g. sea-ice, glaciers, permafrost, snow, are fragmented across multiple institutions, sometimes part of research programmes, and often are not subject to standards and regulations, so have highly variable output. Use of commonly agreed standards would allow data centres and agencies to provide increased confidence for routine information provision. Many mountain regions have remained insufficiently monitored, since observing stations are sparse at high elevations, leading to an altitudinal bias, e.g. on precipitation. Hydrometric stations are disproportionately at low elevations and tend to measure larger mountain rivers, rather than headwater streams at high elevations. Furthermore, the monitoring of snow, glaciers, permafrost, and of critical tropical highland ecosystems is sparse, mostly uncoordinated, primarily, within time-bound research projects, with their data not always accessible.

Sea-Ice monitoring and prediction – Improvements are needed in sea-ice (and coupled ocean-sea ice) modelling with regards to both, the Arctic and the Southern Ocean sea ice, in particular on data assimilation and forecasting. This is hampered in part by the general spatiotemporal under-sampling of the polar oceans, especially for wide-swath of the Antarctic sea-ice zone, and difficulties in deriving and evaluating year-round accurate products of various key sea-ice parameters such as sea-ice thickness, snow depth on sea-ice and sea-ice age from remotely sensed data in both hemispheres. There are hemispheric differences in the sea-ice and its snow cover, which on the one hand make it difficult to translate direct observations into sea-ice variables, while on the other challenging the global modelling approach. The presence of sea-ice has consequences for SST and heat exchange. Uncertainty related to the onset of ice sheet instability arises from limited observations, inadequate model representation of ice sheet processes, and limited understanding of the complex interactions between the atmosphere, ocean and the ice sheet.

Operational sea-ice regional monitoring for navigation – Support of national ice services is necessary to enable routine sea-ice information for mariners to support life and safety. As Arctic sea-ice has been becoming younger and with that more variable in terms of, e.g., thickness, drift and deformation, it is increasingly critical that operational ice information services evolve to include more high precision and accuracy near real-time information on sea-ice areas and features and ice forecasting.

Glaciological modelling – Glaciological process models are needed for ice flow dynamics, changing geometries, with links to hydrological modelling. Also, there is a need for albedo data and models, understanding of particulate loading and cleansing

⁹ Hock Regine, Hutchings Jennifer K., Lehning Michael: Grand Challenges in Cryospheric Sciences: Toward Better Predictability of Glaciers, Snow and Sea-Ice; Frontiers in Earth Science, Vol 5, 2017, 64 pages, <https://doi.org/10.3389/feart.2017.00064>

processes with links to NWP for dust and particulate (e.g., black carbon, wildfire) deposition on glaciers.

2.1.11 Hydrological Services

Hydrological services are required for all aspect of water management: flood and drought risk assessment and mitigation, water supply for drinking water, agriculture, industry, hydropower, navigation, recreation/tourism and ecosystems, with direct impact on well-being of populations. The UN Sustainable Development Goal 6 (SDG 6) on water, the Sendai framework for disaster risk reduction and the Paris Agreement on climate call on improved water management.

Hydrological services encompass a large variety of data products (current status information, seasonal and long-term trends, statistics, design characteristics, etc.), forecasts and predictions from minutes to seasons, warnings including maps and charts. Such products need appropriate knowledge of current and future state of the whole water cycle, including evaporation and evapotranspiration, precipitation, soil moisture, surface and sub-surface run-off, groundwater fluxes, including water quality. WMO is developing key activities such as the HydroHub (water monitoring) and HydroSOS (Status and Outlook products) to support Members' efforts. Assessing the hydrological cycle / (water balance) requires measurements of numerous variables at all space and timescales, many of them being part of other areas (e.g. atmosphere, climate, cryosphere, ocean) of the High Level Guidance and is a good example of the benefit of the Earth System Approach.

Typical terrestrial measurements are for instance for river, lake, reservoir stage and groundwater level, discharge, flow velocity, sediment, water temperature and other chemical, physical and biological parameters. Soil moisture at different soil layers is key as well. Cryosphere parameters are listed below. Atmosphere variables are for instance rainfall, wind speed, humidity, air temperature, radiation, evapotranspiration. Ocean parameters relevant to hydrology are those measured in coastal areas and estuaries, typically water level of delta and estuaries, backwater curves and tidal dynamics, algae, biological parameters and salinization of rivers and groundwater.

Cryosphere needs special attention. Most hydrological land surface models applied in moderate climate with snow formation, polar and high mountain regions lack the representation of key cold-region processes, e.g. snowpack dynamics, snow redistribution, vertical transport of water vapour through the snowpack, energy budget, thermal interaction between snowpack and the frozen soil, glacier dynamics, Aufeis formation, seasonal dynamics of permafrost active layer depth, suppressed evapotranspiration from cold, open water, ice jams, snow dams, etc. Seasonal snowpack affects soil moisture, depth of the active layer and (spring) river discharge.

Observing requirements of the cryosphere for hydrological and water resource information as mentioned above include seasonal snowpack and accumulated SWE, year to year changes in glacial mass extent, routine river and flood observation and forecast information including ice jam flooding during freeze up and breakup, on seasonal to sub-seasonal forecasts of air temperatures and precipitation to predict accurately the timing and severity of spring breakup ice jam flooding, freeze up, observations and improved monitoring of permafrost as well as research indicating how changes in permafrost affect operational rainfall-run-off models and groundwater. As permafrost melts and the landscape changes, rainfall/run-off relationships change as well. This is poorly understood or modelled dynamically for operational uses. In the longer term, permafrost melt is a link to GHG emissions.

SWE is a crucial variable for snowmelt conditions and proper run-off modelling. Accurate retrieval of SWE is notoriously difficult in mountainous regions and needs to be improved. Also, estimation of water amounts is influenced by canopy and remains challenging during melting snow conditions, which are of high importance for water resource management, hydropower energy production, etc.

Robust seasonal snowpack observation and modelling across large domains are needed for climate change simulations.

The hydrological cycle and hydrological regimes are influenced by human activities, such as hydropower dams, pumping for irrigation, industry and drinking water, etc. Accordingly, it will be important to get data of water use (flows and volumes of abstractions, recharges, operation of water reservoirs, etc.). It is to be noted that this type of data is seldom shared, being connected to private and national strategies, and moreover often outside the remit of NMHSs. Nevertheless, coordination with other UN organizations in charge of such topics, typically FAO for irrigation, might be beneficial.

The existing WMO regulation on hydrometry network design (often at national or basin scale) must be revised in order to take into account on one hand the most recent scientific knowledge to address the complexity and interconnection of processes at all space and timescales, and on the other hand new needs from users. The concept notes on hydrological variables for GBON, the implementation of the unified data policy together with the revision of the RRR process will provide the opportunity to revise the approach for network design. This activity is part of the hydrological action plan approved by the extraordinary session of the World Meteorological Congress in 2021 (Cg-Ext(2021)).

2.2 Findings and recommendations from the series of NWP impact of observations workshops and other domains

NWP forms the basis of most weather and climate predictions and related products and services for the WMO application areas. Both surface-based observations and satellite observations contribute significantly to the accuracy of NWP. The WMO NWP Impact of Observations Workshops have significant influence on the overall development of the observing system and on the associate WMO regulatory and guidance material. The series of workshops has become a well-established forum for exchange of information about observation impact in NWP (global and regional) and the interpretation of results.

The series of workshops is a key component of the RRR process. The results inform WMO and its Members, as well as data assimilation development work at NWP centres and research institutes, on recommendations to improve and develop the space-based and surface-based observing system. The recommendations from the workshops have a significant influence on national implementation activities of Members. The recommendations from the workshops give advice on the most efficient combination of space-based and surface-based observations in the data assimilation of the NWP systems and guide WMO Members on how to operate their observing networks in a cost-efficient way.

With the Earth System approach of the WMO Strategy 2020–2023, the models operated for global NWP Application Area need observational data from various components of the Earth System. The Earth System approach therefore provides opportunity for cooperation across different domains (ocean, atmosphere, land, snow and ice, hydrology, ...).

Essentially there are three reasons to carry out observation impact studies:

- (a) optimizing the use and impact of observing network topology we have currently,
- (b) Testing of new innovative (potential) additions to the observation network (new techniques and methods);
- (c) Justifying the continued investment in existing observations capability.

In order to deliver this there is a constant effort to improve these studies.

In the following sections a summary of key activities for the maintenance and evolution of WIGOS, as well as findings and recommendations from the impact workshops will be given. Observation networks evolve rapidly with new technologies and, at the same time, services develop rapidly in parallel, including in the private sector. Observation impact assessment has been used for a long time in NWP, ocean and atmosphere domains, and is evolving in other domains. Some methods are transferable across domains. Therefore, results will be presented separately for NWP from other domains.

2.2.1 International Workshops on the Impact of Various Observing Systems on NWP

The series of International Workshops on the Impact of Various Observing Systems on NWP was initiated in 1997 with active participation from major NWP centres from the beginning. Workshops have been organized every four years by the former Commission for Basic Systems (CBS). They identify science questions to be addressed and recommend specific impact studies. The workshops analyse their results and make recommendations to WMO and its Members for evolving surface- and space-based observing systems design based on conclusions concerning the contributions of the various components of the observing system to forecast skill at short and medium range. These Workshops have become a major platform for sharing and discussing the results of recent observation impact experiments and have had significant influence on the overall development of both space-based and surface-based observing systems, and on associated WMO regulatory and guidance material.

Results from observing system experiments (OSEs), with both global and regional aspects, have been presented. Conclusions have been drawn concerning the contributions of the various components of the observing system to forecast skill at short and medium range. Since the start of these workshops, some significant changes and developments have affected the global observing system, and additional effort has been devoted to mesoscale data assimilation systems. There has also been a continued trend toward using techniques other than OSEs to document data impact, such as adjoint- and ensemble-based forecast sensitivity-based observation impact (FSOI and EFSOI) and estimates of analysis uncertainty.

The final report with presentations on the sixth workshop was published on the WMO website¹⁰. The seventh was held online as a virtual event in December 2020. The overall attendance included experts in data assimilation and observation impact, experts in climate change and seasonal forecasting, representatives from space agencies and from private industry, as well as managers from observing networks.

In the following a synthesis of recommendations from this workshop for the evolution of the observing system in response to the Vision for WIGOS in 2040 is given.

¹⁰ https://old.wmo.int/extranet/pages/prog/www/WIGOS-WIS/reports/6NWP_Shanghai2016/WMO6-Impact-workshop_Shanghai-May2016.html

Key points for the evolution of WIGOS

It is important to exchange internationally all observations that have a demonstrated positive impact on global NWP. A free and unrestricted exchange of all relevant observing data has now been adopted by Cg-Ext(2021) through [Resolution 1 \(Cg-Ext\(2021\)\)](#) as a fundamental principle with the new WMO Unified Policy for the International Exchange for Earth System Data.

In this context, the GBON concept, which plays an essential role as backbone for all products and services provided by NMHSs, is important. The concept, which aims to address the foundational requirements of global NWP and climate reanalysis, will help to reduce the inhomogeneity in network density and reporting practices. In parallel with the GBON development, WMO is working with a group of about 30 international development and climate finance partners to develop the Systematic Observations Financing Facility (SOFF), to provide resources to help implement and operate GBON in those parts of the world where the local resources need assistance. The development of the SOFF is important mechanism to close the existing gaps in the GBON. See [Section 2.4.1](#) and [Section 4](#) below for further details on GBON and SOFF respectively.

International exchange is important not only for observations needed for global NWP but also for those targeted primarily at regional NWP and local applications. Impacts on regional (limited area) forecast skill were shown to arise from a combination of direct assimilation of observations within the limited area domain and through the influence of the lateral boundary conditions provided by the global model.

New observing technologies coming into operation have been shown to provide positive impacts on NWP, including ESA's Aeolus wind lidar mission. Improvements in impacts on model accuracy, compared with those demonstrated at previous workshops, have also been noted for many observation techniques.

Weather Radar data assimilation continues to offer a promising avenue for further positive impact on NWP. There is an urgent need for standardization of radar products and data formats in order to support data exchange, at least at regional level. There is also a need for long-term archival as called for by [GCOS](#).

Findings Concerning Specific Observing Systems

In global NWP:

- (a) Radiosondes. Significant improvements were seen from assimilation of high-resolution vertical data, from descent profiles in addition to ascent profiles, from dropsondes provided by special campaigns, and by taking account of sonde drift.
- (b) Satellite radiance processing and assimilation. Microwave radiances (MW) are the single most important observation type in terms of impact. Growing impact has been noted from assimilation of "all-sky" microwave radiances. Improved impacts, for both MW and IR radiances, have been seen through continued attention to thinning, quality control, radiative transfer modelling and specification of observation errors.
- (c) Radio occultation (RO). Positive impacts on NWP humidity fields, in addition to temperature and wind fields, were noted. Improved impacts have come from improved quality in COSMIC-2 data and increased volumes in RO data in general, without any sign that impact has saturated. The all-weather capability has reduced errors in NWP models. Improved impacts from advances in the processing and assimilation methods have also been noted.

- (d) Aircraft observations. Benefits have been obtained by assimilating observations at higher spatial resolution, including for Tropical Cyclone (TC) forecasts. Positive impacts have been noted from newly available observation types: TAMDAR, MODE-S and AMDAR humidities.
- (e) Atmospheric motion vectors (AMVs). Benefits have been seen from increased numbers and types of AMVs, including those from recently launched satellites. Also, assimilation of observations at higher spatial/temporal resolution has shown some positive impacts.
- (f) Ground-based GNSS. Improved impacts have been noted from assimilating observations at higher temporal resolution.

In regional NWP:

- (a) Weather radar observations. These observations provide information on precipitation (both rate and type) and on (radial) winds. Trends towards assimilation of reflectivity have continued. Several centres have noted improvements in impacts, including on precipitation fields generally and on the forecasting of heavy precipitation at the mesoscale, and even to model state variables beyond nowcasting lead times.
- (b) Aircraft observations. In some regions these provide the most important inputs into regional NWP. The growing importance and potential of MODE-S was noted, with impact particularly on upper-air winds and temperatures.
- (c) Ground-based GNSS. Benefits have been reported by an increased number of centres: on short-range forecasts of precipitation (location and intensity of heavy rain) and of humidity and clouds.
- (d) Surface precipitation (gauge) observations. Positive impacts on humidity analyses were noted.
- (e) Growing impact from assimilation of radiances (microwave and infrared) was reported.

Also:

- (a) Ocean observations were reported to have a critical impact on the quality of ocean reanalyses of SST and sea-ice amount and thickness. Observations include in situ temperature and salinity subsurface profiles (particularly Argo), SST, sea-ice concentration (SIC), sea-ice thickness (SIT) and sea-level anomaly (SLA). These observations are also important for forecasting in the medium, monthly and seasonal ranges.
- (b) Impacts in polar regions. Strong seasonal dependences have been noted, with surface-based observations providing more impact in winter and satellite MW radiances in summer. Additional radiosondes provided during the SOP of YOPP were found to be beneficial. Forecast impacts of Arctic observations have been demonstrated, both within the Arctic itself and in the northern hemisphere mid-latitudes.

2.2.2 Findings and recommendations in other domains

(Ocean, land, hydrology, cryosphere, atmospheric composition)

Atmospheric Composition

WMO GAW set up an ad hoc Task Team on Observational Requirements and Satellite Measurements as regards Atmospheric Composition and Related Physical Parameters (TT-ObsReq) to review the user requirements specifically for atmospheric composition. The TT-ObsReq also analysed the role of atmospheric composition observations in support of different WMO application areas ([GAW Report No. 221](#)). After the second workshop of the TT-ObsReq (12–13 August 2014, Zürich), the committee identified key parameters needed for monitoring and forecasting atmospheric composition. This Task Team was transformed into the Expert Team on Atmospheric Composition Network Evolution and Design in 2019 and continued filling in OSCAR database with the observational requirements of the atmospheric composition variables in support of monitoring and forecasting applications as described above.

The variables which were identified as priority are listed in [Annex 6](#).

Summary of results for the Ocean Domain from the Earth System Prediction Scoping Workshop in Dec 2019

Ocean forecasting is performed by national operational centres, research institutes and agencies and academia. The coordination and improvement of global and regional ocean analysis and forecasting systems are organized in the frame of the [OceanPredict](#) Science programme. OceanPredict provides a platform for communication and knowledge exchange run by scientists and experts in operational oceanography from around the world, allowing them to accelerate, strengthen and increase the impact of ocean prediction. Ocean Data Assimilation Systems (ODASs) are used in seasonal and, recently, weather-to-sub-seasonal predictions. They can provide initial conditions for initialized coupled atmosphere-ocean General Circulation Model (CGCM) runs that provide seasonal-decadal predictions. An Earth System approach is already highly beneficial for ocean prediction. For instance, a reliable ocean state is needed for coupled predictions as air-sea interactions are expected to have large impacts on tropical convection. Coupling with hydrology is also needed for the coastal zone e.g. coastal hydrodynamic-biogeochemical modelling.

The ocean observing community is comprised of a much broader spectrum of funders and implementers than is the case for meteorological observations, including satellite agencies, operational meteorological services, research agencies and institutes, academia and science foundations, and the private sector. It is principally coordinated through networks with voluntary collaboration at global, regional and national levels. The GOOS Strategy 2030 envisages a fully integrated 2030 ocean observing system providing the critical ocean information needed to address climate change, generate forecasts, protect ocean health and support sustainable growth, with participation from all nations.

Observation evaluation activities are not, in general, as mature for the oceans as is the case for meteorological observations. While there are efforts in research and operational groups, there is no coordinated recurrent observation impact assessment activity. Such activities rely on external funding and are mostly conducted in well-established centres (in USA, Canada, Europe, Japan, Australia and others). Copernicus will develop a new service line in Copernicus-2 for joint OSE/OSSE activities to help design the evolution of the future observing system (satellites/Sentinel and surface-based).

The GBON is currently focusing on observations made from the land surface in support of global NWP and climate reanalysis requirements. GBON could be expanded into observations made over and within the oceans, although the current principles behind GBON would have to be revisited in order to address areas in the global ocean where there is no national jurisdiction.

More specific recommendations from the workshop for the evolution of the observing system were:

- (a) A large part of marine and ocean observing systems is currently maintained by research funding with limited duration. The ocean observing community should ensure sustained funding for the key observing systems.
- (b) Observational impact statements from WMO would help the ocean community to get make progress in observation evaluation activities.
- (c) Research activities are needed on new observing techniques and to find the best mix of surface-based and satellite data. Environmental technologies need to be developed to encourage and expand global ocean observation from many coastal nations.

2.3 Space-based observations

The space-based backbone component of the WIGOS Vision 2040 is based on a system of sun-synchronous low-earth-orbit satellites in three orbital planes and a ring of geostationary satellites providing complete coverage outside the polar areas, complemented by satellites in other orbit planes and satellites in drifting orbits. With the advent of 4-d variational assimilation the old concept for strictly collocated observations, e.g. microwave and IR sounding, does not necessarily carry well in the future. The temporal time differences can now be well-adjusted by data assimilation, which also compensates, at least to some extent, for differences in viewing geometry. Due to the need for increased temporal and spatial coverage, the additional orbits of the WIGOS Vision will be of increasing importance, in particular since mature microwave sounding technology offers possibilities for accommodation onto smaller satellite platforms, e.g. constellations of CubeSats.

In-orbit calibration reference measurements are currently available for the infrared from IASI and CrIS and are strongly required in the future. In that sense, the polar orbiting baseline system today performs two separate functions 1) baseline observations and 2) reference measurements for calibration. An optimized future architecture for calibration reference measurements must therefore be studied, also for VIS/NIR and MW.

Coordination Group for Meteorological Satellites (CGMS)

The CGMS provides a forum for the exchange of technical information on meteorological and environmental satellite systems as well as research and development missions in support of the WMO RRR, the IOC-UNESCO, and other users. The activities of CGMS support operational monitoring and forecasting of weather, space weather and the climate.

The "Baseline" configuration constitutes the commitments and plans of CGMS members to provide particular observations and services in support to WIGOS. The planning for the sustainment of the baseline and for the implementation of new elements remain consistent with the principles of the Vision for WIGOS in 2040. For this purpose, CGMS periodically reviews the baseline that constitutes the commitments and plans of CGMS members to provide particular observations, measurements, and services and WMO

periodically conducts a Gap Analysis against the baseline and against the Vision for WIGOS in 2040.

The 2020 review of the CGMS baseline concluded that the baseline is still a comprehensive response to the Vision for WIGOS in 2040, addressing the key application areas. However, in the coming years CGMS members will be launching several satellites with new capabilities expanding the response to the Vision, and CGMS therefore agreed to include the following measurement capabilities in the CGMS baseline:

- (a) short-wave infrared spectrometers for monitoring of GHGs (CO₂ and CH₄),
- (b) Multi-viewing, multichannel, multi-polarization imaging for aerosols,
- (c) ultraviolet limb sounding spectrometry for profiles of ozone and trace gases.

In addition, a number of new satellite programmes are under planning or consideration by CGMS members, that offer the potential to expand the response to the Vision either through application of new technologies or through extending the coverage of existing capabilities (see [CGMS High Level Priority Plan](#)).

To reflect the latest WMO position on the baseline satellite data requirements as expressed by the global NWP community and to identify backbone and additional data and associated user requirements to complement the GBON, [INFCOM](#) adopted a decision on "Satellite data requirements for global NWP". The document captures the established requirements for the exchange of satellite data for global NWP with a view for the next 5–10 years and aligns itself with the RRR process and the Vision for WIGOS in 2040. As Earth System modelling with a stronger coupling between different domains of the Earth System will continue to evolve, data from existing or new sensors will need to be added to the backbone system. The document will be the basis for further possible improvements in the future and inclusion in the CGMS baseline document. Requirements from additional Application Areas will follow during 2022.

Committee on Earth Observation Satellites (CEOS)

In support of the Group on Earth Observations (GEO) objectives and as the space component of the Global Earth Observation System of Systems (GEOSS), CEOS has developed the concept of virtual, space-based Constellations. A Virtual Constellation is a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular parameter or set of parameters of the Earth System.

The CEOS Virtual Constellations coordinate space-based, ground-based, and/or data delivery systems to meet a common set of requirements within a specific domain. They leverage inter-Agency collaboration and partnerships to address observational gaps, sustain the routine collection of critical observations, and minimize duplication/overlaps, while maintaining the independence of individual CEOS Agency contributions. The current set of Virtual Constellations contributing to the WIGOS vision are

- (a) [Atmospheric Composition](#) (AC-VC);
- (b) [Land Surface Imaging](#) (LSI-VC);
- (c) [Ocean Colour Radiometry](#) (OCR-VC);
- (d) [Ocean Surface Topography](#) (OST-VC);
- (e) [Ocean Surface Vector Wind](#) (OSVW-VC);

- (f) [Precipitation](#) (P-VC);
- (g) [Sea-Surface Temperature](#) (SST-VC)

An example of a key achievement of the virtual constellations is the OST-VC coordination of the high accuracy processing of altimetry data for the Mean Sea Level Essential Climate Variable.

New Opportunities by Commercial Data Providers

Today, commercial satellite data have already demonstrated the quality and their valuable impact to NWP models especially in the field of radio occultation measurements. In addition, there are promising commercial missions for cryosphere and new space-based observations being planned for example related to microwave sounding and precipitation radars. Furthermore, NOAA's Satellite Observing System Architecture study 2018 concluded that the agency should rely in the future on a hybrid architecture that includes both Government satellites and commercial data. NOAA's Commercial Weather Data Pilot launched 2020 will serve as one such demonstration project where NOAA will evaluate commercial data to demonstrate the quality of the data and its impact to weather forecast models, and to inform NOAA's process for ingesting, evaluating, and utilizing commercial data in the future. Also, similarly EUMETSAT has approved the acquisition of the commercial radio occultation data and currently processing it and disseminating it for use in NWP modelling. Thus, we expect to see more and more space agencies utilizing private sector satellite missions together with the governmental missions. When commercial satellite missions are providing new capabilities for space-based observations, they are also a new way of contributing to the implementation of Vision for WIGOS 2040, where data sets are partially relying on the private sector satellites and yet following the WMO data policy, which commits to broaden and enhance the free and unrestricted international exchange of Earth System data.

2.4 Surface-based observations

Since the adoption of the Vision for WIGOS in 2040, several important developments have taken place making it possible now to propose to Members more specific actions to be undertaken over the next five years. Other developments discussed in this section are less mature and will become more important in future, when more fully explored.

2.4.1 Guidance On Expansion Of GBON Network

Global NWP and climate reanalysis play essential roles as backbones for many products and services provided by WMO Members to their constituencies, even at regional and local levels. Within the WMO RRR process, all application areas currently listed, with the sole exception of Space Weather, have some level of dependency on global NWP and climate reanalysis products.

The global systems delivering these products depend on access to globally consistent sets of observations provided by surface- and space-based observing systems. WMO facilitates, coordinates and monitors the collection and international exchange of such observations.

The international exchange of observations in meteorology has a long history and has evolved significantly over time. Congress adopted [Resolution 1 \(Cg-Ext\(2021\)\)](#), on the WMO Unified Data Policy for the International Exchange of Earth System Data, which will be broadening and enhancing the free and unrestricted international exchange of such data.

Preliminary reports from the WIGOS Data Quality Monitoring System (WDQMS) NWP pilot showed continued poor availability of surface-based observations in many areas of the world. This limits the ability of all WMO Members to provide weather and climate products and services of high quality to their users.

In order to ensure that observational requirements for global NWP and climate reanalysis are met more effectively, a new approach has been proposed, in which the basic surface-based observing network that is essential to support these applications is designed and defined at the global level. This network is the Global Basic Observing Network, or GBON.

The WDQMS Web-based monitoring tool illustrates, e.g., the availability of surface land pressure observations received by one or more global NWP centres and shows that on average 20–25% of WMO Members are compliant with GBON provisions¹¹, 25–30% are not in full compliance and the rest are not currently in a position to comply with GBON due to several reasons, including for example a lack of resources.

The GBON is a subset of the surface-based subsystem of WIGOS, used in combination with the space-based subsystem and other surface-based observing systems of WIGOS, to contribute to meeting the requirements of global NWP, including reanalysis in support of climate monitoring. The GBON responds to global NWP requirements that cannot currently be met, or fully met, by space-based observing systems alone.

Notes on GBON stations/platforms:

- (a) The geographically relevant component of the GBON provides an essential base component within each Regional Basic Observing Network.
- (b) GBON is based on a global design and the implementation is monitored globally.
- (c) The specification for GBON is given in tabular form in [Annex 4](#) (from GBON Workshop, February 2020). These are derived from the observational requirements for global NWP that are recorded in the OSCAR/Requirements database together with an analysis of the operational technologies for collecting such observations and availability of observations from other sources.
- (d) The list of GBON stations/platforms will be drawn from the list of all available stations/platforms in the WIGOS as registered in OSCAR/Surface by the Members.

The Eighteenth World Meteorological Congress adopted in 2019 the GBON concept through [Resolution 34 \(Cg-18\)](#) and requested the Infrastructure Commission to draft relevant provisions on the design, implementation and management of the GBON. This will be defined in the [Manual on the WMO Integrated Global Observing System](#) (WMO-No. 1160), Section 3.2.2 Global Basic Observing System. GBON stations must comply with the WIGOS quality management. Progress on GBON implementation and commitments of Members and relevant international organizations and programmes to the GBON will be monitored. The Regional Associations in collaboration with INFCOM will coordinate the actual monitoring activities. Some monitoring functions and incident management will be coordinated through the WDQMS.

¹¹ At the time of writing this report, GBON provisions are not yet into force although Members are already encouraged to make existing observing stations comply with the GBON Technical Regulations, in particular with regard to data availability and the more frequent reporting of data. GBON provisions are scheduled to come into force as of 1 January 2023.

GBON sets out an obligation and clear requirements for all WMO Members to acquire and exchange internationally the most essential surface-based observational data. Whilst some regions provide a good and robust supply of surface-based observations, some areas of the world, notably Small Island Developing States (SIDS) and Least Developed Countries (LDCs), significantly lack the infrastructure and capacity to meet GBON requirements. In 2020, WMO undertook a GBON gap analysis which provided a quantitative estimate of the number of surface-based observing stations that will need to be installed, rehabilitated or upgraded, and exchange data in order to meet the GBON requirements. The SOFF will support LDCs and SIDS to generate and exchange basis observational data critical for GBON, i.e. to improve weather forecasts and climate services. It will provide technical and financial assistance for which the GBON monitoring will guide investments. [Section 4](#) of this document will give more information on the SOFF initiative.

At INFCOM-1 part II in November 2020, Resolution 4 on GBON was adopted together with recommendation of GBON Technical Regulations. It was further reviewed and recommended by the Executive Council through Recommendation 4 (EC-73) and approved by the Extraordinary Session of the World Meteorological Congress in October 2021 (Draft Resolution 5.2/1).

The Earth System approach and other overarching priorities of the Strategic Plan of WMO require that further implementation options for the evolution of GBON should be reviewed. The review should include: the impact on WMO Programs of various observing technologies, the need to stimulate further development of emerging observing technologies for both space-based and surface-based observing systems, and further strengthening of collaboration with the research community and its involvement in the RRR process.

In [Section 2.1](#) of this document the priorities for evolving and optimizing observing networks were discussed and key observational gaps were identified. From this the following expansions of GBON should be further examined by SC-ON in coordination with the Study Group on GBON:

- (a) Ocean observations;
- (b) Climate monitoring, applications and services;
- (c) GHGs, ozone, aerosol (for details see [Section 2.1](#));
- (d) Cryosphere (for details see SOGs in [Section 2.1](#)),
- (e) hydrology (for details see SOGs in [Section 2.1](#)).

2.4.2 GBON And RBON Relationship

In 2019, the Eighteenth World Meteorological Congress adopted Technical Regulations for the Regional Basic Observing Network (RBON) while those of the Regional Basic Synoptic and Climatological Networks (RBSN and RBCN) are no longer into force (see [WIGOS Manual](#) (WMO-No. 1160), Paragraph 3.2.3). Compared to GBON, which is addressing the requirements of global NWP and climate data reanalysis only, RBON is meant to complement GBON and replace and expand the RBSN and RBCN networks by addressing observational user requirements of WMO Application Areas prioritized for key regional weather, climate, water and other environmental challenges by the regions. GBON will address additional observing technologies such as surface-based remote-sensing observing stations, including weather radars, hydrological stations, and ocean observing stations. However, while GBON is targeting stringent requirements in terms of

space and time resolutions and frequency of observing cycle for specific types of observing systems, namely surface-based weather stations and radiosondes, RBON is instead looking at the composite nature of the observing system and targeting observational user requirements of the required variables at the threshold level (see OSCAR/Requirements database). The Infrastructure Commission is defining criteria for the design of RBON at the regional level and their decision is expected by the end of 2022. From 2023 onwards, such design is to be conducted by the regional association working groups on infrastructure in consultation with the Members of the region, and the composition of RBON eventually decided by the regional association. Members are urged to contribute to the composition of the RBON regional networks.

2.4.3 Analysis Of Cost-effectiveness Of Observing Capabilities To Deliver The Required Information And Products

An important element of the design considerations for an observing system is its cost-effectiveness. Due to the pressure on public funds many NMHSs have been forced to demonstrate clearly the importance of their observational and data-processing infrastructure and research for providing essential public information, forecast and warning services to their national communities.

The observing components of meteorological, hydrological and climatological services are amongst the costliest parts of the total service provision. It is a central aim of WIGOS to promote and facilitate the development of observing systems that deliver improved products to users in a more cost-effective way.

The former CBS encouraged Members to assess the cost-effectiveness of observing systems. A complete cost-benefit calculation would assess annualized observing system costs, impact of observations on each Application Area of the RRR process, impact on services and benefits to users attributable to impact on services. As an example, the Met Office (UK) investigated the impact per cost for observations in global NWP by using an adjoint-based technique, called FSOI, to assess the impact for each observing system type. For further details see the full [Met Office study](#). There is the need for more such work including in other domains, and Members are encouraged to participate in further studies.

A recent study¹² conducted by the World Bank, WMO and Met Office, estimated that improvements in the coverage and exchange of surface-based observations to meet the GBON specifications can deliver additional global socioeconomic benefits of over US\$ 5 billion annually. It is concluded that surface-based observations should be treated as a critical public good, with public oversight and open exchange within the meteorological and climatological communities.

2.4.4 Opportunities For Synergies And The Optimization Of Observing Systems

Regional and global cooperation between NMHSs and with their respective national and regional environmental protection organizations, research institutions and academia can bring significant enhanced capability by delivering more and improved observations, which Members would not be able to deliver on a national basis. Collectively observation data could be delivered over the ocean and other remote areas, gaps at regional level could be closed and through centralized services such as centralized quality monitoring, a shared workload and an improved cost efficiency could be achieved.

¹² World Bank and WMO Study on the Value of Surface-based Meteorological Observation Data (see [link](#))

In this section examples of successful regional and global cooperation programmes are given to encourage Members to join these or to support opportunities for synergies in their Region.

Aircraft-based Observations

The global AMDAR programme was initiated by the World Meteorological Organization (WMO) and its Members, in cooperation with aviation partners and has led to the development of the AMDAR observing system. In the beginning, national AMDAR programmes were set up between Members and their national airlines. The AMDAR system utilizes predominantly existing aircraft on-board sensors, computers and communications systems to collect, process, format and transmit meteorological data to ground stations via satellite or radio links. Once on the ground, the data are relayed to NMHSs, where they are processed, quality-controlled and transmitted on the WMO Global Telecommunications System (GTS) of the WIS. Subsequently regional programmes such as the EUMETNET-ABO (Aircraft-Based Observations) were set up with the benefit of an optimized data collection process, centralized quality monitoring and cost-effective management.

WMO maintains the international regulatory material and standards for operation of the AMDAR observing system and, through its Technical Commissions, oversees the maintenance and development of the AMDAR observing system and the work programme on ABO through the coordination of Technical Commission expert teams. WMO Members continue to develop and expand the AMDAR observing system in line with the recommendations of the RRR process and Statement of Guidance as well as findings from NWP impact studies. Resource material related to national and regional AMDAR programme development can be found in the [WMO AMDAR Resources/AMDAR Programme](#) Development area.

The data collected are used for a range of meteorological applications, including meteorological NWP, public weather forecasting, climate monitoring and prediction, early warning systems for weather hazards and, importantly, weather monitoring and prediction in support of the aviation industry.

For NWP, AMDAR delivers accurate profiles (ascent/descent) from the vicinity of airports with good spatial and temporal coverage over USA, Europe, Australia/New Zealand, Eastern China and large parts of South America. Flight level AMDAR observations are available from major flight routes. AMDAR observations are increasingly complemented by aircraft data from ICAO and ATM regulated systems (ADS-C and ADS-B/Mode-S).

Whilst the Programme has been successfully growing and functioning in Europe, North America, Asia and Oceania, there remain significant areas, such as Northern and Central Africa, Eastern Europe, Western and Central Asia, the Southwest Pacific and the Middle East, where coverage is limited. One of the reasons for this is limited funding available in these regions for Programme expansion.

Acknowledging the benefits of AMDAR data, IATA and WMO propose to work jointly on expanding the Programme to new geographical areas whilst giving participating airlines better control over and access to the data they provide to the Programme. The WMO-IATA Collaborative AMDAR Programme (WICAP) will develop and establish the cooperation intended to achieve these objectives. Among other things, the WICAP aims to implement a more efficient and simplified process for airlines to join and contribute to the Programme, and to set up processes for a sustained funding mechanism and proposed regional structure to support AMDAR operations and expansion. This will also facilitate participation by LDCs and SIDS. Through the establishment of a more efficient business relationship between AMDAR Programme operators (NMHSs), data users, data providers and other stakeholders, an enhanced global aircraft-based observation data

coverage will be achieved, including focusing on efforts to extend water vapour and turbulence measurements globally.

Under WICAP, the operation of a number of aspects of the AMDAR Programme will become more centralized, including the establishment of requirements for data, the establishment of agreements, the processing of AMDAR data, and the sharing of programmatic costs and infrastructure by the WMO Members choosing to participate in the Programme. Requirements will be gathered and analysed by WMO Regional Associations, with airline partnerships and data processing functions to be coordinated at the Regional level also. More detail and information on all aspects of the proposed operation of WICAP can be found in the full WICAP Concept of Operations, available as [Information Document](#).

WMO Regional Associations and their Members are encouraged to continue towards the establishment of regional AMDAR programmes under WICAP in accordance with the WICAP Implementation Plan. The participation in these WICAP regional programmes will not initially replace the existing national and regional AMDAR programmes, although it is expected that the opportunity will be offered to migrate to WICAP.

In October 2020 the Working Arrangements on the Establishment and Operation of the WICAP were signed between IATA and WMO. The further development of the WICAP implementation is guided by the JET-ABO, an Expert Team under the Standing Committee on Earth Observing Systems and Monitoring Networks (SC-ON). The WICAP Governing Board which consists of a group of officials and technical representatives appointed by IATA and WMO had its first meeting in early 2021. It is still the goal to implement the full governance and regional operational structures of WICAP by end 2023. Latest information on the WMO-IATA Collaborative AMDAR Programme can be found on the [WICAP website](#) of the WMO Community platform.

EUMETNET

EUMETNET is a network of 31 European National Meteorological Services, established to foster collaboration among Members to increase efficiency, effectiveness and international influence. Its primary focus areas are observations, forecasting services and aviation. The EUMETNET observations programme is the major EUMETNET activity, and its focus is to manage and develop the European Composite Observing System (EUCOS). It also contributes to wider global observing efforts through supporting the development and operation of the WIGOS. The key aim of the EUMETNET Observations 'Capability Area' is to enhance the performance of the European observing system to enable improvements in Nowcasting, NWP, Aviation Meteorology and Climate Monitoring. Following recent consultation with European user communities, it has been concluded that their highest priority needs relate to the improvement of km-scale forecasting.

In addition to these operational programmes, the EUMETNET Observations Capability Area also provides:

- (a) A research and development programme, which aims to progress the design and evolution of EUCOS in order to satisfy a growing need for observations whilst maintaining future costs at an affordable level;
- (b) A Regional WIGOS Centre (RWC) for monitoring observation network performance across a significant portion of WMO Regional Area VI and ensuring corrective actions are taken when required;
- (c) A Framework for collaboration between Members on additional subjects of common interest including for example data quality control, surface instrumentation, crowdsourcing and radiosonde operations;

- (d) International representation on behalf of Members, to support wider global efforts to enhance the WIGOS, contribute to related European initiatives such as Copernicus and influence international decisions in the interest of EUMETNET Members.

The Met Office (UK), working together with the German Meteorological Service (Deutscher Wetterdienst), is responsible for the EUMETNET Observations Capability Area for the programme phase 2019–2023.

The EUCOS Operational Programme has brought significantly enhanced capability, which Members would collectively be unable to deliver on a national basis by:

- (a) delivering more observations over the ocean, optimized aircraft measurements over Europe, water vapour data from GNSSs and new data from European wind profiler systems and weather radar wind profiles;
- (b) improving NWP results through establishing the EUCOS Studies Programme to advice on observing network design – together with the EUCOS Science Advisory Team different data impact studies were launched to give guidance on how to design the EUCOS in order better to meet the user requirement;
- (c) optimizing the future EUCOS upper-air observing network by making best use of the radiosonde network and incorporating profile measurements from commercial aircraft, wind profilers, weather radars and integrated water vapour retrieved from ground-based GNSS measurements – EUCOS coordinates the harmonization of national upper-air networks due to global, regional and national requirements;
- (d) Delivering a centralized quality monitoring service with increased network performance through the EUCOS quality monitoring and fault correction procedures;
- (e) Being part of the WIGOS and facilitating the implementation of the WMO evolution proposals for Europe;
- (f) Sharing workload and costs for integrated programmes;
- (g) compensating national operators where NMSs make more observations to the benefit of all.

According to the EUMETNET Strategy for Observations 2020–2025 the European NMHSs would be willing to widen the EUCOS idea to other regions. The experience with collaboration in EUMETNET, and particularly in EUCOS, offers a potential model for collaboration to the benefit of other regions and may help in closing gaps in the global observing networks. The following activities of the EUMETNET Observations Capabilities Area are of special interest to close existing gaps in the observing system:

- (a) OPERA: this Programme's objectives are to provide a European platform to exchange expertise on weather radar issues, to exchange single site radar data from the approximately 180 operational weather radars of its European members and to develop, generate and distribute high-quality pan-European radar composite products.
- (b) E-Profile: the E-PROFILE Programme manages the European network of radar wind profilers and automatic lidars and ceilometers for the monitoring of vertical profiles of wind and aerosols including volcanic ash.

- (c) E-ABO: the E-ABO Programme carries out measurements of high quality of upper-air meteorological variables from aircraft.
- (d) E-SURFMAR: the E-SURFMAR Programme coordinates, optimizes and progressively integrates European activities for surface marine observations.
- (e) E-GVAP: the E-GVAP Programme aims to provide EUMETNET partners with European GNSS delay and water vapour measurements for operational meteorology.
- (f) E-ASAP: the objective of the EUMETNET-ASAP (E-ASAP) Operational Service is to coordinate and optimize weather balloon observations over data-sparse ocean regions.

Other specific pilot programmes

- (a) RA III cooperation with hydrological observations
- (b) Others (may be added during later updates of the document)

2.4.5 Strategy And Guidance To Members On Urban Observations

The [Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services \(IUS\)](#) (WMO-No. 1234) provides a basis to assist WMO Members in the development and implementation of Integrated Urban Services to address the variety and specific needs of city stakeholders in their countries. The scope of IUS include climate, weather, environment (including air and water quality, ecology, biota, greenhouse gases) and water. NMHS are best positioned to deliver IUS due to their expertise, infrastructure and historical early warning role. [Annex 5](#) provides an extended discussion of the gaps of IUS for WIGOS.

By 2050, 80% of the world's population will be in urban centres with safety and security of people, the environment, critical infrastructures and the economy to protect. A single hazardous event can result in a cascading process that can have multi-faceted impacts (e.g. flooding lead to transportation interruptions or power outages and disrupt rescue and recovery operations), requiring consistent, accurate multi-hazardous early warnings for decision-making. Weather, climate, environment and water issues dominate urban design and emergency management operations. This drives the need for an integrated, seamless, Earth System, value chain approach to urban service provision. Integration can occur anywhere along the value chain from the observation to the decision-making stage.

Urban observations and derived products are directly needed to understand urban processes and science, to develop rural-urban statistical relationships and model parameterizations, to develop climatologies, for early warnings, for real-time verification, for maintaining situational awareness, for use by downstream automated decision-support systems used in emergency management or in other multi-hazard decision-making processes.

Existing guidance in all WIGOS Application Areas are relevant as IUS is multiscale and range from global, to regional, to local (neighbourhoods), to micro (building) spatial scales. Also, the urban boundary layer is three-dimensional and consists of the inertial, roughness and canopy sublayers (~100 m to 2 km). Atmospheric chemical processes vary at even finer spatial and temporal scales (~seconds). However, urban observations and networks differ significantly due to the methods of observations, heterogeneity of sensors and technologies, multiple-loci sensor installation, urban environment (surface

cover, built up areas, permeability), multiple measurement heights due to local obstruction issues as well as the suite of variables.

Common to all, and a major gap, is detailed information on the urban environment and a standard classification is fundamental to understand the representativeness of the observations, to specify measurement and site requirements, as well as to compare and efficiently transfer scientific results. An international community-based effort to acquire and disseminate local climate zone and micro urban environment information has been initiated (World Urban Database and Access Portal Tools). This environment information, as well as the instrument and siting information and perhaps wind data, must be included and frequently updated in the metadata.

Few NMHS have urban meteorological stations while many environment agencies have deployed high quality air quality stations with meteorological sensors; some municipalities have deployed compact weather station networks; most rivers as well as some sewer system in urban areas are gauged; research, demonstration projects and test beds have deployed networks of remote-sensing and in situ technologies; and mobile vehicles have meteorological or AQ sensors when combine can provide basic and reference tier observations. Crowdsourcing technologies include cell phone microwave towers, vehicle technologies (temperature; precipitation detectors for wiper activation; lidars, radars and cameras for driver assistance), mobile phone (temperature, pressure, UV), crowdsourcing applications (weather reports, twitter activity, Instagram) can provide comprehensive tier observations along the value chain to enable high impact IUS verification. Integration of these networks will enable new capabilities, increase capacity, reduce duplication and costs. As IUS evolve, accuracy expectations will increase requiring the monitoring of additional factors (e.g. accumulating debris blocking sewers and urban rivers) that will require the development of new technologies and a commensurate adaptation by the prediction system. Given the breadth of issues, reference urban stations are needed to resolve the interpretation and data quality issues.

IUS observation network design will depend on the service requirements. While there are good and specific examples of IUS, implementation of IUS may be considered marginal on a global scale. There is ongoing activity to formalize the observation, metadata and service requirements. Management, knowledge of available and access to IUS data and products, exchange mechanisms, intellectual property, privacy, rapid research to operations and operations to services technology transfer and demonstrated mutual benefits of integration and partnerships all along the value chain are challenges requiring leadership, capability and capacity development.

2.4.6 Recommendations On The Use Of New Observing Technologies

2.4.6.1 *Guidance on use of surface-based emerging technologies*

Part of the strategy of SC-MINT for the future of environmental measurements is to provide guidance on the implementation of new measurement technology and to identify the potential of emerging measurement technologies and techniques. Measurement Lead Centres, expert teams and Regional Instrument Centres as well as a research community will continue to play a crucial role in transitioning new technologies to operation.

A necessary condition for the operational introduction of any new observing system is commercial visibility and availability. Furthermore, all new instruments and systems needs to be tested and evaluated under realistic operational conditions over a sufficiently long timespan. This testing is needed to enable a comprehensive assessment of practicality and robustness of operation as well as to define a reliable estimate of the accuracy of measurements and quality of derived value-added products. The operational

readiness of a particular instrument or system can be classified using the concept of standardized technology readiness levels. Finally, all life cycle and operating costs must be objectively analysed because affordability is a major constraint, and an acceptable cost/benefit ratio is required before any new observing instrument or systems can be operationally implemented.

A tiered network concept, originally established by GCOS, is now being considered also for other networks by INFCOM. The development of this architecture, if adopted, will be an important development for the evolution of WIGOS. Measurement Lead Centres could take the role of reviewing and trialling new and emerging technologies and instruments and systems and develop guidance for their use.

See also [Section 2.1](#) for the gap analysis and [Section 2.5](#) on most pressing needs for the further development of sensor technology.

Ground-based Remote-Sensing Techniques

Several ground-based remote-sensing methods, both active and passive, are suitable for operational meteorology. They can be roughly divided by wavelength into either the "optical range", including UV and IR, or the "microwave range". The wavelength used determines the physical propagation and scattering properties: the measuring range of optical systems depends on optical thickness in the atmosphere, whereas microwave sounding systems can generally penetrate clouds and precipitation. For very short (UV) wavelengths, molecular scattering is relevant. Otherwise, scattering mainly occurs at suspended particles (aerosol, clouds, precipitation) in the air. For wavelengths in the decimetre range and larger, clear-air (refractive index) scattering is useful. Passive systems analyse the atmospheric radiation generated by thermal emission. Any future extension of the observing system with remote-sensing systems must consider these physical wave propagation constraints of each method, which largely explain most of the capabilities as well as limitations.

Remote-sensing methods can generally provide high temporal resolution data, with active methods additionally providing vertically resolved profiles of thermodynamic variables, such as wind, temperature and humidity, as well as indirect quantitative information about small liquid and solid particles (clouds, aerosols) suspended in the atmosphere.

A new generation of ground-based remote-sensing instruments, often called "profilers", is either already operationally used such as wind profilers (both radar and lidar based) or is currently under development focusing on measurements of temperature, humidity, aerosol or cloud-related properties.

Uncrewed Platforms

The rapid pace of the technical development has meanwhile enabled the development of largely autonomous "robotic" vehicles, with the most prominent class being robotic aircrafts (UAS) which span a wide range from fully automated boundary layer copter-sondes¹³ up to aircrafts such as NASA's Global Hawk¹⁴ (no longer in service). Depending on their size, such UAS platforms can carry both surface-based as well as remote-sensing sensors.

¹³ Potential Socioeconomic and Environmental Benefits and Beneficiaries of UAS Atmospheric Profiles from 3D Mesonet in: Weather, Climate, and Society Volume 13 Issue 2 (2021) (ametsoc.org)

¹⁴ NOAA's Sensing Hazards with Operational Unmanned Technology (SHOUT) Experiment Observations and Forecast Impacts in: Bulletin of the American Meteorological Society Volume 101 Issue 7 (2020) (ametsoc.org)

Proposals have already been made to employ a network of autonomous multi-copter UAS to establish "3D Mesonets", but a number of practical questions remain to be answered, such as airspace operating regulations as well as the limits posed by adverse weather conditions. The ABO newsletter 21 contains a summary of UAS in operational meteorology.

High-altitude and long-endurance UAS are especially interesting with regard of their ability to fill gaps in remote areas, especially with regard to high impact weather.

Examples for uncrewed platforms for ocean applications are Argo floats, Saildrones, moored and drifting Buoys, sea level gauges, high frequency (HF) radars and animal borne sensors. Further examples of uncrewed vehicles are under-ice Argo-type floats and other similar vehicles for evaluation of sea-ice thickness.

The Infrastructure Commission adopted a Plan for a Global Demonstration Project on Uncrewed Aircraft Systems (UAS) Use in Operational Meteorology (see [Decision 5.1.1\(7\)/1 \(INFCOM-1\(III\)\)](#)). Members interested to participate in the Demonstration Project are invited to contact the WMO Secretariat.

Technical Readiness of New Observing Systems

From a good management practice point of view, it is always necessary to consider the performance of individual instruments before they are implemented operationally. Clear identification of the measurement's principle – direct sensing or remote-sensing, and the physical transducing method itself are important to identify resolvable technical design issues at an early stage.

The readiness of a particular instrument for operational use can be classified using the so-called technology readiness level ([TRL](#)) management tool. Assignment of instruments into TRL's may be challenging, and should be performed a clear set of defined criteria that are unambiguous and objective as possible:

- (a) Actual system proven in operational environment;
- (b) System complete and qualified;
- (c) System prototype demonstration in operational environment;
- (d) Technology demonstrated in relevant environment;
- (e) Technology validated in relevant environment;
- (f) Technology validated in lab;
- (g) Experimental proof-of-concept;
- (h) Technology concept formulated;
- (i) Basic principles observed.

Any successful analysis must show a sufficient technical (instrument) availability (say > 95% over the course of a year), all-weather outdoor operability, as well as a sufficient data availability and data quality that is "fit for purpose" - linked to criteria in OSCAR/Requirements.

2.4.6.2 *Strategy and plan for the use of big data, crowdsourcing and other sources of observation from the private sector, general public and third parties*

During recent years, the exploitation of modern data-driven methods (artificial intelligence, deep learning) and the use of crowdsourced data have gained attraction for use in nowcasting applications. Although the availability of traditional surface-based and remote-sensing data remains of major importance, such additional data can add information, especially on finer geographical and temporal scales. The use of these data depends generally on national requirements and priorities of the particular NMHS and is based on individual contracts. Examples of sources of data from the public and private sector, non-conventional and crowdsourcing data are:

- (a) Data from public institutions;
- (b) Pressure and other values from smartphones;
- (c) Sensors in vehicles;
- (d) Internet of Things sensors;
- (e) Input from the general public;
- (f) Estimates of precipitation from attenuation of communication links;
- (g) Lightning location systems;
- (h) Ground-based GNSS array for total precipitable water;
- (i) Small Uncrewed Aircraft Systems (UAS) for package and parcel delivery;
- (j) Opportunistic observations from the maritime industry and uncrewed observing vehicles in the ocean;
- (k) Constellations of small satellites providing GNSS-RO.
- (l) and others.

In general, crowdsourced data are provided or gathered free of charge, but governments may choose to contract with an aggregator for acquiring from open systems, performing quality control and provision to the Government in appropriate formats via dedicated communications pathways in real time, in lieu of establishing “in-house” capabilities.

In the USA, the examples above can be expanded to include environmental observations that are conventional in nature but do not come from networks operated by the national Government, which supplies the backbone of observing capabilities. One example is mesonets operated by state governments or the private sector. These are professional-grade observing systems that maintain high quality infrastructure and provide high quality observations and attendant metadata. Typically, the cost of procuring the data from these systems provides a cost advantage over the federal Government building and maintaining federal networks. Mesonets have now grown beyond provision of standard near-surface meteorological observations and provide vertical profiles from ground-based remote-sensing, gap-filling short-wavelength radars under the national Doppler coverage umbrella, and many variables pertaining to the land surface and hydrology, including soil moisture and temperature at multiple depths, and the components of the surface radiation and energy budget.

From crowdsourcing of ubiquitous and freely available, but lesser quality data, to high end professional, private and non-federal networks, the goal is to fill gaps in national backbone capabilities by forming public-private partnerships that offer a financial advantage to the Government over building and operating a Government capability. This requires trade-offs that most often impact data rights and redistribution categories and have implications for the ability to share data with global partners, as discussed below in more detail.

Low-cost Sensors for Atmospheric Composition Observations

New atmospheric composition data sources are emerging and information is increasingly produced by low-cost sensor (LCS) devices. A recently completed experts review of market available LCS for measuring atmospheric composition concluded that LCS must not be viewed as fully operational replacements for more sophisticated measurements systems and should be used with caution (WMO Report No 1215: An update on low-cost sensors for the measurement of atmospheric composition, Edited by Richard E. Peltier, December 2020). While LCS units can provide meaningful data and represent an opportunity to expand knowledge on local environmental conditions, they are not yet at the level of robustness in which reference monitoring is required. In part, this is because there remain several scientific complexities that must be considered such as full characterization and a well-designed quality assurance and calibration procedure that must be continually applied. Since these technologies are generally on a trajectory of ever-improving capability with advances in features, better atmospheric coupling, precision, quality and reliability, and, often, decreasing procurement costs, their further development and suitability for different applications should be regularly evaluated.

2.4.6.3 Guidance on how to develop partnerships

Stakeholders from all sectors and from all parts of the global community depend on output from global models for the development and delivery of critical services. This can only work if data, both observations and model output, are exchanged globally. It is important to address gaps in Earth System observations through increased engagement between NMHSs and partnering communities. Public-Private Sector engagement and cooperation with Academia is important and will open new opportunities along the Earth System monitoring and prediction value chain. In order to maximize the mutual benefit of this, policies, legislation and business models still need to be developed further and mutually adapted.

Over recent years, WMO, in cooperation with various partners, has been developing a new approach for greater engagement between the public, private and academic sectors operating in the global weather enterprise. In 2018 and 2019 – at the seventieth session of its Executive Council and the Eighteenth Session of the World Meteorological Congress – WMO refined guidance and policies to encourage and enable Members to pursue mutually beneficial partnerships and engagement with all sectors and stakeholders in order to enhance weather, climate and water services for business, individuals and society as a whole. Detailed information on Public Private Engagement, including guidelines and on the WMO Open Consultative Platform (OCP) "Partnership and Innovation for the Next Generation of Weather and Climate Intelligence" can be found on the [WMO website](#).

The following examples might help Members to develop partnerships with the private sector, where appropriate.

In procuring third-party data from non-governmental sources, the goal should always be to obtain rights to redistribute the data to other global partners in the spirit of [Resolution 1 \(Cg-Ext\(2021\)\)](#). However, beyond a certain price point this becomes untenable for budgets. In general, the approach the United States takes is to secure,

and pay for, contracting rights to distribute to global partners data with a global footprint, or vertical profiles from various sources that are most valuable to all global NWP centres. In some cases, the United States will fully fund the purchase of such redistribution rights; this is the goal for the increasing footprint of purchase of GNSS-RO data from commercial sources. Naturally, this comes at an increased cost because the provider of the data has no other governments in their market space. Another model is a global cost sharing mechanism, whereby individual governments will buy observations over their sovereign territory or in partnership with WMO Regional NHMSs, and all share their sources with each other in real time to affect an open availability of the total global footprint. This is the model for the WMO Global AMDAR Programme.

In other cases, data thought to be of limited utility to global NWP are purchased with limited redistribution rights in various tiers. The National Mesonet Program data is limited mostly to NOAA-only use, giving those networks both access to a private market of data users and other Government agencies and various levels from the federal to local. As might be expected, this provides the greatest cost advantage to NOAA. The lightning data, GPS-Met, and some ship/buoy observations operate in this limited data rights paradigm.

One peculiarity of the USA relative to other NHMSs is that they do not provide commercialized products and services. They reserve the right in contractual arrangements to distribute, freely and openly, any forecast products and services that incorporate third-party data, even if they agree not to redistribute the raw observational data themselves. This may pose a challenge for other NMHSs that commercialize products and services. Often, a private provider of observational data is also in the market for provision of products and services using their own data, and any agreement with NMHSs to use their observational data would possibly be with the understanding that the NMHS does not create commercial products and services in their private market space.

A compendium of Good National Practices at national level for Public-Private Engagement and other related resources are available [here](#).

2.4.7 Environmental Sustainability Of Observations

The WMO Instruments and Methods of Observations Programme (IMOP) sets technical standards, quality control procedure and guidance for the use of meteorological instruments and methods in order to promote worldwide standards. Appropriate safety procedures have been developed for the use of mercury and the selection of radiosonde materials.

The Minamata Convention on Mercury of the United Nations Environment Programme (WMO-No. 8, Vol I, Ch 1) bans all production, import and export of observing instruments containing mercury. This agreement is a global treaty to eliminate the use of mercury to protect both human health and environment from its adverse effects.

GAW atmospheric composition observations sometimes employ biodegradable ozonesonde packaging, in response to strengthened environmental regulations in Antarctica which will limit non-recovered ozonesonde flights. Other countries have adopted pre-paid shipments of found sondes in order to reuse and refurbish recovered instruments and encourage protection of the environment. Brewer spectrophotometers used to have mercury-based switches in their electronics, but these have been replaced with more environmentally friendly components.

In the case of radiosondes, the [Guide to Instruments and Methods of Observation](#) (WMO-No. 8) gives also suggestions on how environmental pollution could be reduced.

In the context with the future development of GBON the environmental impact of various observing technologies was discussed and must be always considered. INFCOM adopted Resolution 4 (INFCOM-1) on the future of GBON which stresses the importance of this aspect. Many Members have started to adopt cleaner and sustainable technologies and INFCOM will coordinate further guidance on this issue. Members are encouraged to follow INFCOM developments and apply new guidance as it becomes available.

2.4.8 Risk Management And Mitigation

Due to COVID-19, there has been a substantial reduction of observations, used as input to critical applications supporting service delivery in the WMO domain areas of weather, climate and water. The most immediate impact has been a rapid decline in the overall availability of aircraft observations. Especially in developing countries, where a significant number of observations stations still rely on human intervention for reading instruments or transmitting observational data, an impact on the availability of surface observations could be seen. The marine observing system has also been impacted, especially by ships participating in the WMO Voluntary Observing Ship (VOS) Programme.

This has again demonstrated the importance of resilience in the observing system and the need to address this, through network planning and a balanced development of the observing systems across different system components. Substantial reductions have occurred during the pandemic for example with aircraft observations, in the ocean observing systems and the surface-based observing networks, particularly the manned observing stations.

These impacts of COVID-19 on WIGOS observing systems' operation and data availability have been analysed in the WMO Bulletin Vol 69(2)¹⁵. Similarly, the GOOS launched a COVID-19 impact survey¹⁶ in April 2020 to assess and forecast the pandemic's impact on global ocean observations.

As mitigation, some Members have responded to these shortfalls in observing capabilities through, for example, increasing the frequency of radiosonde launches to mitigate the effect of reduced aircraft observations. In addition, at least two private companies made additional data freely available to certain NWP centres during the peak of the crisis. The reliance on third-party data such as ABO, where their availability is determined by commercial and operational constraints, reveals the need for Members to invest in core observations that are made solely to serve the need of weather, climate, water and environmental services. The COVID-19 crisis also highlights the value of redundancy in measurement systems, whereby the same variable can be measured by more than one technology or instrument, and the importance of the design and implementation of adaptive observing strategies. The collectively experience gained during this pandemic can be used to build more resilience into the observing system. In this regard, the WMO Executive Council is developing guidance, and preliminary guidance on the operation and maintenance of Members' systems impacted by COVID-19 is available in Annex 2 to draft Decision 3.1/1 (EC-74).

¹⁵ Lars Peter Riishojgaard: Impact of Covid-19 Restrictions on Observations and Monitoring, WMO Bulletin 69(2), 2020

¹⁶ Emma Heslop et al; Covid-19's impact on the ocean observing system and our ability to forecast weather and predict climate change, GOOS briefing note, June 2020

2.5 Actions with high priority regarding the evolution of space-based and surface-based observing systems

In the preceding sections key observational gaps and recommendations on how to fill them have been identified. In addition, recommendations from NWP workshops on the impact of observations have been analysed in terms of the contributions of the space-based and surface-based components of the observing system to improve forecast skill.

This section provides recommendations to Members to help prioritize their actions to evolve the observing systems to achieve the Vision for WIGOS in 2040. We recall that in 2018 a subset of 10 such actions were adopted by the Eighteenth World Meteorological Congress ([Resolution 40 \(Cg-18\)](#)) (see Annex 3) as priority items originating from the EGOS-IP. Taking into account recent developments such as the new WMO structure, the work plan of the INFCOM Standing Committees, recently at Cg-Ext(2021) adopted Technical Regulations (e.g. GBON, the WMO Unified Policy for the International Exchange of Earth System Data), the EGOS-IP action lists were reviewed by the Infrastructure Commission Joint Expert Team on Earth Observing System Design and Evolution (JET-EOSDE) subgroup on High Level Guidance (HLG) and those that remain relevant and urgent have been included in the recommendations given below.

The Earth System approach is a key new aspect of the WMO Strategy. An increasing variety of observing systems are of interest to WMO application areas. Scientific and technical advances over the past decade have advanced the physics of the models and the computing capacity available such that the current limitation of our ability to improve weather/climate forecast quality, resolution and time horizon is the availability of data. This includes data from the Earth System domains traditionally excluded due to model and capacity limitations. Current global NWP models need data from various components of the Earth System model, thus requiring more observations of the atmosphere, the deep ocean, the ocean and land surfaces, rivers and lakes, atmospheric composition, sea-ice and the cryosphere in general.

The Vision for WIGOS in 2040 presents a likely scenario for how user requirements for observational data may evolve in the next few decades. With this information NMHSs, space agencies and other observing system developers will be able to adopt their planning activities accordingly to develop the space-based and surface-based components of the WIGOS. The current High Level Guidance document focuses on the time frame of the next five years and gives recommendations on activities needed now.

Given these priorities and the new, clear strategic directions of WMO, and considering that global NWP is regarded as foundational application area for the Earth System approach, the following actions of high priority, which rely on expert knowledge from the Application Areas and the JET-EOSDE Working Group on HLG, are recommended when implementing the WIGOS over the next 5 years (table numbering is for tracking purposes, it is not an indication of relative priority).

General Recommendations to Members 2023–2027		
Action No.		Performance monitoring
1.1	Implement the GBON concept – All Members to implement GBON fully in their countries. LDCs and SIDS, through support of development partners and financial mechanism such as SOFF, contribute to the expansion of GBON networks in their territories and prioritized observation locations.	Through WDQMS monitoring centrally and at the RWCs.
1.2	Implement the new WMO Unified Policy for the International Exchange of Earth System Data.	Through monitoring of global NWP centres and WDQMS.
1.3	Members (and Space Agencies) to advance the implementation of the WIGOS Vision 2040, for instance wind lidar and a comprehensive space-based carbon monitoring system together with other issues identified by the WMO Annual Gap analysis, through the implementation of additional sustained space-based observation capabilities.	Measure the status of the WIGOS Vision 2040 through a WMO gap analysis of current and future committed capabilities against the WIGOS Vision 2040 requirements and presented to the Space Agencies through CGMS and CEOS for their consideration and inclusion in the CGMS Baseline and for CEOS future initiatives.
1.4	Members (and Space Agencies) to respond to the satellite data needs as expressed in WMO position papers, like the INFCOM approved “Satellite data Requirements for global NWP”, for relevant applications areas via coordination primarily through CGMS, but also CEOS.	Measure the availability and exchange of core and recommended (as per Res. 1/2021) satellite data as stated in the position papers against actual implementation of the space-based component as captured in OSCAR/Space.
1.5	Ensure all operators producing observations do so in accordance with the rules and standards of the WIS and WIGOS.	WIS operational monitoring, centrally and at global and regional NWP centres.
1.6	Support the development of a tiered network concept by INFCOM – GCOS and WIGOS both recommended that networks should be part of a tiered system of networks, to include new sources of data in partnership with the private sector and third parties. Work on GRUAN, GSRN, GBON and RBON will be key to ensuring higher level tiers (reference and baseline) are filled.	Increased availability of GRUAN and GSRN stations, as monitored by climate reanalyses, NWP centres and WDQMS. National level delegation of observing capabilities to tiers (count of stations).
1.7	Members to take continued actions to protect MW radio frequencies for meteorological applications, in particular	Observation frequency bands available / not

General Recommendations to Members 2023–2027		
Action No.		Performance monitoring
	by active participation in the preparation of the next World Radiocommunication Conference (WRC) planned in 2023 and 2027.	available with required level of protection.
1.8	Members to inform SC-ON of any existing and future meteorological application/usage involving frequency domain.	Ensure that all these new requirements are well known and protected at international level.
1.9	Support establishing standards and best practices for several types of measurements through cooperation between developed and developing countries, enhance training and share experience.	Availability of data as per OSCAR/Surface.
1.10	Investigate and develop new emerging measurement technologies which are listed in the Annex 2	Number of new prototype technologies in use.

Recommendations to Members on the Evolution of Observing Systems 2023–2027		
Action No.		Performance monitoring
2.1	Exchange internationally all observations that have a demonstrated positive impact on global NWP, in compliance with GBON and the new WMO Unified Policy for the International Exchange of Earth System Data, which was adopted at the Extraordinary World Meteorological Congress in October 20212021.	Availability of data as per OSCAR/Surface and OSCAR/Space. Standard monitoring indicators used in NWP, and WDQMS
2.2	More timely availability and wider distribution of several types of in situ and remote sensed measurements. Special examples are wind profiles at all available levels, particularly in the tropics, and temperature and humidity profiles at high latitudes and sparsely populated land areas. In addition, more accurate atmospheric composition data are needed.	Availability of data as per OSCAR/Surface and OSCAR/Space. Standard monitoring indicators used in NWP, and WDQMS
2.3	Make further efforts to fill gaps in global coverage of surface observations. Give special focus on more observations of sea-ice thickness, snow depth, water equivalent of snow cover, soil moisture and ocean surface salinity.	Availability of data as per OSCAR/Space and OSCAR/Surface. Standard monitoring indicators used in NWP, and WDQMS.
2.4	Global dissemination of radiosonde measurements – High-resolution BUFR data from all sites including radiosondes operated during campaigns only, provide measurements from descending	Number of radiosonde stations reporting in BUFR. Number of descending profiles available on GTS. Availability of data as per

Recommendations to Members on the Evolution of Observing Systems 2023–2027		
Action No.		Performance monitoring
	radiosondes, protect radiosondes in remote locations or re-activate silent radiosonde stations.	OSCAR/Surface. Standard monitoring indicators used in NWP, and WDQMS.
3.6	Develop innovative in-situ profiling techniques that can provide cost-effective and extended upper-air measurements [China]	Application of innovative measurement techniques, such as Round-trip Drifting Sounding System. [China]
2.5	Develop network of remote-sensing profiling stations – Network of remote-sensing profiling stations to be developed to complement radiosonde and aircraft observing systems, ensure the regional and global exchange of profiler data.	Number of profiling stations providing data in real time to WIS/GTS. Availability of data as per OSCAR/Surface. Standard monitoring indicators used in NWP, and WDQMS.
2.6	Wider distribution of weather radar data – There is an urgent need for standardization of radar products and data formats. Data should be exchanged at least regionally, and a long-term archive should be established. Deploy and maintain weather radar in developing countries that are sensitive to storms and floods.	Number of weather radar datasets available at regional data centres.
2.7	Continued efforts to extend the coverage for aircraft data – AMDAR observations should be complemented by aircraft data from ICAO and ATM regulated systems such as ADS-C, ADS-B/Mode-S. Members should support the WMO-IATA cooperation. Additional observations from TAMDAR should be used when possible. Expand in service Aircraft for a Global Observing System (IAGOS) activity to improve air quality and climate model validation. Members are encouraged to assess new technologies such as UAS and take steps at national level to assure their legal operations.	Number of observations from data-sparse areas available in the aircraft monitoring system.
2.8	Integrate, extend and sustain hydrological observations of WHOS in compliance with WIGOS standards and share the data in support of hydrological monitoring system.	Data/stations shared through WHOS.
2.9	More and sustained observations of physical ocean variables both at, and below the sea surface [United Kingdom]. Coordinate with GOOS Ocean Obs Programme.	JCOMM-OPS and standard monitoring indicators from NWP centres.
2.10	More studies are encouraged on the cost-effectiveness of observing systems, that is, measures of their value (or impact) in relation to their cost.	Number of studies presented at observation impact workshops.

Specific recommendations for Sensor Technology, for Members 2023–2027		
Action No.		Performance indicator
3.1	Install more ground-based GNSS stations.	Number of ground-based GNSS stations available on WIS/GTS.
3.2	Extend spatial density of Doppler wind profilers.	Number of radar wind profiler stations available on WIS/GTS.
3.3	Evaluate new lidar systems for routine profiling of temperature and water vapour.	Test reports from SC-MINT expert teams.
3.4	Water level and tide gauges for monitoring of sea level rise.	JCOMM-OPS and standard monitoring indicators from NWP centres.
3.5	Allocate resources and plan for assessment of new technologies across Earth System domains (remote-sensing, low-cost, citizen science) for systematic use in complement to standard measurements.	Not yet set.

Specific recommendations for Integrated Urban Services, for Members 2023–2027		
Action No.		Performance indicator
4.1	Establish information about the urban environment (land cover, built areas, building height, surface permeability).	Number of conurbation environment classification maps in the WUDAPT database.
4.2	Establish integrated collaborative IUS reference stations.	IUS observation requirements and metadata standard defined. Number of IUS reference stations available on the WIS.
4.3	Development of IUS urban observation networks through collaboration and cooperation and their demonstration.	Number of demonstration projects conducted, or test beds established. Number of IUS capacity development workshops. Cost-benefit (value chain perspective) report or number of warnings/decisions. Number of conurbations with IUS observation networks. Number of co-design and documented products.

Specific recommendations for Integrated Urban Services, for Members 2023–2027		
Action No.		Performance indicator
4.4	Expand support of GHG mitigation efforts in cities and other sub-national stakeholders through further cooperation with Members.	Number of pilot projects conducted. Determining impact of mitigation activities. Improved best practice guidelines.

Specific recommendations for Space Systems, for Members 2023–2027		
Action No.		Performance indicator
5.1	Advance the space component of the Greenhouse Gas monitoring system, including the consideration of novel technologies such as lidar, in collaboration with IG ³ IS and other GHG measurement services.	Annual WMO-CGMS Gap Analysis Uptake of space-based measurements in GHG measurement services
5.2	Advance the new generation of GEO satellites, including advanced imaging, lightning mapping and high spectral resolution IR sounding for the whole geostationary ring;	Annual WMO-CGMS Gap Analysis
5.3	Advance the atmospheric Radio Occultation constellation, with the long-term goal of providing 20000 good quality occultations per day on a sustained basis;	Annual WMO-CGMS Gap Analysis
5.4	Work towards operational hourly daytime UV/VIS mapping of air quality from GEO orbit;	Annual WMO-CGMS Gap Analysis Number of geostationary platforms making tropospheric air quality relevant measurements Improved timeliness of observations to end users Data sharing metrics
5.5	Work towards achieving scatterometer measurements achieving the 6-hour sampling requirement	Annual WMO-CGMS Gap Analysis
5.6	Work towards operational 3D wind and aerosol profile observations from space-based lidar	Annual WMO-CGMS Gap Analysis
5.7	Work towards providing global hourly Microwave sounding observations	Annual WMO-CGMS Gap Analysis
5.8	Work towards providing continuity of precipitation and cloud radar measurements	Annual WMO-CGMS Gap Analysis
5.9	Provide operational altimetry measurements for very high latitudes cryospheric monitoring.	Annual WMO-CGMS Gap Analysis.

Specific recommendations for Space Systems, for Members 2023–2027		
Action No.		Performance indicator
5.10	Enhance satellite observations as an integral part of the observing system. Take into consideration needs for atmospheric composition observations in measurement system development, data reporting, and exchange.	Uptake of atmospheric composition space-based observations in measurement systems.
5.11	Ensure continuity of MR/IR limb sounding observations	
5.12	Study the architecture for future absolute calibration reference missions, covering VIS/NIR, IR and MW	Annual WMO-CGMS Gap Analysis

IUS concepts and guidance and observation requirements are being formalized; however, there is general agreement on the first order gaps, priorities and actions. See [Annex 5](#) for an extended discussion of the priorities.

[Annex 2](#), Statement of Guidance Gap Overview per Variable, lists available technology to measure the required variables and gives comments on costs, complementarity of technologies and capacity development aspects.

2.6 Recommendations on data policy and data availability

The Extraordinary Session of the World Meteorological Congress in October 2021 (Cg-Ext(2021)) adopted the Resolution 1 on the WMO Unified Data Policy for the International Exchange of Earth System Data. As a fundamental principle of WMO and in consonance with the expanding requirements for its scientific and technical expertise, WMO commits itself to broadening and enhancing the free and unrestricted international exchange of Earth System data. The Congress agrees to have one unified data policy for all WMO domains and disciplines. The scope of the data policy shall cover Earth System data exchanged among Members, the Annex of the resolution list the minimum set of core data that Members shall exchange on a free and unrestricted basis. It also identifies certain recommended data that should be exchanged by Members to support Earth System monitoring and prediction efforts. INFCOM is requested in coordination with SERCOM and the RB to draft Technical Regulations to support the implementation of this resolution until WMO Congress in 2023. For further details see the complete resolution.

The ad hoc working group GODEX-NWP (global data exchange for NWP) provides a forum to discuss and resolve practical issues with data exchange of all Earth System observations required by the global NWP centres, for both satellite and surface-based observations.

2.7 Radio frequency coordination

The specific radiocommunication services allocated in the Radio Regulation are of prime importance for meteorological and related environmental activities. These frequency band allocations and their protection are essential for meteorological data collected by Earth exploration systems (including remote-sensing) and surface-based observing systems, including in particular radiosondes, weather radars, radiometer and wind profiler radars.

In order to ensure the long-term usage of these meteorological equipment, and in particular due to the pressure on radio spectrum created by new deployment of future commercial communication technologies, it is of prime interest for WMO Members to actively contribute to any radio-frequency regulation evolution at national, regional or international levels and in particular regarding the preparation of next World Radiocommunications Conferences planned in 2023 and 2027.

Furthermore, due to the needed long period to obtain new rights to operate future meteorological systems, any new development or improvement involving radio-frequency to inform SC-ON.

3. GUIDANCE ON THE DEVELOPMENT OF A NATIONAL IMPLEMENTATION STRATEGY FOR THE VISION OF WIGOS IN 2040

In this section an example is given of how the Deutscher Wetterdienst (DWD) proceeded to develop a national strategy to implement the Vision for WIGOS in 2040. The development of the national observing systems must be in correspondence with national strategic goals of the Meteorological Service taking WMO requirements into account. The starting point for the development of a national implementation strategy is the WMO RRR process and the Vision for WIGOS in 2040 document.

When developing a national strategy on the evolution of the observing systems, experts from different application areas and technical experts from network design and instrumentation must contribute to the national implementation strategy. This is very important since many different aspects must be taken into account. The user requirements must be harmonized with accuracy and reliability of the measurements, quality monitoring and quality control procedures, financial constraints and implementation timelines.

The following sections give a summary of DWD's approach.

3.1 Survey of national requirements for the different application areas

Integrated into WMO Technical Regulations and Guidance for regional and global observing systems, the national observing network must comply with special national requirements. These cover requirements of the warning and forecasting processes for the general public, aviation services, climate monitoring and forecasting and will be delivered through nowcasting applications, NWP and climate models. The strategy of DWD includes several dedicated goals:

- (a) Development of a seamless forecasting system from observation to 12-hour forecasting with 5-minute time resolution of remote-sensing and surface-based data;
- (b) Improved data availability for weather monitoring, forecast and warning processes, use of third-party data;
- (c) Deliver improved services for air traffic safety and total airport management;
- (d) Improved climate research and climate services with sustained data acquisition and support of reference networks.

3.2 Compilation of technology-free national requirements and network design principles

Based on the national requirements under [Section 3.1](#), a summary of the technology-free requirements was compiled (similar to OSCAR/Requirements) and, in addition, relevant combinations of in situ and remotely sensed techniques including satellite programmes that could fulfil the requirements were listed.

The WIGOS Observing Network Design principles give guidance on different aspects to be considered when designing and/or enhancing the observing system. Taking these into account, detailed needs for the observing system were specified, such as data availability monitoring, quality requirements, accuracy, timeliness, homogeneity and sustainability.

3.3 Concept on the development of the National Observing Capabilities

Based on the information from the preceding sections a vision was developed for the long-term view on the development of the integrated national observing system.

The national implementation strategy, developed on the basis of the vision, was split into three development lines:

- (a) integrated forecast system;
- (b) complete automation of the ground-based observing networks;
- (c) combination of different measured quantities from surface-based and satellite measurements to estimate meteorological relevant variables (i.e. state of the ground, sunshine duration).

3.4 Proposals for pilot activities

Finally, within the development lines detailed project plans for pilot activities were developed, with deliverables, budget lines, timetables, etc.

4. CAPACITY DEVELOPMENT OPPORTUNITIES AND GUIDANCE BASED ON SYSTEMATIC OBSERVATIONS FINANCIAL FACILITY (SOFF) AND COUNTRY SUPPORT INITIATIVE (CSI)

Many developing countries and countries with economies in transition do not have the capabilities or the resources to provide the essential surface-based observations. This is a challenge for the consistency and the homogeneity of observations, especially at the global scale. Efforts are therefore needed to support these countries, especially LDCs and SIDS, by providing guidelines and organizing training and capacity building events in the respective Regions, as well as assisting them to develop, strengthen and maintain their infrastructure thanks to new financing instruments.

Capacity Development Opportunities

Facilities and initiatives such as the [SOFF](#) and [CSI](#) are designed to assess systematically capacity gaps and take active measures to develop capacity, in particular for LDCs and SIDS. These mechanisms are intended to be beneficial at both short and long terms. SOFF will particularly support countries to generate and exchange basic observational data critical for improved weather forecasts and climate services. It will provide technical

and financial assistance in new ways – applying internationally agreed metrics and the requirements of the GBON – to guide investments, using data exchange as a measure of success, and creating local benefits while delivering on a global public good. The SOFF will contribute to strengthen climate adaptation and resilience across the globe, benefiting in particular the most vulnerable.

The creation of the SOFF is led by the WMO in collaboration with a wide range of international organizations, including the members of the [Alliance for Hydromet Development](#). The Alliance unites efforts of major development and climate finance partners to close the capacity gap on high-quality weather forecasts, early warning systems and climate information. The Alliance Members commit to strengthen the capacity of NMHSs for sustained operation of observational systems and data exchange that meet WMO standards for minimum monitoring coverage and reporting frequency.

The weather forecasts and climate predictions upon which society depends would not be possible without the real-time, international exchange of observational data from all over the world. The GBON will significantly improve the availability and international exchange of surface-based observational data. This can deliver benefits of over US\$ 5 billion¹² annually.

The benefits of increased surface-based observations through GBON will be most felt in regions that are most vulnerable to climate change and its impact including Africa, South America, South-West Pacific and parts of Asia. GBON sets out an obligation and clear requirement for all WMO Members to acquire and to exchange internationally the most essential surface-based observational data at a minimum level of spatial and temporal resolution.

Whilst some regions provide a good supply of surface-based observations, some areas of the world, notably SIDS and LDCs lack significant infrastructure and capacity to meet GBON requirements. Closing these gaps requires a new way of financing. The [SOFF](#) is being established to provide technical and financial assistance in new ways. SOFF will use data exchange as a measure of success. In its initial phase, SOFF aims to support 68 SIDS and LDCs to achieve sustained GBON compliance.

SOFF support will be provided to the country in three phases. In the Readiness phase, the country's hydromet status will be assessed, the GBON gap defined, and a plan developed to close the gap. The investment phase enables countries to close the GBON investment and capacity gap. The Compliance phase supports sustained GBON compliance and enables access to improved weather forecasts and climate analysis products.

At COP25 in December 2019, the Alliance for Hydromet Development was launched. The creation of the SOFF is envisaged to become an action of high priority for the Alliance. For the transition period, WMO decided to establish the CSI, as a complementary vehicle to support development and climate finance partners in ensuring that their financing for observations responds to GBON obligations.

In GBON's design, lack of observations meeting GBON requirements from SIDS and LDCs is recognized. The overarching GBON driver is global NWP, setting an "obligation" for all Members to provide essential observations meeting basic requirements. "Culture of compliance" as promoted in the plan for the WIGOS Initial Operational Phase 2020–2023 is a strategy for increasing the amount of data exchanged, and the degree to which data adhere to established WMO standards. While such approaches imply a tightening of how the expected use of global Earth System infrastructure is prescribed to Members, there are also potential benefits to SIDS and LDCs in the form of access to resulting NWP model output and early warning system output, including improvements to NWP by using more/better observations as the observational gaps are reduced. The WMO Unified

Policy, as approved by Cg-Ext(2021), for the international exchange of Earth System data is meant to provide for such equitable sharing of data, whether the data be observational or model output, as long as the data are identified as either “core” or “recommended”. For example, “core” data *will include Global analysis and prediction fields provided by global numerical weather prediction (NWP) systems of designated producing centres of the Global Data Processing and Forecasting System (GDPFS), as specified in the Manual on the Global Data-processing and Forecasting System (WMO-No. 485)*. This is of great potential benefit in a capacity development context, as it offers the ability to balance the GBON requirements on access to observations for NWP with the providers’ needs to access high-quality weather forecasts, output from early warning systems and climate information.

In recent years, inequities and disparities between developed and developing countries have increased with regard to availability of, and ability to leverage and benefit from, innovations to information and communications technology (ICT). This applies to both computational resources to manage and process data, and network capacity to share data and information. Cloud computing has the potential to become a game-changer in this regard, if leveraged equitably, and initiatives are underway to demonstrate it. For example, the [European Weather Cloud](#) (European Centre for Medium range Weather Forecasts (ECMWF), EUMETSAT, and National Meteorological Services of their Member States) is being established and can serve as a proof-of-concept for Regional Association VI. With observations and model output being collected on cloud computing platform(s), the following can be envisaged with capacity development in mind:

- (a) In cloud availability of (i) more observations than would be potentially available locally through conventional message-switching systems for a typical Member; (ii) NWP model output; (iii) other outputs of Earth System observing and modelling capabilities; (iv) visualization/display functionality (this is particularly valuable at early stages of capacity development, to provide as low a barrier as possible e.g. for accessing forecast guidance in graphical forms); (v) computational resources and software frameworks for creating customized workflows. This is useful for Members with intermediate and advanced capacities to create applications and information supporting their mandates; (vi) possibly archived data; and (vii) training course material.
- (b) Development, operation and maintenance of the cloud computing platform collectively, through a consortium of Members and/or through a service provider.
- (c) Technical point of failure for an individual Member becomes, in principle, reduced to network connectivity to the cloud.

Such a proof-of-concept, and other similar experiences, can be elaborated and extended to global application, benefiting all WMO Members. Such technical strategies can thereby be greatly beneficial for data sharing and capacity development.

Metrics for assessing success, in the form of quantified amounts of data exchange, e.g. for monitoring of SOFF activities, should be bidirectional. Availability of observations from a Member, with the goal of fulfilling its GBON obligations, can be paired with availability of NWP model output supporting that Member. This would put an onus on the global NWP centres to make their outputs available. This is already being done to some extent, e.g. the ECMWF provides NWP model output in graphical form and is taking steps towards making its NWP model data available according to Open Data policy. Increased availability of NWP model outputs from the global NWP centres would go a long way towards providing incentives and equity that can help drive GBON and WIGOS compliance and supporting capacity development.

Training Opportunities

The Plan for the Initial WIGOS Operational Phase 2020–2023 includes promoting a number of activities supporting capacity development. In particular, guidance, learning material and training events are organized at the regional level with support of the RWCs and the Regional Training Centres (RTCs), covering topics such as collection of WIGOS metadata in [OSCAR/Surface](#), use of the [WDQMS](#), and of the Incident Management System (IMS). Such material is available from the [WIGOS Learning Portal](#).

SC-MINT have been developing and promoting education and training material and recommend competency-based training events in the field of environmental measurements, instrumentation and traceability, in collaboration with RTCs, Regional Instrument Centres, Regional Marine Instrument Centres, Regional Radiation Centres and Measurement Lead Centres. A series of workshops on topics such as Transitioning to Automated Ground-based Measurements, and on Quality, Traceability and Compliance have already been held in several WMO Regional Associations and will be extended to other Regions, as appropriate. These, and other planned training activities, cover topics found in the Compendium of WMO Competency Frameworks for Instrumentation, Calibration, Meteorological Observations and Observing Programme and Network Management. Presentations and recordings from these workshops and associated training material is also available from the WIGOS Learning Portal.

The GAW Training & Education Centre (GAWTEC) is responsible for training and education of station personnel from global and regional GAW stations by teaching measurement techniques and data analysis, including those for ozone observations using Brewer and Dobson instruments and ozone sondes. GAW also sponsors VOC training courses and workshops focused on measurement techniques, methods, QA-QC, and data submission.

Some countries have satellite receiving stations or receive satellite data through the WIS, but they lack the expertise to utilize the information to their benefit. The Virtual Laboratory for Training and Education in Satellite Meteorology ([VLab](#)) can help; it is a global network of specialized training centres and meteorological satellite operators working together to improve the utilization of data and products from meteorological and environmental satellites. The VLab can continue to coordinate with CEOS [Working Group for Capacity Building and Data Democracy](#) (WGCapD) to further enhance skills of users in the developing countries by making a broad range of trainings on Earth observations and their applications accessible via the [CEOS Training Calendar](#). The training calendar can be used to find or promote trainings relating to a broad set of thematic areas and geographies offered by CEOS members and associates, the Group on Earth Observations (GEO) members, and other organizations engaged in providing trainings on Earth observations. Continued participation in the [Earth Observation Training, Education, and Capacity Development Network](#) (EOTEC-DevNet), a joint initiative of CEOS, CGMS, GEO, WMO and UNOOSA capacity development groups, is encouraged to address an important need for the coordination of various capacity building, outreach and training activities across the full value chain from space-based observations to downstream services and end users.

Recommendations

The following high-level recommendations are made:

- (a) Developed Countries are encouraged to make their NWP outputs available to Developing Countries per WMO Unified Data Policy for the International Exchange of Earth System Data; efforts can be envisaged at the regional level to promote cloud computing solutions to serve such a purpose;

- (b) LDCs and SIDS are encouraged to make applications to strengthen or further develop their GBON observing infrastructure using SOFF as appropriate;
- (c) It is particularly challenging to sustain capacity once it is developed, when targeted efforts in the form of projects with associated resources transition into regular organizational programmes that may not be adequately resourced. Efforts should therefore be made at the national level to assure sustainability of the implemented GBON infrastructure.

In addition, the following guidelines are proposed for the allocation of priorities for technical cooperation activities for the meteorological observing systems (by order of priority):

- (a) Set up projects to improve/restore existing and to build new upper-air observational capabilities of the RBON¹⁷, with emphasis on the activation of silent upper-air stations and the improvement of coverage over data-sparse areas (in particular as regards the purchase of equipment and consumables, telecommunications and the training of staff).
- (b) Extend AMDAR coverage to developing countries, LDCs and SIDS to supplement scarce upper-air observations or to provide a cost-effective alternative to countries that cannot afford costly upper-air sounding systems, taking advantage of the WICAP (see [Section 2.4.3](#)).
- (c) Set up projects related to improving of data quality, regularity and coverage of surface observations of the RBON with emphasis on the activation of silent stations and the improvement of coverage over data-sparse areas.
- (d) Set up projects related to the introduction and/or use of new observing equipment and systems including, where cost-effective, surface-based AWSs, AMDAR, ASAP and drifting buoys.

Technical cooperation for achieving reliable communications would make a valuable contribution to ensure that observational data, once collected, can be widely exchanged.

Finally, the following recommendations should be taken into account when addressing the evolution of observing systems in developing countries:

- (a) Define geographical areas to which priority for additional observations should be assigned, if additional funding were available.
- (b) Assign high priority, at the Regional level, to maintaining a minimum radiosonde network with acceptable performance.
- (c) Employ data rescue activities to preserve the historical observation record in developing countries and those of historical observing stations, and make long-term datasets available for activities including reanalysis, research, adaptation, monitoring and other climate services.
- (d) Encourage Regional Associations, in concert with the Infrastructure Commission, to define field experiments over data-sparse areas, for a limited time, to evaluate how additional data would contribute to improve

¹⁷ GCOS Surface Network (GSN) and GUAN stations are part of the RBON (Regional Basic Observing Network)

performance at the regional and global scales, following the example of the African Multidisciplinary Monsoon Analysis (AMMA18) field experiment.

- (e) Examine the extent to which automated stations could become a viable, cost-effective alternative to manual stations for the surface network in the future and investigate improved configurations of automated and manual stations.
- (f) Follow the Observing Network Design Principles (see WMO-No. 1160, Section 2.2.2.1 and Appendix 2.1) and proper change management practices when changes are made to the climate observing systems through close collaboration between observations managers and climate scientists¹⁹.
- (g) For nowcasting and risk mitigation in vulnerable areas, the availability of a robust (against extreme weather conditions) telecommunication infrastructure is an issue. Utilize robust telecommunication networks.
- (h) Use the regional centre concept to provide access to specialists who could conduct training and maintenance of more complex systems including AWS.

A significant step forward has been made at WMO Cg-Ext(2021) in October 2021 by approving the draft resolution 4.2/1 which endorses the establishment of SOFF which will provide technical and financial support for the implementation and sustained operation of GBON in LDCs and SIDs. The Secretary-General, in collaboration with the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP) and the United Nations Multi-Partner Trust Fund Office to pursue the creation of SOFF as a United Nations Multi-Partner Trust Fund as a matter of urgency.

5. COMMUNICATION PLAN ON THE NEED TO RESPOND TO THE VISION FOR WIGOS IN 2040

The priority actions proposed in this High-Level Guidance document for the evolution of space-based and surface-based observing systems in Section 2.5 above must be communicated among key stakeholders and agents of implementation. The key messages must be communicated to various target audiences to engage them effectively. During the WIGOS operational phase, NMHSs, working with national partners, are expected to take on greater responsibility for the national implementation of WIGOS.

Fostering a culture of compliance with the WIGOS Technical Regulations is a key priority during the initial operational phase of WIGOS. Through the WIGOS Indicators adopted by the Executive Council (see [Decision 4.2\(4\)/1 \(EC-73\)](#)) progress in the WIGOS national implementation can be monitored. Those indicators allow a more realistic assessment of Member's compliance with WIGOS implementation and evolution of observing systems. The plan for the WIGOS Initial Operational Phase, approved by the Executive Council (see [here](#)), includes a section on the culture of compliance as one of the priorities of the plan.

The key messages of this guidance document will be communicated to stakeholders and agents of implementation, which are:

- (a) Technical managers and executives of NMHSs;

¹⁸ see <http://amma-international.org/>

¹⁹ see WMO-TD No 1378 on: https://library.wmo.int/doc_num.php?explnum_id=4545

- (b) International partner organizations and programmes;
- (c) National partner organizations;
- (d) Space agencies;
- (e) Scientific partners from universities;
- (f) funding organizations and donors.

To communicate the content of the High-Level Guidance document, the following communication channels and activities can be used:

- (a) WIGOS training events and the WMO RTCs for information exchange,
- (b) Regional WIGOS Centres;
- (c) WIGOS National Focal Points;
- (d) presentation of results of the High-Level Guidance where opportunities exist, at side events during meetings organized by partners and other stakeholders.

The activities will be regularly reviewed and updated, considering the implementation progress and feedback from all stakeholders.

WIGOS RELEVANT DOCUMENTS, REGULATORY AND GUIDANCE MATERIAL

1. WIGOS relevant documents

During the development and pre-operational phase (2016–2019) for WIGOS, several documents and supporting tools, as well as regulatory and guidance material, have been developed. In addition, a plan for the WIGOS Initial Operational Phase (2020–2023) has been developed.

In this Annex the relevant WIGOS documents, tools and regulatory material are linked up and advice is given how they are connected.

WIGOS is a core activity and a basic WMO infrastructure element supporting all WMO programmes and application areas. WIGOS provides the global framework, the management and design tools for all contributing observing systems to optimize user-driven investments for sustainable developments to deliver weather, climate, water and related environmental services. This is particularly the case for the following types of observations:

- (a) Weather and climate observations of the Global Observing System (GOS) and the GCOS networks;
- (b) Atmospheric composition observations, i.e. the observing component of the Global Atmosphere Watch (GAW);
- (c) Hydrological observations of the WMO Hydrological Observing System (WHOS);
- (d) Cryosphere observations, i.e. the observing component of the Global Cryosphere Watch (GCW);
- (e) marine meteorological and oceanographic observations of the Global Ocean Observing System (GOOS).

Details can be found at the WIGOS webpage:

<https://public.wmo.int/en/programmes/wigos> and <https://community.wmo.int/activity-areas/wigos>

Further details on WIGOS components Implementation Plans can be found under:

- (a) Global Cryosphere Watch (GCW) Implementation Plan, version 1.6 (24 January 2015) and version 1.7 (19 April 2016),
- (b) WMO Global Atmosphere Watch (GAW) Implementation Plan: 2016–2023. GAW Report No. 228. World Meteorological Organization, 2017,
- (c) The Global Observing System for Climate: Implementation Needs. GCOS-200. WMO, 2016,
- (d) Implementation Plan of the Global Framework for Climate Services (GFCS). WMO, 2014,
- (e) WMO Hydrological Observing System (WHOS) Phase II – Initial Implementation Plan, WMO, May 2018.

During the pre-operational phase of WIGOS from 2016–2019, the main activities were structured along five priority areas, namely: (1) National WIGOS implementation; (2) WIGOS Regulatory Material complemented with necessary guidance material to assist Members with the implementation of the WIGOS Technical Regulations; (3) Further development of the WIGOS Information Resource (WIR), with special emphasis on the operational deployment of the OSCAR databases; (4) Development and implementation of the WDQMS; and (5) Concept development and initial establishment of RWCs. Details are given in the Plan for the WIGOS pre-operational phase 2016–2019 ([PWPP](#)). The WMO Congress noted in 2018 ([Resolution 37 \(Cg-18\)](#)) the progress made during the WIGOS implementation and pre-operational phase and decided that the system should be considered operational, effective from 1 January 2020, and should be continued as a core WMO activity. Therefore, the Commission for Observation, Infrastructure and Information Systems (INFCOM) endorsed a plan for the WIGOS Initial Operational Phase (2020–2023) at its first session which was then adopted by EC-73 (see [here](#)). The highest priorities for WIGOS during this period are:

- (a) National WIGOS implementation, including necessary capacity development, partnership agreements and integration of observing systems for all application areas.
- (b) Fostering a culture of compliance with the WIGOS Technical Regulations.
- (c) Implementation of the Global Basic Observing Network and the Regional Basic Observing Networks.
- (d) Operational deployment of the WIGOS Data Quality Monitoring System.
- (e) Operational implementation of Regional WIGOS Centres.
- (f) Further development of the OSCAR databases.

High priority will be given to those activities that will assist Members in developing and implementing their National WIGOS Implementation Plans, with special emphasis on the LDCs, Landlocked Developing Countries and SIDS where the needs are the highest.

The plan for the WIGOS Initial Operational Phase (2020–2023) was built upon the capabilities developed during the pre-operational phase. Noting the Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP), Cg-18 invites Members and identified implementation agents to take steps better to address implementation of some specific EGOS-IP actions, as listed in [Annex 3](#) of this document.

A [Communication and Outreach Strategy](#) has been designed to support the implementation of WIGOS. The Strategy aims to ensure that all relevant information about WIGOS – the concept, benefits, impacts, key implementation activities, progress and challenges – is easily accessible to all WMO Members and stakeholders.

The [RRR](#) compiles information on Members evolving requirements for observations in currently 14 Application Areas to meet the needs of all WMO programmes. The comparison of user requirements with observing system capabilities for a given application area is called a Critical Review. This is reviewed by experts in the relevant application areas and used to prepare a SoG, the main aim of which is to draw attention to the most important gaps between user requirements and observing system capabilities, in the context of the application (see also [Section 2.1](#)). With WMO's Earth System approach and consideration of evolving user requirements and the increased role of the private sector, the RRR and its processes is being reviewed by INFCOM during the intersessional period 2020–2023.

A detailed compilation of all variables and requirements for the different application areas is given in the OSCARs data base ([Observing System Capability Analysis and Review Tool](#)). New releases of OSCAR/Space and OSCAR/Surface were made operational during the second half of 2020.

The [Vision for WIGOS in 2040](#) document presents a likely scenario to guide the evolution of the WIGOS in the coming decades and an ambitious but technically and economically feasible vision for an integrated observing system that will address identified observational requirements. It anticipates a fully developed and implemented WIGOS framework that supports all activities of WMO and its Members within the general areas of weather, climate, water, and other related environmental applications. The Vision attempts to address the needs of all the Application Areas with WMO programmes and co-sponsored programmes to which WIGOS responds. The Vision considers that future observing systems 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.

NMHSs are no longer the sole providers of meteorological observations. Instead, typically a variety of organizations are now running observing systems of interest for WMO application areas. It is a principle of WIGOS to integrate these observations into one overall system to the extent possible.

The [GBON](#) is a fundamental element of WIGOS. GBON is aimed particularly at strengthening the surface-based components of the observing system, and it will address those observing requirements that cannot currently be met by space-based observing systems. It represents a new approach in which the basic surface-based observing network is designed, defined and monitored at the global level. Once implemented, GBON will improve the availability of the most essential surface-based data, which will have a direct positive impact on the quality of weather forecasts. The WMO community website includes the concept, an executive summary and presentations on GBON.

The draft GBON provisions and draft process for the nomination of GBON stations was discussed at the first Session of the WMO Infrastructure Commission (see [WMO-No. 1251](#), abridged final report of the session) and was submitted to EC-73 after review by Members. The draft GBON provisions were finally adopted by the Extraordinary Session of the World Meteorological Congress in October 2021; these will come into force on 1 January 2023.

2. WIGOS Regulatory and guidance material

The Technical Regulations are designed to ensure adequate uniformity and standardization in the practices and procedures to facilitate cooperation in meteorology and hydrology among Members, see Technical Regulations ([WMO-No. 49](#)), Volume I – General Meteorological Standards and Recommended Practices, Part I – WIGOS.

The Manual on WIGOS specifies the obligation of Members in the implementation and operation of WIGOS. It facilitates cooperation in observations among Members, and it ensures adequate uniformity and standardization in the practices and procedures employed (Manual on WIGOS ([WMO-No. 1160](#)), 2019 edition)

The 2018 updated version of the Guide provides material relevant to some of the new WIGOS related regulations. The topics covered include the new system of WIGOS station identifiers, the new requirements to record and make available metadata as specified in the WIGOS Metadata Standard, the new OSCAR tool to be used by Members to submit metadata for WMO global compilation, and the new observing network design (OND)

principles. The principles give guidance for NMHSs how to design and evolve their observing networks. Members are encouraged to follow the OND principles. For the evolution of the global observing system in the period 2020–2023 the tiered network approach is important, through which information from reference observations of high quality can be transferred to other observations and used to improve their quality and utility. For details see Guide to the WMO Integrated Observing System ([WMO-No. 1165](#)), 2017 edition updated 2018.

The Guide to Meteorological Instruments and Methods of Observations ([CIMO Guide](#)) gives advice on good practices for meteorological measurements and observations. It sets technical standards, quality control procedures and guidance for the use of meteorological instruments and observation methods in order to promote development and worldwide standardization. At present, observing technologies such as remote-sensing instruments operating on-board satellites and on the earth surface (e.g. weather radars) provide the main source of information about the Earth's atmosphere and surface. Comprehensive technical and operational information on the use of radiofrequencies by meteorological systems are given in the WMO/ITU handbook "Use of Radio Spectrum for Meteorology" ([Handbook on the use of Radio Spectrum](#)). It is most important that the meteorological community defend the needed frequency band against other commercial users. WMO expert teams, experts from space agencies and regional cooperation programmes such as EUMETREQ have conducted many studies to protect frequency bands and represented WMO at ITU level. These efforts must continue. Furthermore, it is of prime importance that any new application or equipment using radio frequency are known at international level (ITU) in order to ensure the appropriate protection. As process to develop regulatory text at international level needs long delays, an advance information to WMO expert teams is essential to ensure adequate protection. In addition, the efforts of the WMO Expert Team on Radio Frequency Coordination must be supported by national experts.

WIGOS provides a number of tools that can be useful in the implementation of WIGOS at global, regional and national levels. OSCAR is a resource developed by WMO in support of Earth Observation applications, network planning studies and global coordination. The [OSCAR](#) is a web-based inventory of all surface- and space-based stations/platforms of WIGOS, it has the following components:

- (a) OSCAR/Surface and OSCAR/Space contain information about surface- and space-based observing system capabilities.
- (b) OSCAR/Requirements contain user requirements for all Application Areas supporting WMO Programmes, and
- (c) OSCAR/Analysis will be used to compare those requirements with the observing system capabilities (RRR, Critical Review). The tool is being further developed and further functionality and information will be added as appropriate.

OSCAR/Space has been available at the WMO Secretariat since 2012, the latest version 2.6 being released in October 2021. It was a major software upgrade with several new features related to the Gap Analysis and the Search Tool. Today OSCAR/Space contains information related to 1000 instruments. Approximately 650 of those are dedicated for Earth Observations and 350 for Space Weather Missions. It is a reference source for information maintained by WMO for the benefit of satellite users and satellite operating agencies worldwide.

OSCAR/Surface has been developed jointly by WMO and MeteoSwiss since 2014 for the surface, requirements and analysis components. Improvements are routinely being added through regular OSCAR/Surface releases, for example, the October 2021 release

added a feature for automatic inclusion of monitoring information from the WMO Data Quality Monitoring System to reflect actual operational status of observing stations in OSCAR/Surface.

To learn more about OSCAR and other WIGOS Tools, visit the [WIGOS Learning Portal](#) which contains a number of tutorials and training courses. It contains learning material for OSCAR/Surface, for WDQMS and other WIGOS related topics, such as videos, presentations, documents, links, etc., as well as the materials delivered at regional training workshops.

The [WDQMS webtool](#), closely connected to OSCAR, is a resource developed by WMO, and hosted by ECMWF, to monitor the performance of all [WIGOS](#) observing components.

The current operational version of the webtool monitors the availability and quality of observational data based on near-real-time monitoring information from the four participating global NWP centres: the German Weather Service (DWD), the ECMWF, the Japan Meteorological Agency (JMA) and the USA's National Centres for Environmental Prediction (NCEP). The tool links availability and quality of surface-based observational data from those WIGOS Monitoring Centres with the WIGOS metadata and user requirements from OSCAR, providing information on network/station issues to WMO Members and to RWCs for follow up. The NWP monitoring is currently available for surface land stations (SYNOP reports) and upper-air Radiosonde land stations (TEMP and PILOT reports).

At EC-69 indicators for the monitoring of the progress of the WIGOS national implementation were approved and at the [WIGOS readiness](#) website the progress can be monitored (as of 1 June 2019).

ANNEX 2

STATEMENT OF GUIDANCE GAP OVERVIEW PER VARIABLE

Table 1 below provides an overview of observational gaps extracted from the Statements of Guidance of WMO Application Areas, with indication of priorities for addressing them, available and emerging technologies, and some comments or recommendations to be considered.

Table 1: Requirement variables and their gaps from the Statements of Guidance

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
u and v-comp of wind in the 3D domain.	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or poor over ocean and sparsely inhabited land Very few in situ wind observations from the Polar Regions. In the lower stratosphere, only radiosondes provide wind information With hyperspectral infrared sounders becoming available on geostationary satellites, this may provide further improvement of the analysed 3D wind field <p>High Resolution NWP:</p> <ul style="list-style-type: none"> In many regions however, the lack of reliable observations is obvious. The quality of data retrieved from well-maintained wind profilers is good, whereas the quality of winds from the Velocity Azimuth Displays (VAD) technique may be questionable. In addition, geostationary satellite derived wind information gives acceptable information because of the high observing frequency and the high horizontal resolution, although generally limited to single level wind observation at few levels determined with a poor accuracy. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Wind coverage in Polar Regions is essentially absent. The temporal resolution of wind profiles from radiosondes is marginal to acceptable. 	<p>Radiosondes, pilot balloons, Aircraft winds, Wind profiler radars, Weather radar winds, VAD Multi-static Doppler wind measurements, Indirect wind measurements: Multi-spectral VIS/IR imagery with rapid repeat cycles. Satellite hyperspectral infrared sounders</p>	<p>Mode-S (operationally assimilated at the Met Office since 2020, global NWP and High-resolution NWP, Li 2021)</p> <p>Doppler lidar (Aeolus mission operationally assimilated at ECMWF since 2020 global NWP)</p> <p>Unmanned Aerial Vehicles (UAV) for high resolution model.</p> <p>Ground-based Doppler lidar,</p>	<p>Mode-S: Free data, profiling capability near airport, good coverage at cruising level</p> <p>Aeolus was designed in the 1990s, and supposed to last at least 3 years, so there are many aspects of the technology that could be improved in a possible future operational mission.</p> <p>UAV: Limited Height (depend on country regulation) MeteoSwiss done experiment with fully automated drone going up to 2 km height. (Leuenberger et al 2020)</p> <p>In 2022–2023 the WMO JET-ABO team is looking to organize a global demonstration project which will focus on the data quality, standards and formats for meteorological data as well as an assessment of the impact of data assimilation on regional NWP. Possible collaboration with third parties using drone (10 years' time)</p>

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<ul style="list-style-type: none"> Satellite winds are of acceptable to marginal accuracy and vertical coverage is marginal <p>Aeronautical Meteorology:</p> <ul style="list-style-type: none"> Higher accuracy in the wind forecasts may be achieved by an enhanced collection of aircraft-based observational data (e.g. down linked from AMDAR, ADS-B (Automatic Dependent Surveillance) and Mode-S systems) and observed in the terminal areas. Furthermore, scanning weather radars often face problems for near-surface measurements because of the presence of many non-meteorological artefacts which heavily contaminate the signal. 		<p>within boundary layer and in optically thin clouds</p> <p>Radiosonde descent measurements.</p> <p>Round-trip drifting Sounding System. [China]</p>	<p>Diode laser technology allows cheaper lidar technique than before. Does not suffer like radar from ground clutter, frequency allocation. Useful for airport, urban meteorology (Barlow 2011).</p> <p>Wind Doppler lidar will be with other instrumentations used for the Research Demonstration Project (RDP) Paris 2024 Olympics.</p> <p>A low-cost and innovative profiling technique, the three-stage Round-trip Drifting Sounding System based on China's Beidou Navigation Satellite System, that can provide cost-effective and extended sounding data is ready for operational use. By releasing one sounding balloon, it provides successively the ascending vertical profile, the floating horizontal profile and the descending vertical profile of high-resolution sounding data. The special profiling technique is ready for operational use after more than 3,000 successful test-runs in 5 years. [China]</p>
Surface pressure	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over some areas in the tropics and the Arctic Surface pressure is not observed by present or planned satellite systems except for some small contribution from radio occultation data and measurements of SoG for GNWP – 4 – differential atmospheric optical depth for a gas of known composition such as oxygen (e.g. the NASA's OCO-2 mission) <p>Long-Term Reanalyses for climate studies</p> <ul style="list-style-type: none"> Because long historical in situ observation data of surface pressure exist, the data are mostly used as the primal 	Ships, drifter buoys, moored buoys, surface stations, NIR spectrometer	Saildrones over ocean	<p>Sensitivity studies using atmospheric data assimilation systems indicates sea-surface pressure data in the mid- and high – latitude have large impacts on weather forecast skills. But the impact of sea-surface pressure data in the tropics is not clear.</p> <p>Pressure sensors are relatively expensive compared with sensors of other standard surface atmospheric elements such as temperature, humidity, and winds. It becomes the obstacle for installing it on moored buoys.</p>

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<p>observation data in the long-term reanalyses for climate studies, and it will be supportive for those applications to continue in situ surface pressure observations.</p> <p>Ocean Applications:</p> <ul style="list-style-type: none"> Ships and drifter buoys take standard surface observations of several atmospheric variables, including sea-surface pressure. Only a small number of moored buoys take sea-surface pressure. In relatively shallow waters, oil platforms do the same, but the frequency and spatial coverage are marginal for marine services applications. The resolution of surface pressure observations should be increased to possibly improve accuracy of total sea level forecasts in the coastal and estuarine regions, especially during extreme weather events. 			
<p>Near-surface u and v-comp of wind, as a 2D field</p> <p>Usually at 10 m</p>	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over some areas in the tropics and the Arctic Altimeters on polar satellites provide information on wind speed only with global coverage and good accuracy. However, horizontal and temporal coverage is limited <p>High Resolution NWP:</p> <ul style="list-style-type: none"> The interpretation of local wind data is complicated in mountainous terrain, where local diurnal circulations are common polar orbiting satellite surface wind information is very useful for global models, but its temporal frequency is marginal for forecasts at mesoscale <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> The interpretation of local wind data is complicated in mountainous terrain, where local diurnal circulations are common wind measurements can be locally good, but for many regions just acceptable or even marginal for nowcasting applications 	<p>Scatterometers on polar orbiting satellites, Ships, buoys, Passive polarimetric radiometers, L-band microwave imagers, Local observing mesoscale networks, Doppler lidars and terminal Doppler weather radars, Boundary layer wind profilers, IR hyperspectral sounders, VIS/IR imagery,</p>	<p>GNSS reflectometry (GNSS-R) missions; passive MW; SAR</p>	<p>See "ocean wind stress" for use of surface wind data to force ocean general circulation models.</p>

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<ul style="list-style-type: none"> Over ocean, ships and buoys provide wind observations of acceptable/marginal frequency and accuracy <p>Aeronautical Meteorology:</p> <ul style="list-style-type: none"> Boundary layer wind profilers provide useful information on vertical shear and turbulence but are limited in sampling the horizontal wind changes over the flight paths for alerting wind shear. Cloud-motion winds are rarely capable of providing data continuously in the planetary boundary layer over land. <p>Ocean Applications:</p> <ul style="list-style-type: none"> For ocean wave calculation, the data coverage is not sufficient, and the accuracy of the satellite surface wind data is insufficient, especially in the stormy wind speed range. 	realization of a day/night band, GNSS reflectometry (GNSS-R) missions; passive MW; Synthetic Aperture Radar (SAR)		
Air temperature in the 3D domain	<p>Global NWP:</p> <ul style="list-style-type: none"> Over most of the Earth – ocean and sparsely inhabited land – coverage of in situ data is marginal or absent <p>High Resolution NWP:</p> <ul style="list-style-type: none"> With respect to the high-resolution NWP requirements in the boundary layer, the vertical resolution of satellite sounders is still marginal. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Current systems, with the exception of radiosondes and AMDAR/MODE-S, do not have the vertical resolution required to resolve the PBL top, and so their capability is poor for such applications as forecasting the initiation of convection (i.e. geostationary satellites or ground-based radiometers). 	Radiosondes, aircraft, polar satellites, radio-occultation, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral sounders, VIS/IR imagery, realization of a day/night band, MW imagery, MW cross-track upper stratospheric and mesospheric sounders, VIS/NIR/SWIR/IR mission for continuous polar	Raman-Lidar HSRL-DIAL differential absorption lidar Radiometer Radiosonde descent measurements. Round-trip drifting Sounding System. [China]	Raman-lidar: commercially available, very detailed measurements of the first 3 km, meet breakthrough requirement for now casting. Can get expensive for network deployment. (Lange 2019). Limited by cloud. HRSL: not commercially available, developed, by National Centre for Atmospheric Research (NCAR) and Montana State University (MSU). (Stillwell et al 2020). Limited by cloud. Radiometer. Commercially available. Poor vertical resolution but can detect temperature inversion in lowest km. Gets better vertical skill in Arctic condition. MeteoSwiss currently testing the impact on their high-resolution model by direct brightness temperature data assimilation.

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
		coverage (Arctic and Antarctica)		
Humidity of air in the 3D domain	<p>Global NWP:</p> <ul style="list-style-type: none"> available from radiosondes in populated land areas, and from ships in the North Atlantic (the E-ASAPs). In these areas, horizontal and temporal resolution is usually acceptable (but sometimes marginal, due to the high horizontal variability of the field) Over most of the Earth – ocean and sparsely inhabited land – coverage is marginal or absent Polar orbiting sounding instruments provide information on tropospheric humidity with global coverage. Although the vertical resolution of passive microwave humidity sensitive radiances is only sensitive to the large scale <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Humidity field retrieval from remote-sensing system has a poor vertical resolution for NWC Doppler weather radar coverage is marginal since it relies on ground clutter targets (available only near the radar). <p>Aeronautical Meteorology:</p> <ul style="list-style-type: none"> Satellite sounding systems (microwave sounders) are beginning to have a positive impact over oceanic areas when such data is used in data assimilation for NWP, but vertical resolution and 	Radiosondes, aircraft, Polar orbiting sounding instruments, geostationary satellites, ground-based radiometers, AMSU, multi-spectral sensors, GNSS radio occultation (basic constellation), Constellation of high-temporal frequency MW sounding, UV/VIS/NIR/IR/MW limb sounders	DIAL Raman-Lidar HSRL-DIAL GNSS (slant, tomography) Ground-based radiometer DAR MODES S BENDING ANGLE Round-trip drifting Sounding System. [China]	Broadband Dial prototype by Vaisala have been tested in wide variety of climate, (Newson et al 2020, Roininen and Münkel 2017, Mariani et al 2020, Yeung et al 2020). Should soon be commercially available. Limited to the first 3 km by the amount of aerosol and cloud. Raman-Lidar and HRS: measure temperature and humidity (see previous comment and reference on temperature measurement). GNSS give integrated water vapour, slant delay data assimilation might propagate a bit of vertical information, very dense (5 to 25 km receiver spacing) network might allow tomography. (Brenot 2014) Ground-based radiometer: limited vertical resolution, nearly integrated water vapour quantity, as for temperature Meteo suisse is currently evaluating their impact. (commercially available)

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<p>regular availability are still considered insufficient for the purposes of aeronautical meteorology.</p> <ul style="list-style-type: none"> For that reason, moisture sensors on AMDAR aircraft will become very important if the problem of sensitivity and accuracy at very low humidities at Upper Tropospheric and Stratospheric levels can be resolved. 			<p>Scanning azimuthal radiometer Themens 2014 (project stage) with additional channel in window region might give more spatial degree of freedom than a vertical pointing radiometer, still nearly integrated quantity</p> <p>DAR; differential absorption radar, give water vapour profile in cloud, being developed at the Jet Propulsion Laboratory (JPL), (Roy et al 2020)</p> <p>Mode-S bending angle: project stage.</p> <p>https://www.meteorologicaltechnologyinternational.com/news/aviation/technique-for-tracking-humidity-through-aircraft-signals-wins-top-european-award.html</p>
water temperature just below the surface. (not the radiative skin temperature)	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over some areas of the Earth, but recent improvements in the in situ network have enhanced coverage considerably <p>High Resolution NWP:</p> <ul style="list-style-type: none"> because of the important cloud coverage, the SST information provided by satellite IR imagers is very limited. Extending the buoy and ship data coverage, which still is often marginal, may thus bring valuable information. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Same requirements as SoG High-Resolution NWP <p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Ships and moored and drifting buoys provide in situ observations with acceptable accuracy, but coverage and frequency are poor or marginal over large areas of the Earth. Geostationary satellites provide hourly SST data with the resolution of 1–4 km. Although the data are absent in cloud- 	<p>Ships, buoys, infrared and microwave instruments on polar satellites, Geostationary imagers with split window measurements, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral sounders, VIS/IR imagery, realization of a day/night band, MW imagery, MW cross-track upper stratospheric and</p>	<p>CIMR – a novel satellite microwave sensor with enhanced spatial resolution (compared to SSM/I-SSMIS and AMSR-E – AMSR2)</p>	<p>The need for complementary IR-MN measurements should be underlined. There is a need for vicarious calibration activities (ship-based IR radiometers such as the M-AERI).</p> <p>CIMR will offer high-quality SST together with unprecedented accuracy of SIC estimates, hence reducing this uncertainty source in polar regions.</p>

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<p>covered area, the horizontal and temporal resolution is acceptable for resolving diurnal cycle, but its coverage does not extend to higher latitudes.</p> <p>Long-Term Reanalyses for climate studies</p> <ul style="list-style-type: none"> SST is an essential variable for long-term reanalyses for climate studies, along with surface pressure data, because there are long historical databases and it has crucial impacts on the climate state. Continuing SST observations are also necessary for those applications. <p>Ocean Applications:</p> <ul style="list-style-type: none"> The goal for high quality SST in the open ocean is ideally 5 km spatial scale with accuracy 0.5K, and fast delivery (availability within 1 hour). In coastal regions, the goal is 1 km with accuracy of 0.5K and a delivery delay of 1 hour. Coverage of ships and moored and drifting buoys is marginal or poor over some areas of the global ocean for calibration of satellite data and validation of satellite products and model fields. Coverage of ships and moored and drifting buoys is marginal or poor over some areas of the global ocean for calibration of satellite data and validation of satellite products and model fields. A combination of both infrared and microwave data is needed because each has different coverage and error properties. In addition, microwave radiometers cannot be used for coastal applications because of (a) rather coarse spatial resolution and (b) contamination by land signals. Improvements in the accuracy of satellite SST in shallow water regions and near sea-ice edges will help improving ocean forecasting performance. 	<p>mesospheric imagers, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica)</p>		

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
Sea-ice coverage and ice thickness.	<p>High Resolution NWP:</p> <ul style="list-style-type: none"> Data interpretation can be difficult when ice is partially covered by melt ponds. Operational ice thickness monitoring will be required in the longer term but is not currently planned. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Same requirements as SoG High-Resolution NWP <p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Assimilation of the SIC observed by satellite microwave radiometers such as SSMI/SSMIS or AMSRE/AMSR2, etc. is often conducted in sub-seasonal to longer prediction systems and confirmed that it has a crucial impact to reproduce accurate sea-ice initial states. The current observation capacity during the freezing season is sufficient if the current quality of sub-seasonal to longer prediction systems is considered. Observational biases in summer became better quantified in the meantime but still hinder useful assimilation of such data for summer months. Some research indicates that assimilation of sea-ice thickness is effective to improve predictions of the sea-ice extent in ice-melting seasons. In situ sea-ice thickness has rather limited availability. Sea-ice thickness assessments produced with satellite observations like ICESat (Ice, Cloud and land Elevation Satellite) have high spatial resolution but narrow swath width. CryoSat and CryoSat-2, through use of a satellite in low Earth orbit, monitor variations in the extent and thickness of polar ice. SMOS sea-ice thickness data are restricted to detect thin sea-ice (< 1 m) and has complex error characteristics. These satellite-based sea-ice thickness products are overall poor to marginal accuracy. Continuous observations are desirable for operational use in sub-seasonal and longer predictions. Assimilation of ice surface temperature is also tested. It likely has some impacts on predictions of the atmospheric state in the polar and subpolar regions. 	<p>Polar orbiting, high inclination orbit satellites equipped with (i) passive microwave instruments (SSMIS, MWRI, AMSR2, SMAP, SMOS) for SIC, snow depth, thickness, age, and drift, (ii) scatterometers (ASCAT, OSCAT) for sea-ice age and drift, (iii) SAR (Sentinel-1, RADARSAT-2, TerraSAR-X, others) for high-resolution SIC, drift, and age, (iv) laser or radar altimeters (ICESat-2, CryoSat-2, Saral/AltiKa, Sentinel-3) for sea-ice thickness and snow depth, and v) VIS/NIR/IR sensors (AVHRR, MODIS, VIIRS, Landsat, Sentinel-2/-3) for surface temperature,</p>	<p>Increased use of ship-based X-Band radars for wave observations and sea-ice ridges.</p> <p>With new generation of icebreakers, there is scope for a standardized (semi-) automated underway system for sea-ice and snow observations.</p> <p>Increased understanding of GNSS-R provides additional observations.</p> <p>Copernicus Imaging Microwave Radiometer (CIMR)</p> <p>passive microwave instruments, scatterometers on polar satellite, conventional aircraft and coastal radar,</p>	<p>Arctic: Potential for coastal stations near fast ice and drifting sea-ice.</p> <p>Antarctic: Antarctic Fast Ice Network (AFIN) sites as a potential add-on to an already established infrastructure.</p> <p>Smaller, cheaper, more environmentally friendly ice-buoys with enhanced instrumentation, reduced cost of satellite data telecommunication, air-deployable.</p> <p>More coastal High Frequency radars, more systematic observations during field expeditions / from ships using VIS/NIR/IR and MW sensors for satellite product evaluation.</p> <p>Enhance spatiotemporal coverage, maturity, and scope of ship-based sea-ice and auxiliary data (met/ocean parameters) across research, tourist vessels, ships-of-opportunity.</p> <p>Enhance overlap between and understanding of operational and climate community requirements for sea-ice observations.</p> <p>Standardized sea-ice protocols from operational to research sea-ice observations.</p> <p>More observations from ground-, and underwater vehicle-based, moored, and airborne sensors for algorithm development and product evaluation needed, especially for Arctic seasonal sea-ice and the Antarctic as a whole.</p>

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<ul style="list-style-type: none"> Snow depth on the sea-ice is important for the polar-region climate and a key parameter for sea-ice thickness retrieval using altimetry. Several efforts estimating the snow depth from satellite data (Passive microwave sensors, combination of radar and laser altimeters) exist. <p>Ocean Applications:</p> <ul style="list-style-type: none"> Although surface-based reports can provide excellent detail about the ice, especially its thickness and surface topography, it is generally recognized that for most areas, the surface reports are not really adequate to describe ice conditions fully. Inclement weather – fog, precipitation and low cloud – will restrict or interrupt the observations and the usual problems of flying restrictions at the aircraft base may also be a factor even if the weather over the ice is adequate for observing. Satellite coverage may be broad at low resolution or cover a narrow swath at high-resolution. In the latter case, data from a particular location may be obtained only at intervals of several days. Accurate ice-related observations, such as ice thickness, ice concentration, ice age, snow depth on sea-ice, ice albedo and melt pond coverage, ice surface temperature, and ice velocity, are needed for model validation and data assimilation applications. Sea-ice velocity assimilation is tested in some systems. Convergence/divergence fields of sea-ice are of interest to modellers because of relevance to the opening of leads and/or polynyas and sea-ice deformation. In situ observations of SIC, thickness, age, surface albedo and temperature, snow depth and type, and drift are required to validate satellite measurements. 	<p>albedo, and melt pond coverage, Airborne sensors of the above-listed types</p> <p>Other conventional aircraft observations / reconnaissance</p> <p>Coastal and ship-based radar</p> <p>High Elliptical Orbit VIS/IR mission for continuous polar coverage (Arctic and Antarctica), Wide-swath radar altimeters, Lidar (single wavelength) Interferometric radar altimetry, hyperspectral VIS</p> <p>Visual observations from coastal settlements, lighthouses and ships</p> <p>Ground-based observing stations at sea / during expeditions including ice radar, Ice buoys, Ice tethered</p>	<p>visible and infrared airborne and satellite imagery, laser airborne profilometers, scatterometers, side-looking (airborne) radar (SLAR / SLR) or SAR, satellite or airborne), Visual observations from coastal settlements, lighthouses and ships, SSMR (ice concentration), SSMIS (ice concentration), AMSR2(ice concentration), VIIRS (ice surface temperature)</p>	

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
		platform observations, moored and underwater vehicle-based upward looking sonar		
Temperature and salinity in the 3D domain.	<p>Global and high-resolution NWP:</p> <ul style="list-style-type: none"> Ocean heat content, which is estimated from ocean subsurface temperature, has crucial effects on the development of tropical cyclones. Thus, assimilation of ocean subsurface temperature data is effective when a coupled atmosphere-ocean model is used for the prediction. In situ observations are not sufficient to catch mesoscale eddies with large heat content anomalies, so it is better to have additional support from satellite sea-surface topography data. <p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Argo profiling floats provide near-global coverage of temperature and salinity profiles to ~2000 m, mostly with acceptable to good vertical (every ~5 m) and spatial resolutions (around 3-degree); however, floats are absent in sea-ice-covered areas and shallow marginal seas. The number is relatively small near the equator due to equatorial divergence, so the moored buoys near the equator are an important complement. The tropical moored buoy network (TAO/TRITON, PIRATA, RAMA) has better than marginal spatial resolution, but the number of TRITON buoys in the western tropical Pacific is drastically reduced due to shortages in the maintenance budget of its managing agency. It is preferable to increase the vertical resolution of temperature and salinity observations near the surface in order to constrain oceanic mixed layer variations. The Pacific moored buoy network is currently transiting to a new design proposed by TPOS2020 project, with higher vertical resolution in the mixed layer and a smaller number of buoys in 	Free-drifting profiling floats, (Argo floats), SOOP (XBTs), Moored buoys (PIRATA, RAMA, TAO/TRITONTRITON), research vessels (XBTs, CTDs), Underwater gliders, Animal platforms		

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<p>off-equatorial regions. A lack of sustained funding for the tropical moored buoy network is a matter of concern.</p> <ul style="list-style-type: none"> There is no system for observing subsurface temperature and salinity on the continental shelves surrounding the Greenland and Antarctic Ice Sheets, even though ocean conditions have been shown to play a major role in ice loss in both places. <p>Ocean Applications:</p> <ul style="list-style-type: none"> The subsurface temperature measurements of the Expandable Bathy Thermographs (XBTs) are coordinated by Ships-Of-Opportunity Programme (SOOP). Temperature and salinity profiles of CTDs and XBT temperature profiles are also provided by research vessels over many of the targeted, frequently repeated, and high [horizontal resolution] density lines. However, sampling of about half of the targeted lines remains poor. Temporal resolution of those observations is generally marginal, but acceptable in some ship-specific lines, for monitoring oceanic volume and heat transport changes on sub-seasonal-to-seasonal timescales and validation of ocean predictions in specific vertical sections. It is insufficient for other ocean applications, especially for coastal applications. CTDs and XBTs provide data with good vertical resolution (typically 1 m) in delayed mode, but real-time data are constrained by limitations in the traditional GTS character codes currently being used. Large number of temperature and salinity profiles observed by Argo floats also are useful for ocean applications, but their temporal resolution is marginal for marine services. The number of ocean temperature and salinity observations is insufficient in coastal seas, which constrains model forecasting validation and data assimilation applications within coastal regions. Underwater gliders are being deployed by various institutions for a wide range of applications. Deployments are mostly in proximity of the coasts due to logistical constraints. There is an effort in the US for deploying gliders for Hurricane applications during the Atlantic Hurricane season. 			

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Sea Level	<p>Ocean Applications:</p> <ul style="list-style-type: none"> • Due to the increased demand for tsunami, storm surge and coastal flooding forecasting and warning systems, and for calibration/validation of the satellite altimeter and models, this part of the spectrum needs to be covered from now on, and should be considered when choosing a new instrument and in the design of in situ sea level stations. Additionally, there has been an emphasis on making as many GLOSS gauges as possible deliver data in real and/or near-real time, i.e., typically within an hour. An ongoing issue with these data is that sea level measurements have not been well integrated into NMHSs. • For storm surge and tsunami forecasting a spacing of 10 km is required, while for climate modelling 50 km spacing will meet the threshold. This will therefore require a denser network than is available today. • A sampling of sea level averaged over a period long enough to avoid aliasing from waves, at intervals of typically 6 seconds or less if the instrument is to be used also for tsunami, storm surges and coastal flooding forecasting and warning. • Gauge timing be compatible with level accuracy, which means a timing accuracy better than one minute (and in practice, to seconds or better with electronic gauges) – marginal accuracy. • Measurements must be made relative to a fixed and permanent local tide gauge benchmark (TGBM). This should be connected to several auxiliary marks to guard against its movement or destruction. Connections between the TGBM and the gauge zero should be made to an accuracy of a few millimetres at regular intervals (e.g. annually) – acceptable accuracy. • GLOSS gauges to be used for studies of long-term trends, ocean circulation and satellite altimeter calibration/validation need to be equipped with GPS receivers (and monitored possible by other geodetic techniques) located as close to the gauge as possible. • The readings of individual sea levels should be made with a target accuracy of 10 mm – acceptable accuracy. • Gauge sites should, if possible, be equipped for recording tsunami and storm surge signals, implying that the site be equipped with a pressure sensor capable of 15-seconds or 1- 	GLOSS gauges, Satellite altimeters, Wide-swath radar altimeters and high-altitude, inclined, high-precision orbit altimeters		See "ocean topography" for sea level observations used for estimating interior ocean temperature and salinity distributions and ocean currents.

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	<p>minute sampling frequency, and possibly for recording wave conditions, implying 1-second sampling frequency – poor accuracy.</p> <ul style="list-style-type: none"> Gauge sites should also be equipped for automatic data transmission to data centres by means of satellite, Internet, etc., in addition to recording data locally on site. Basins prone to tsunamis and storm surges (e.g. Bay of Bengal, Gulf of Mexico and Pacific Islands) require a higher density of sea level observations. Sea level measurements should be accompanied by observations of atmospheric pressure, and if possible, winds and other environmental parameters, which are of direct relevance to the sea level data analysis. To cover the whole mesoscale and coastal domain it is necessary to increase the spatial sampling by merging (in an optimal way with cross-calibration) different altimetry data sets. NASA's pending wide-swath altimeter mission the SWOT mission will help address this challenge, with launch anticipated around Feb 2022. 			
Surface Salinity	<p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Some research vessels take time series of sea-surface salinity (SSS) along their ship track by thermosalinographs (TSGs). Although the coverage and frequency are poor, it can be used for validation of initialized and predicted ocean fields. Valuable data also comes from some of the tropical moorings, in particular from the TRITON buoys, although data coverage is rather limited. Surface salinity is also measured by satellite such as Aquarius, SMOS, and SMAP with good coverage, acceptable to good spatial and temporal resolution, but marginal accuracy. Time averaging is required for achieving the acceptable accuracy. Constraining salinity in the ocean data assimilation is still a challenge, since there is large uncertainty in the freshwater flux (precipitation, evaporation and river run-off), affecting the surface salinity and mixed layer properties. SSS observations can complement the lack of rain gauges in ocean areas. In that sense, it is preferable to add a salinity 	Aquarius, SMOS, and SMAP, TSG, TRITON buoys, remote-sensing, Low-frequency MW imagery	Drifter buoys CIMR	<p>Satellite remote-sensing of SSS in the Polar regions suffers from low sensitivity of the measured signal to changes in salinity. In addition, sea-ice causes biased estimates. SSS retrieval accuracy in the polar regions needs to be improved, e.g. by revised algorithms, merging of different (satellite) observations, providing an enhanced number of more mature in situ observations.</p> <p>Enhance space-based salinity observing system to increase sampling and reduce uncertainty, especially in polar oceans.</p>

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	<p>sensor to drifter buoys. That can provide information, with global coverage, on precipitation, together with SST and SLP information.</p> <ul style="list-style-type: none"> Satellite salinity measurements can also provide a constraints on estimates of evaporation-minus-precipitation and potentially run-off from large rivers. <p>Ocean Applications:</p> <ul style="list-style-type: none"> Coverage is marginal or poor over some areas of the global ocean. There is a requirement for high quality SSS in the open ocean, ideally with accuracy < 0.1 SA on a 10 km spatial scale, and fast delivery (availability within 1 hour). In coastal regions, higher density is required (accuracy < 0.1 SA on a 1 km spatial scale). Remote-sensing instrumentation is currently transitioning from experimental to operational. There is a requirement to constrain this state variable at the surface where the variability is greatest, and the mass fluxes are known to have large errors. Improvements in the accuracy of satellite SSS (as well as SST) in shallow water regions will help improve ocean forecasting performance. 			
Snow cover, snow depth and snow water equivalent	<p>Global NWP:</p> <ul style="list-style-type: none"> Many SYNOP messages omit snow depth observations when snow is not present on the ground and large regions and countries show extremely sparse SYNOP stations reporting snow depth Making available the national snow data to the NWP community would be very useful Gaps still exist in some of the countries of the northern hemisphere and in most of the southern hemisphere Visible and near infrared satellite imagery provide information of good horizontal and temporal resolution and accuracy on snow cover extent (but not on snow mass) in the daytime in cloud-free areas. There is a major gap in the cryosphere observing system 	Surface stations, infrared satellite imagery, Microwave imagery, passive microwave AMSR and SSM /I, High-resolution multi-spectral VIS/IR imagers, Multi-spectral VIS/IR imagery with rapid repeat	Ship observations Combining snow radar coverage with new, highly accurate digital elevation models of glacier surfaces (from airborne Lidar or satellite platforms) SAR snow depth mapping using Interferometric L-	Lower atmosphere and impassable area measurements using drones Increased use of video cameras to support local forecasting. With new generation of icebreakers, there is scope for a standardized (semi-) automated underway system for snow cover over sea-ice and over ice floes observations. Snow from ice-buoys, Snow on sea-ice – still a gap;

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	<p>as none of the current instruments can provide reliable estimate of snow water equivalent from space</p> <ul style="list-style-type: none"> Snow cover over sea-ice also presents data interpretation problems. Future satellite missions with a capability to measure snow water equivalent would be extremely relevant for coupled assimilation developments, consistently benefiting the surface and atmospheric data assimilation in NWP systems <p>High Resolution NWP:</p> <ul style="list-style-type: none"> Surface stations measure snow cover with good temporal resolution but marginal horizontal resolution and accuracy (primarily because of spatial sampling problems) Visible / near infrared satellite imagery provides information of good horizontal and temporal resolution and accuracy on snow cover (but not on its equivalent water content) in the daytime in cloud-free areas Microwave imagery offers the potential of more information on snow water content (at lower but still good resolution) but data interpretation is difficult. Snow cover over sea-ice also presents data interpretation problems, but this is less crucial for high resolution NWP than global NWP because of the very few models covering such areas. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Same requirements as SoG High-Resolution NWP <p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Snow depth and SWE observations are insufficient (poor) for the purpose of initializing sub-seasonal to seasonal predictions. Although surface SYNOP stations report measurements of local snow depth with high accuracy, the coverage of SYNOP stations reporting snow depth is not adequate (poor) (see also SoG for the global NWP). Microwave imagery has also the potential for improvement of snow mass assessment in the land analysis. <p>Hydrology:</p>	<p>cycles, VIS/IR imagery, realization of a day/night band, MW imagery, Scatterometers, Wide-swath radar altimeters and high-altitude, inclined, high-precision orbit altimeters, Low-frequency MW imagery, GNSS reflectometry (GNSS-R) missions, passive MW; SAR imagery and altimeters (Laser and RADAR), Lidar (single wavelength) – can be mounted on UAVs, Wide-swath radar altimeters, and high-altitude, inclined, high-precision orbit altimeters</p> <p>VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica),</p>	<p>band data from SAOCOM-1 A and combined L- and S-band data from NISAR (in development by NASA/ISRO)</p> <p>Future Laser altimetry / Interferometric Swath Altimetry for vertical registration of glacier images, for mass balance estimates</p> <p>Planned Canadian Ku-band Terrestrial Snow mass Mission (TSM) to obtain high-resolution SWE estimate</p>	<p>Progress made on addressing high mountain cryosphere, combining optical/radar imaging, altimetry and gravimetry; and DEM differencing from stereo optical data. Snow extent and glacier mapping still largely dependent on optical ~10 metre res. global, decadal and freely/openly accessible datasets from Landsat, ASTER and Sentinel-2, complemented by high spatial res. (<10 m), limited coverage optical images (and stereo data) from SPOT, Pleiades, Cartosat-I etc.</p> <p>Multi-agency coordination or satellite constellations required to achieve revisit frequency to meet needs of snowmelt run-off operational services</p> <p>Currently not possible to measure solid precipitation, snow depth or SWE accurately in mountains. Lack of operational product capturing SWE satisfactorily at appropriate spatial scales</p>

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	<ul style="list-style-type: none"> Access to SWE data by NHMS can be challenging since SWE is often measured by regional agencies responsible for hydrological forecasting or water management or by hydropower companies. SWE data can also consist of manual snow surveys that are not necessarily available in near-real time. SWE from automatic stations is also affected by limited spatial representativity (same as snow depth, see SoG High Resolution NWP). Visible and near infrared satellite imagery provides information of good horizontal and temporal resolution and accuracy on snow cover and surface albedo in the daytime in cloud-free areas. None of the current instruments on-board satellites can provide reliable estimate of SWE from space. Current SWE retrievals from microwave sensors are available at low resolution and cannot provide accurate estimate of SWE in mountains headwaters. Airborne observatories using scanning Lidar and imaging spectrometer can provide accurate measurements of snow depth and albedo. This information can be combined with model information to get SWE and snowmelt estimate. However, such method is restricted to small-scale mountain catchment. Modification of the hydrological cycle and hydrological regimes, and input for water management, flood and drought through HydroSOS among other tools. 	Gravimetry missions, Ice-mounted instruments, in situ ice-floe observations, ice buoy observations Snowmelt mapping developing based on SAR image data at several days. Terrain flattening required to remove shadowing effects in mountains (dependent on digital elevation models)		
Soil moisture	<p>Global NWP:</p> <ul style="list-style-type: none"> Some land surface stations report soil moisture routinely (e.g. Soil Climate Analysis Network (SCAN) network in US) but coverage is limited, and the data requires regular recalibration <p>High Resolution NWP:</p> <ul style="list-style-type: none"> Measurement accuracy of microwave radiometers, as well as temporal resolution, is generally good, while the horizontal resolutions still is, at best, marginal. <p>Nowcasting and VSRF:</p>	Passive L-band microwave imagers (e.g. SMOS, SMAP) Active microwave scatterometers, ASCAT, Microwave imagery, Low-frequency MW imagery, MW sounder and imagery in inclined orbits,	Cosmic Ray Soil Moisture Sensors – field scale: essd-12-2289-2020.pdf (copernicus.org)	

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	<ul style="list-style-type: none"> Measurement accuracy of scatterometers (ASCAT) as well as temporal resolution are acceptable, while the horizontal resolutions still is, at best, marginal. <p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> At present only the SCAN provides a network of real-time vertical profiles of soil moisture and coverage is limited to the whole United States' area. A network of similar measurements covering the global domain would be very useful. The current operational soil moisture product from ASCAT has acceptable spatial resolution but marginal accuracy. Passive L-band microwave imagers such as SMOS and SMAP have great potential. <p>Agricultural Meteorology:</p> <ul style="list-style-type: none"> Optimum monitoring of soil moisture requires in situ measurements to depths of 20, 50, and 100 cm every 5–7 or 10 days, with horizontal resolution better than 100 m. <p>Hydrology:</p> <ul style="list-style-type: none"> Most of the active and passive microwave instruments provide some soil moisture information for regions of limited vegetation cover. However, under many conditions remote-sensing data are inadequate, and information regarding moisture depth remains elusive. Unfortunately, none of the instruments provide a satisfactory combination of spatial resolution and repeat cycle time (2 to 3 days). The AMSR data comes close to providing soil moisture or land wetness information that may be marginally useful for mesoscale models, but the timeliness of these data remains challenging. 	SAR imagers and altimeters, GNSS reflectometry (GNSS-R) missions; passive MW; SAR		
Near-surface air temperature, usually at 2 m	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over large areas of the Earth. Over land, surface stations measure with horizontal and temporal resolution which is good in some areas and marginal in others <p>High Resolution NWP:</p>	Ships, buoy, surface station, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral		

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	<ul style="list-style-type: none"> Measurement accuracy is generally good, though this can be difficult to use where surface terrain is not flat, because of the sensitivity of the measurements to local variability that high resolution NWP models still resolve more accurately than global models. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over large areas of the Earth Satellite instruments do not observe these near-surface variables directly 	sounders, VIS/IR imagery, realization of a day/night band, MW imagery, MW cross-track upper stratospheric and mesospheric sounders, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica)		
Near-surface, usually at 2 m.	<p>Global NWP:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over large areas of the Earth. Over land, surface stations measure with horizontal and temporal resolution which is good in some areas and marginal in others <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Coverage is marginal or absent over large areas of the Earth Satellite instruments do not observe these near-surface variables directly 	Ships, buoy, surface station, IR hyperspectral sounders, UV/VIS/NIR sounders, GNSS radio occultation (basic constellation), Constellation of high-temporal frequency MW sounding, UV/VIS/NIR/IR/MW limb sounders		

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Land ice surface skin temperature	<p>Global NWP:</p> <ul style="list-style-type: none"> Accuracy is affected by cloud detection problems and surface emissivity uncertainties, and interpretation is difficult because of the heterogeneous nature of the emitting surface for many surface types The diurnal cycle of surface temperature is usually not well sampled except for sensors on-board geostationary satellites (e.g. SEVERI on MSG) that cannot provide global coverage <p>High Resolution NWP:</p> <ul style="list-style-type: none"> Similar issues apply as for global NWP 	Satellite infrared and microwave imagers and sounders		
Lake ice surface skin temperature	<p>Global NWP:</p> <ul style="list-style-type: none"> Accuracy is affected by cloud detection problems and surface emissivity uncertainties, and interpretation is difficult because of the heterogeneous nature of the emitting surface for many surface types The diurnal cycle of surface temperature is usually not well sampled except for sensors on-board geostationary satellites (e.g. SEVERI on MSG) that cannot provide global coverage <p>High Resolution NWP:</p> <ul style="list-style-type: none"> Similar issues apply as for global NWP <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Similar issues apply as for global NWP 	Satellite infrared and microwave imagers and sounders		

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Vegetation type, cover and NDVI	<p>Global NWP:</p> <ul style="list-style-type: none"> limitation to make efficient use of the available data is that coupled models need to be recalibrated (surface – boundary layer interactions) when the vegetation type or characteristics (e.g. LAI) evolve <p>Hydrology:</p> <ul style="list-style-type: none"> in some cases, the NDVI and vegetation type products may not be interchangeable because of slightly different spectral bands. 	satellite imagery from visible and near infrared channels, MODIS, Multi-spectral VIS/IR imagery with rapid repeat cycles, VIS/IR imagery, realization of a day/night band, Narrow-band or hyperspectral imagers, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica), Radar and lidar for vegetation mapping		
<p>Clouds</p> <p>Cloud cover as well as cloud height, cloud base and cloud top temperature.</p> <p>Cloud parameters</p>	<p>Global NWP:</p> <ul style="list-style-type: none"> Surface stations estimate cloud cover and cloud base with a temporal resolution and accuracy that is acceptable but a horizontal resolution that is marginal in some areas and missing over most of the Earth. At present the primary problem is not with the cloud observations themselves but with their assimilation, arising from representativeness problems and weaknesses in data assimilation methods and in the parameterization of cloud hydrometeors and other aspects of the hydrological cycle within NWP models. <p>High Resolution NWP:</p>	Surface stations, infrared imagers and sounders, active optical (lidar) and microwave (radar), geostationary satellite instruments, polar orbiting satellites, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral	<p>Space-based cloud radars (Baggatalia et al 2020)</p> <p>Ground-based FMCW cloud radar</p>	Ground-based cloud radar. FMCW technique allows high sensitivity with

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	<ul style="list-style-type: none"> satellite visible/infrared measurements give marginal accuracy because of the poor relationships between cloud top temperature and the underlying clouds and precipitation physics Microwave measurements are affected by sensitivity to land surface emissivity and by similar optical properties of cloud water and light rainfall. Therefore, and for high resolution NWP models, microwave imagers and sounders offer information on clouds of marginal accuracy, horizontal and temporal resolution. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> geostationary satellite data are missing for the high latitudes where polar orbiting satellites provide valuable observations with acceptable frequency due to the convergence of orbital tracks. <p>Aeronautical Meteorology:</p> <ul style="list-style-type: none"> Cloud drop size information for icing forecasts is currently not directly observed. Observations from satellites are at the top of a cloud layer, and then only when this layer is viewable from space. Only radiosonde and aircraft data could provide acceptable vertical resolution of these parameters, but cycle times and horizontal resolution are marginal to poor. Dualpolarization weather radars, particularly if operated in the X-Band, again holds promise for acceptable accuracy in determining the amount and distribution of SLW droplets, but while now common in some countries are still far too rare to have a significant global impact. Automatic determination of cloud amount / cloud base height from single ceilometer measurements could be challenging at locations with complex topography (e.g. valleys, coastal stations and large cities with high aerosol loading). 	<p>sounders, UV/VIS/NIR sounders, VIS/IR imagery, realization of a day/night band, MW imagery, IR dual-angle view imagers, cloud radars, Sub-mm imagery, UV/VIS/NIR/IR/MW limb sounders, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica), NIR spectrometer, Hyperspectral MW sensors</p>		<p>less energy than pulse radar. Commercially available. (Delanoë 2016)</p>

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<p>Precipitation</p> <p>Type and amount (over a given time period, usually 24 hours)</p>	<p>Global NWP:</p> <ul style="list-style-type: none"> The horizontal resolution is poor in large parts of the world, and where coverage is good the data is often not available for international exchange. Ground-based radars measure instantaneous precipitation with good horizontal and temporal resolution and acceptable accuracy, but over a few land areas only Geostationary infrared imagers offer some information at much higher temporal resolution through the correlation of surface precipitation with properties of the cloud top, but accuracy is marginal due to the indirect nature of this relationship. <p>High Resolution NWP:</p> <ul style="list-style-type: none"> weather radar with accuracy that depends on its frequency and on the rain intensity. Sea clutter makes observations performed by scans at low elevations difficult to be exploited above the sea. Beam blockage is also often an issue in mountainous regions and over populated areas because of buildings. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Rapid imaging (on the order of minutes) is critical to nowcasting, but it is not yet provided by all geostationary satellites The detection of precipitation is marginal for microwave imagers and, depending on the wavelength of the instrument, good to poor for scatterometers <p>Hydrology:</p> <ul style="list-style-type: none"> Terrestrial observations are being made but overall global access to groundwater data (rates of recharge and abstraction in particular) is highly limited. IGRAC has compiled global level information on groundwater resources. Gravimetric observation techniques (such as from GRACE) for very large groundwater bodies are available but yet to be fully proven in operational circumstances. The use of GOCE data is being explored. 	<p>Surface station, Ground-based radars, Microwave imagers and sounders, Geostationary infrared imagers, Radar polarimetry, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral sounders, VIS/IR imagery, realization of a day/night band, MW imagery, MW sounder and imagery in inclined orbits, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica), GNSS radio occultation; additional constellation for enhanced atmospheric/ionospheric soundings (including polarimetric), including LEO-LEO radio occultation for additional</p>	<p>Attenuation of mobile phone signal by rain. Emerging technologies electronically-scanning (phased-array) adaptive radars will acquire data in unconventional ways, necessitating adaptation by data exchange and processing infrastructure.</p>	<p>This requires collaborations with mobile phone providers, can be very useful in country equipped with very spare weather radars network. (Turko 2020) 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.</p> <p>expansion of non-NHMS networks, including volunteer and private sector networks, with automated dissemination/collection to national archive centres.</p>

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	<ul style="list-style-type: none"> With regard to satellite-based quantitative precipitation estimation, a mechanism is required to develop front-end products and mainstream precipitation products for operational day-to-day use in National Hydrological Services on a long-term basis. 	frequencies optimized for atmospheric sounding, satellite-based precipitation radars and cloud radars		
<p>Ozone</p> <p>Concentration, in the 3D domain</p>	<p>Global NWP:</p> <ul style="list-style-type: none"> However, to maintain realistic vertical distributions of ozone in NWP models, vertically resolved ozone information is needed. Results from ozone sondes struggle to provide statistically significant insight due to the limited number of available profiles, as some of this data is not internationally distributed. 	high-resolution infrared sounders and more accurate solar backscatter instruments, limb sounders (such as MLS), Scanning Microwave Limb Sounder (SMLS), IR hyperspectral sounders, UV/VIS/NIR sounders, Constellation of high-temporal frequency MW sounding, UV/VIS/NIR/IR/MW limb sounders, Hyperspectral MW sensors,		
Wave height, direction and period	<p>Global NWP:</p> <ul style="list-style-type: none"> Buoys and sensors mounted on oil rigs and platforms coverage is marginal or absent over large areas of the Earth. 	Buoys, sensors, Altimeters on polar satellites,		

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	<ul style="list-style-type: none"> Altimeters on polar satellites horizontal and temporal coverage is limited. Information on the 2D wave spectrum is provided by SAR instruments with acceptable accuracy but marginal horizontal and temporal resolution. <p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> Similar issues apply as for global NWP Information on the 2D wave spectrum is provided by SAR instruments with good accuracy but marginal horizontal and temporal resolution. <p>Ocean Applications:</p> <ul style="list-style-type: none"> The geographical coverage of in situ wave data is still very limited and most measurements are taken in the Northern Hemisphere (mainly off the North American and Western European coasts). Differences in measured waves from different platforms, sensors, processing and moorings have been identified. In particular, a systematic 10% bias has been noted between US and Canadian buoys, the two largest moored buoy networks. Satellite altimeters provide information on significant wave height with global coverage and good accuracy. However, horizontal/temporal coverage is marginal. NASA's pending wide-swath altimeter mission the SWOT mission will help address this challenge, with launch anticipated around Feb 2022. Multiple altimeters are required to provide adequate cross-track sampling. Information on the 2-D frequency-direction spectral wave energy density is provided by SAR instruments with good accuracy but marginal horizontal/temporal resolution. Horizontal resolution of 100 km is required for use in regional models, with fast delivery required (within 6 hours). Real aperture radar capability is expected to be available within 5 years. 	SAR instruments, in situ non-spectral and spectral buoys and ships, Wide-swath radar altimeters and high-altitude, inclined, high-precision orbit altimeters		

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3D aerosol concentration Aerosol parameters	Global NWP: <ul style="list-style-type: none"> Operational visible and near infrared satellite imagery has marginal accuracy 	visible and near infrared satellite imagery, Advanced imagers such as MODIS, Ground-based stations which use sunphotometers such as the Aerosol Robotic Network (AERONET), radiometers, optical spectrometer, Geostationary imagers, Aeolus Doppler wind lidar, Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral sounders, UV/VIS/NIR sounders,, Narrow-band or hyperspectral imagers, Multipolarization SAR; hyperspectral VIS, NIR spectrometer	Raman-lidar HSRL lidar Multiwavelength lidar Polarized lidar Lidar (Doppler and dual/triple-frequency backscatter), ceilometres	The use of laser diode technology has reduced the cost and running cost of all lidars.

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w-comp of wind in the 3D domain	<p>Global NWP:</p> <ul style="list-style-type: none"> There is currently no present or planned capability <p>High Resolution NWP:</p> <ul style="list-style-type: none"> A drastic increase on spatial resolutions of high-resolution NWP models is needed before these models can resolve the clouds and produce some vertical motion which can be compared to (e.g.) Doppler radar vertical velocity observations. 	Geostationary infrared imagery or Doppler enabled microwave sensors, Lidar (Doppler and dual/triple-frequency backscatter) Doppler radar, Doppler Lidar	Dual-wavelength radar (Radenz 2018)	
Visibility	<p>Nowcasting and VSRF:</p> <ul style="list-style-type: none"> not observed over the ocean usually. Near the airports 1-D or 3-D very high resolutions models can estimate visibility and cloud base forecast in the NWC and VSRF range with useful accuracy. These models need several additional high frequency observing stations. For this reason, they are available only in very few airports. generally good at the airports, but marginal elsewhere. LIDAR provides good vertical profiles, but very few instruments are operational worldwide. <p>Aeronautical Meteorology:</p> <ul style="list-style-type: none"> automatic determination of the prevailing visibility would typically require a suite of visibility metres installed at suitable locations within / near the airport. Although reporting Slant Path Visual Ranges (SVR) will have a positive impact on safety and efficiency, no operational technology is recommended so far. For en-route forecasts of VFR flights, both the horizontal resolution and cycle time of existing observing stations reporting aeronautical weather information in METAR code are acceptable only in densely populated areas, and poor over most of the globe. Use of additional observations from synoptic weather stations is recommended. 	Aviation, synoptic surface observing stations, LIDAR		

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	Ocean Applications: <ul style="list-style-type: none"> This parameter can vary substantially over short distances. Accuracy is acceptable in coastal areas and marginal in the open ocean. Horizontal / temporal resolution is poor over most of the global ocean. Typically, visibility is deduced from the output of regional atmospheric models (see regional NWP SoG). 			
Lightning detection (Lightning magnetic flux location)	Nowcasting and VSRF: <ul style="list-style-type: none"> Poor detection efficiency of intracloud lightning. Over most oceanic, sparsely inhabited land and high latitudes, coverage is marginal to acceptable by ground-based networks at least for total lightning information. In these areas the detection efficiency and location accuracy are often poor for intracloud (IC), so that the TL consists mainly of CG lightning. 	Ground-based (total or separately cloud-to-ground (CG) and IC) real-time lightning detection, Lightning imager instruments, Lightning mappers		
Downward short-wave irradiance at Earth surface	Nowcasting and VSRF: <ul style="list-style-type: none"> Usually horizontal resolution is marginal, but when combined with satellite cloud coverage information acceptable quality can be achieved. 	Absolutely calibrated broadband radiometers and total solar irradiance and solar spectral irradiance radiometers		
Ocean wind stress	Sub-Seasonal to Longer Predictions: <ul style="list-style-type: none"> Fixed and drifting buoys and ships outside the tropical Pacific provide observations with marginal coverage and frequency; acceptable accuracy for the same purpose. Although the coverage and frequency of in situ oceanic surface wind data are not sufficient (or poor) for atmospheric data assimilation systems, assimilating those data has a pronounced impact on the analysed wind speed, and thus on wind stress fields, contributing to better oceanic initial conditions. In situ surface wind data are also necessary for calibration of satellite wind stress data. 	Scatterometers, Fixed and drifting buoys and ships, MW imagery, Low-frequency MW imagery, MW sounder and imagery in inclined orbits, GNSS reflectometry		See "surface wind" for the purpose other than for forcing ocean general circulation models

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	<ul style="list-style-type: none"> Overall, the scatterometers provide good coverage and acceptable frequency and accuracy, and scatterometer data complement ocean-based observations. High-quality scatterometer winds are the best products available at the moment and need to be maintained operationally. <p>Ocean Applications:</p> <ul style="list-style-type: none"> High-resolution observations for model forecasts of winds near-surface layers are required to improve accuracy of total water level forecasts in the coastal and estuarine regions, especially during extreme weather events. Surface winds fields from current atmospheric data assimilation systems do not have sufficient accuracy for coastal applications and it is preferable to improve the accuracy by additional data assimilation of surface wind data. 	(GNSS-R) missions; passive MW; SAR, vertical		
Ocean topography	<p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Ocean topography data from satellites are useful for monitoring the ocean heat content and ocean currents, and essential for ocean initialization in Sub-Seasonal to Longer Predictions Long-term commitments for satellite altimetry observation are required Provision of global coverage is an important requisite for higher resolution coupled models (ocean resolution of ~30 km), in which there is partial representation of ocean eddies. Satellite altimetry data require validation with in situ sea level measurements or temperature and salinity profiles. <p>Ocean Applications:</p> <ul style="list-style-type: none"> Ocean topography from satellite altimetry is the most important observation to constrain the dynamics of ocean forecast systems. Satellite altimetry allows estimating geostrophic currents (see "3-D ocean currents"). Current resolution allows resolving the large mesoscale (>150 km) features. The current coverage is not sufficient for coastal areas. Higher resolution will allow better resolution of ocean mesoscale, as well as coastal processes. Next generation altimeter (SWOT) is promising for these purposes. 	Satellite altimeters (nadir and swath radar), satellite gravity mission,		See also "see level" for sea level observations to monitor sea level itself.

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	<ul style="list-style-type: none"> High-resolution geoid information is necessary to estimate accurate ocean topography and geostrophic current fields. The current geoid data provided by the satellite geoid mission is marginal for resolving oceanic mesoscale eddies and ocean current data observed by drifter buoys and hydrological profiles are used for the refinement. 			
Surface heat, radiative and freshwater fluxes	<p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Satellite data provide prospects for several of the components of heat and radiative fluxes, particularly short-wave radiation, but at present, none is used on a routine basis in assimilation for sub-seasonal to seasonal predictions, due to some technical difficulty in use over sea-ice areas. There remain significant uncertainties in estimates of rainfall over the oceans. In addition, the freshwater run-off information from rivers (large estuaries) will become important in some regions the oceans (e.g. the Bay of Bengal). Additional data would always be useful, for example, data to allow better estimation of heat fluxes and P–E (precipitation minus evaporation) could help give a better definition of the mixed layer structure, and reproduction of the barrier layer. Several of components of heat fluxes cannot be observed by satellites. In addition, satellite observations require calibration with in situ observations. Therefore, high-quality marine meteorological stations, which cover all required data for air-sea flux estimations (i.e., sea-surface air temperature and humidity, sea level pressure, surface wind speed, long and short waves radiations, and SST) are required to provide air-sea flux data with sufficient accuracy. The current coverage of such metrological stations is poor. Deployment of meteorological stations in mid- and high latitudes will further enhance this development over the range of conditions that occur at the air-sea interface. 			

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	Ocean Applications: <ul style="list-style-type: none"> High resolution surface heat and freshwater flux data are necessary to force ocean models for coastal predictions. The freshwater run-off information from rivers (large estuaries) has a significant effect on coastal prediction systems, especially for total water level forecasts in the coastal and estuarine regions during extreme weather events. 			
Ocean currents	Sub-Seasonal to Longer Predictions: <ul style="list-style-type: none"> Surface currents measured by drifting buoys are acceptable in terms of accuracy and temporal resolution but marginal in spatial coverage. Moored buoy observation has good in accuracy and frequency but poor to marginal in spatial coverage. Surface ocean current information is necessary to estimate an accurate wind stress field. Ocean Applications: <ul style="list-style-type: none"> Targeting deployments of drifting buoys into regions of high variability such as boundary currents and downstream geostrophic turbulence would help enhance their impact on ocean prediction systems. Moored buoys are good in temporal resolution and accuracy, but marginal or poor otherwise. The Acoustic Doppler Current Profiler (ADCP) provides observations of ocean currents over a range of depths, with acceptable accuracy. Coverage is marginal or poor over most areas of the ocean, with marginal vertical resolution for marine services applications, which require high vertical resolution data in the mixed layer. Sea-Surface Kinematics Multiscale Monitoring (SKIM) is nominated as an ESA-EE9 candidate satellite mission, and plan 	Drifting buoys, Moored buoys, ADCP, Satellite altimetry, HF radars	Sea-SKIM	

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	<p>to provide surface ocean current data. It is expected to improve the coverage of surface ocean current data dramatically.</p> <ul style="list-style-type: none"> The land-based high frequency radar (HF) network can provide high-resolution surface current data. However, the effective observational distance is limited to close to the shorelines and the regional coverage is very limited due to the high frequencies of these systems. 			
Deep sea	<p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Although it is still difficult to assess impacts of those new platforms, deep sea observations may be beneficial for decadal prediction and climate projection, at least for purposes of validating predictions. Deep mooring measurements are useful for climate-related monitoring. <p>Ocean Applications:</p> <ul style="list-style-type: none"> OceanSITES is designed to collect, deliver, and promote long-term high-frequency observations of the full-depth water column (including deep sea data) at fixed locations. Deep sea measurements allow estimating the evolution of deep-water properties, in connection with climate change. Such measurements are currently very sparse. 	ship-based measurements, deep Argo program, OceanSITES		

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Aerosol and greenhouse gases	Sub-Seasonal to Longer Predictions: <ul style="list-style-type: none"> Satellite instruments such as high-resolution infrared sounders and solar backscatters provide accurate measurements of total column ozone. However, vertically resolved ozone information is needed. Microwave limb sounders have the potential to offer good vertical resolution and accuracy. 	high resolution infrared sounders, solar backscatters, Microwave limb sounders		
Solar irradiance	Sub-Seasonal to Longer Predictions: <ul style="list-style-type: none"> Although data are currently available for the limited period (2004–present), and it would be hard to evaluate the accuracy, continuous observation of the spectral irradiance is required for the seasonal to decadal predictions. Some studies suggested that UV (200–400 nm) irradiance analysis with monthly time resolution are required for seasonal to decadal predictions. 	Spectral Irradiance Monitor (SIM) and SOLar STellar Irradiance Comparison Experiment (SOLSTICE) instruments aboard the Solar Radiation and Climate Experiment (SORCE) satellite mission, absolutely calibrated broadband radiometers and total solar irradiance and solar spectral irradiance radiometers,		

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Atmospheric data	Sub-Seasonal to Longer Predictions: <ul style="list-style-type: none"> • Similar to those for the global NWP application. • A general requirement for sub-seasonal to seasonal prediction is the availability of consistent historical observational data sets as well as a continuous provision of accurate observational data in the future. 	Multi-spectral VIS/IR imagery with rapid repeat cycles, IR hyperspectral sounders, UV/VIS/NIR sounders, nadir and limb		
Gravity waves	Aeronautical Meteorology: <ul style="list-style-type: none"> • Observation targeting by requesting ascent/descent data from AMDAR / ADS-B / Mode-S aircraft as well as full resolution in radiosonde profiles would be beneficial. The cycle times and availability of radiosondes immediately upstream of mountain ranges must be considered acceptable only in a few densely populated areas and poor elsewhere. 	water vapour satellite imagery from geostationary satellites, GNSS (like GPS) radio occultation measurements		

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Volcanic Ash aerosol	Aeronautical Meteorology: <ul style="list-style-type: none"> Many volcanoes are found in remote and scarcely populated areas, where reliable eruption detection and determination of the nature of the eruption can only be based on remote-sensing methods. Satellite products are most useful where there are significant concentrations of volcanic ash, although for certain phases of the current event clear signals at long downwind ranges have also been readily detected. Further satellite application research is required to determine more accurate quantitative assessments of volcanic ash plume concentration levels. Satellite products can be affected by the presence of underlying, overlying or shrouding clouds, especially ice clouds. Satellite 'inverse modelling' techniques to better constrain the eruptive source term are currently only available in post-event research mode. 	Satellites, aerosol remote-sensing instrumentation, LIDARs, Ceilometers, Lightning location, Aerosol Probes on-board UAV, Aerosol Sondes, Multi-spectral VIS/IR imagery with rapid repeat cycles, VIS/IR imagery, realization of a day/night band, Precipitation radars and cloud radars, VIS/NIR/SWIR/IR mission for continuous polar coverage (Arctic and Antarctica)		
Sand and Dust aerosol	Aeronautical Meteorology: <ul style="list-style-type: none"> While detection of such phenomena in a qualitative sense appears mature in Visible satellite imagery, automated detection outside daylight hours remains an issue, and surface observations in areas prone to suffer these phenomena are scarce. Visibility, in particular Aerosol Optical Depth (AOD) and wind speed/gustiness are being explored as indicative parameters in the absence of any measurements of aerosol loading. ABO in combination with dedicated products derived from satellite imagery are expected to be most promising. 	Multi-spectral VIS/IR imagery with rapid repeat cycles, VIS/IR imagery, realization of a day/night band		

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Ocean colour, chlorophyll, nitrate, silicate and phosphate concentration	<p>Sub-Seasonal to Longer Predictions:</p> <ul style="list-style-type: none"> Ocean active optical components (chlorophyll 'a', suspended particulate matter, Colour Dissolved Organic Matter) controls the penetration of short waves to the interior ocean and, therefore, can affect near-surface heating and stability, creating a biophysical feedback to the atmosphere that can affect predictions of the water cycle, ENSO, and other climate signals. The resolution and frequency are probably sufficient for the predictions, but model and data assimilation development are required to use the data. <p>Ocean Applications:</p> <ul style="list-style-type: none"> In situ measurements are needed to complement satellite derived ocean chlorophyll concentration observations. These measurements should be accompanied by real-time daily observations of ocean temperature, surface wind and nutrients (i.e. phosphate, nitrate, nitrite, ammonium, silicate). Dissolved Oxygen is an important tracer of physical (e.g. ventilation) and biogeochemical (e.g., photosynthesis, respiration) processes. It is now routinely measured by automatic sensors deployed on eulerian and lagrangian platforms with an enhanced quality. Oxygen can be assimilated in models to improve biogeochemical forecasts and reanalyses. For oligotrophic ocean, nitrate concentration can only be obtained by chemical test in laboratory. Satellite measurements provide high-resolution chlorophyll data. There is a requirement to constrain this state variable at the surface where the variability is greatest. The accuracy in the open sea is acceptable for assimilation by ocean ecosystem models and for marine services. However, the chlorophyll data along the coastal region is poor and need be constrained by in situ data of high quality (e.g. HPLC data). Ships provide chlorophyll, nitrate, silicate and phosphate concentration data of poor spatial-temporal resolution over many regions. These products are poor in terms of timeliness required for marine services applications. 	Satellite Imagers (e.g., SGLI, GOCI, VIIRS), Satellite spectrometers (e.g., MODIS, OLCI), Moored buoys, automatic online water quality analysers,		

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	<ul style="list-style-type: none"> Observations from satellites in the L-band can be used for estimating oceanic salinity near the surface and provide valuable information for validation of prediction systems. 			
Soil temperature	Agricultural Meteorology: <ul style="list-style-type: none"> All categories of agricultural meteorological stations should also include soil temperature measurements. The levels at which soil temperatures are observed should include the following depths: 5, 10, 20, 50 and 100 cm. At the deeper levels (50 and 100 cm), where temperature changes are slow, daily readings are generally sufficient. When soil temperatures are measured in a forest, the reference level for the depth measurement should be clearly indicated: whether the upper surface of the litter, humus or mass layer is considered to be at 0 cm; or whether the soil-litter interface is taken as zero reference. Whenever the ground is frozen or covered with snow, it is of special interest to know the soil temperature under the undisturbed snow, the depth of the snow and the depth of frost in the soil. 	Surface stations		
Surface Water Discharge	Hydrology: <ul style="list-style-type: none"> The quality of such observations is yet to be fully determined and in situ observations for calibration are essential. Several satellite-based methods are available on demand to map the extent of flooding in floodplains or large riverine systems as well as the duration of flooding, including visual, IR and radar sensors. However, in general, hydrological observations from spacecraft are not available for any given location on a daily basis owing to the geometry of spacecraft orbits. In most instances, it may only 	Emerging approaches, including low-cost sensors, videos, citizen science, new satellite programmes (e.g., SWOT), IoT and similar can be tested in the framework of	image velocimetry (IV) Drone based discharge measurement in combination with hydrodynamic modelling Satellite-based measurements:	IV is cost-efficient for both direct measurements and continuous monitoring and safe in operations as does not require boat deployments in the streams. Traditional hydrometric stations provide discharge time series with limited spatial coverage but very high temporal resolution and minimal bias thanks to

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	<p>be possible to obtain data once every two to three weeks at a specific location which is a serious constraint.</p> <ul style="list-style-type: none"> • River discharge is key data to produce hydrological services for water management, including floods and droughts, climate analysis, transboundary water sharing and for understanding the whole water cycle. Hydrological observations are still too sparse in many countries. There are challenges for equipment installation and for maintaining and operating hydrological stations. This is due on one hand to the lack of sustainable national funding and on the other hand on lack of professionals. • Emerging satellite information requires in situ observations for calibration and validation /verification. Several satellite-based methods are available on demand to map the extent of flooding in floodplains or large riverine systems as well as the duration of flooding, including visual, IR and radar sensors. However, in general, hydrological observations from spacecraft are not available for any given location on a daily basis owing to the geometry of spacecraft orbits. In most instances, it may only be possible to obtain data once every two to three weeks at a specific location which is a serious constraint. There is no satellite-based measurement of surface velocities and discharge applied operationally. This might be achieved through surface velocity methods (image-based, radar-based) or through assimilation of water surface elevation and slope in hydrodynamic models. Both approaches are still only at the proof-of-concept phase and limited to large to very large rivers only due to resolution limits. 	<p>several WMO projects.</p> <p>In situ, visual, IR, radar, Hyperspectral MW sensors, acoustic Doppler velocimetry, conventional monitoring stations with sub-daily sampling rates (stage-discharge and index velocity methods)</p> <p>In situ: hydrometric stations monitoring stage (sometimes slope and index velocity), stage-discharge rating curves calibrated using occasional stage-discharge measurements (gaugings)</p>	<p>visual, IR, radar, Hyperspectral MW sensors</p> <p>Low-cost, open-source, easy to use discharge measurement and monitoring technologies</p>	<p>streamgauging measurements. Long-term continuity of discharge time series is required, avoiding gaps and bias/disruption. Satellite-based estimations may provide extended spatial coverage but need ground observations for calibration/validation, so they must be seen as an extension, not a replacement of hydrometric networks.</p> <p>In many programs and networks, modern equipment (e.g. hydroacoustic profilers, satellite communication, etc.) can be problem for continuous operation due to their complexity, maintenance cost and lower robustness. More basic techniques, including low-cost, mechanical and operator-based solutions should be considered in such cases.</p>

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Surface water storage	Hydrology: <ul style="list-style-type: none"> There is a quite similar issue of water storage in river channels, flood plains and large estuaries which is more of a challenge to measure continuously. Generally, observations are not yet available for wetlands, large floodplains and estuaries. This may change with improved digital elevation data. Many observational uncertainties still exist with regard to flow retention in dams, reservoirs, lakes and wetlands; the evaporative loss of water from storage surfaces; and seepage to groundwater stores. 	Terrestrial and altimetric observations, Hyperspectral MW sensors		
Groundwater storage	Hydrology: <ul style="list-style-type: none"> Terrestrial observations are being made but overall global access to groundwater data (rates of recharge and abstraction in particular) is highly limited. IGRAC has compiled global level information on groundwater resources. Gravimetric observation techniques (such as from GRACE) for very large groundwater bodies are available but yet to be fully proven in operational circumstances. The use of GOCE data is being explored. 	IGRAC, GRACE, GOCE, Gravimetry missions		
Evaporation and Evapotranspiration	Hydrology: <ul style="list-style-type: none"> Direct observations are sparse, and most evaporation values are in fact derived estimates. Evaporation in the context of the SOG's refers to "direct" measurements of actual evaporation. Because of the observing methods, even direct measurements are estimates. Terrestrial measurements on a global scale are declining in terms of spatial coverage at a time when traditional in situ observations like evaporation pans and lysimeters are largely discontinued. Access to areal derived evapotranspiration is increasing, however, the availability of ground-truthing data has decreased significantly over time. In terms of spatial resolution, the current data sources are not always adequate for small basin analyses, especially, for example, in terms of deriving evaporation losses from major storages. 	evaporation pans and lysimeters, flux towers, eddy correlation and Bowen Ratio techniques,		

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Permafrost (e.g. active layer thickness, ground temperature, rock glacier creep velocity)	<p>Climate Monitoring: Monitoring of the cryosphere.</p> <ul style="list-style-type: none"> • More systematic permafrost monitoring as partnership between research and operational agencies, at national and regional level, data standardized and exchanged internationally • Long-term sustainability of research stations is required, to facilitate the availability of climatological records. • Gap – Consistent InSAR acquisitions in high resolution modes for terrain change <p>Hydrology:</p>	<p>Satellite-based observations: High-resolution multi-spectral VIS/IR imagers; SAR imagery and altimeters (Laser) and RADAR); GNSS reflectrometry (GNSS-R) missions, passive MW, SAR</p> <p>Surface-based observations (increased number of stations, long-term, data sharing)</p>		<p>Current imaging capability unsuitable for monitoring of rock glaciers in mountain permafrost</p> <p>It is extremely challenging to obtain contiguous, seasonal, cloud-free high-res. optical coastline images (of coastal permafrost) – to enable mosaicking of shoreline retreat</p> <p>Seasonal high res. data needed for process understanding for: Thaw slumps; Rock glaciers; Ice wedges (small ponds)</p> <p>No suitable tool for monitoring rock glaciers in permafrost – future test of L-band InSAR foreseen (JAXA PALSAR-2 not available)</p> <p>Challenge to obtain continuous, multi-sat timeseries over all cold spots</p> <p>Hyperspectral images (phenology) of potential benefit, e.g. PRISMA</p>
Glaciers (e.g. mass balance, equilibrium line altitude, discharge and thickness)	<p>Climate Monitoring: Monitoring of the cryosphere.</p> <ul style="list-style-type: none"> • More systematic glacier monitoring will be established as partnership between research and operational agencies, at national and regional level, and the data will be standardized and exchanged internationally <p>Hydrology:</p>	<p>Satellite-based observations: Wide-swath radar altimeters, and high-altitude, inclined, high-precision orbit altimeters; Multi-polarization SAR, hyperspectral VIS; Gravimetry missions</p> <p>Airborne observations: Lidar</p>	Drones Ground Penetrating Radar (GPR) radio-echo sounding (RES) – glacier volume	<p>Long-term sustainability of research stations is required, to facilitate the availability of climatological records.</p> <p>Snow extent and glacier mapping still largely dependent on optical ~10 metre res. global, decadal and freely/openly accessible datasets from Landsat, ASTER and Sentinel-2, complemented by high spatial res. (<10 m), limited coverage optical images (and stereo data) from SPOT, Pleiades, Cartosat-I etc.</p>

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		Surface-based observations and surveys		
Ice sheets	Climate Monitoring: Monitoring of the cryosphere. <ul style="list-style-type: none"> Operational successor of CryoSat-2 sought as part of evolution in Copernicus (CRISTAL ice and snow topography mission) for ice surface elevation at > 82° lat Consolidated computation of ice shelf calving/iceberg flux Need for continuous tracking of grounding line migration The most significant residual source of uncertainty in sea level rise is Antarctic peninsula Ocean applications:	GNSS radio occultation (basic constellation), SAR imagery and altimeters (Laser) and RADAR) GNSS reflectrometry (GNSS-R) missions, passive MW, SAR Cryospheric observations – surface-based		Need for Left-looking InSAR coverage in central Antarctica – planned to be fulfilled by NASA/ISRO NISAR (L-band SAR) in future Gap in continuity of gravimetric ice sheet mass balance timeseries – now continued by GRACE-FO Need for regular refresh of ice sheet DEMs in dynamic regions (TBD interval)
Ice bergs (e.g. position, size, concentration, draft)	Nowcasting and VSRF: Ocean forecasting: <ul style="list-style-type: none"> Increased transit in the polar regions, including tourist ships, Autonomous AWS ships will allow for timely ice observations (e.g. polar regions, Southern Ocean). 	Near-surface observations over ocean: ship observations Satellite altimetry (CryoSat2), imagery (MODIS)	ENVISAT ASAR images Extra wide-swath (EWS) SAR; Interferometric wide swatch (IWS)	Data of high resolution and high accuracy from research vessels to be distributed in real-time. More systematic infra-red radiometer measurements from ships for satellite validation.
Lake and river ice	High-resolution NWP: Hydrology:	Hydrological and cryosphere observations Volunteer observations of lake/river ice freeze/thaw dates –		Automated measurement of snowfall/snow depth. expansion of automated soil moisture/temperature measurements Volunteer observations of lake/river ice freeze/thaw dates – disseminated internationally and archived.

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
Water use	Hydrology: <ul style="list-style-type: none"> At present only limited information is available on this variable that is also highly heterogeneous in quality and availability (administrative, spatial and temporal). While sectoral information (mostly estimates) are available on a national and local Government basis, global consolidated information on water use both consumptive and non-consumptive is not available and most existing information is extrapolated or derived from relatively few accessible data sources. Countries should make the information on water use internationally available. 	AQUASTAT		
Electromagnetic flux measurements: Solar EUV flux, X-ray flux, radio emissions	Space Weather: <ul style="list-style-type: none"> For monitoring long-term solar variability and for feeding into numerical models of the space environment and atmosphere, measurements of the flux at 2800 MHz frequency (10.7 cm) are used. These are currently only provided by the Penticton Radio Telescope. Long-term continuity and consistency of these data series should be assured. Such measurements obtained by ground-based infrastructure require the contributions of observatories around the globe in order to achieve 24h coverage. Networks that gather such data from around the globe exist but currently do not assure the public availability of the data meeting the above criteria. The Radio Solar Telescope Network (RSTN) operated by the US Air Force covers the globe in real time but not all real time spectra are publically available. The data from the eCallisto network are publically available but few of the stations contribute in real-time. Provision of Solar EUV flux, X-ray flux, and Radio emission data should be evaluated as marginal to acceptable. The key ground-based systems designed for science should develop a real-time mode for space weather applications and become coordinated at a worldwide level to ensure the continuity of observations and good intercalibration. 	NOAA/GOES satellites, Solar Dynamic Observatory (SDO), PROBA2/LYRA, Penticton Radio Telescope, RSTN, eCallisto, X-ray spectrograph at GEO		

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
Solar images: X-ray, EUV, H-Alpha, Calcium-K, White light, Magnetic field	Space Weather: <ul style="list-style-type: none"> Many of ground-based solar observations are semi-operationally supported, with some level of long-term continuity, although lacking the real-time services, while space-based observations, such as SOLar and Heliospheric Observatory (SOHO) (most widely utilized in operational space weather services), SDO, and STEREO PROBA-2, are research missions. Being research missions they are generally not designed to meet the operational timeliness requirements, and most importantly it is not clear if and how their capabilities will be replaced. Provision of Solar images: X-ray, EUV, H-Alpha, Calcium-K, White light, Magnetic field data should be estimated as marginal. The key ground-based systems designed for science should develop a real-time mode for space weather applications and become coordinated at a worldwide level to ensure the continuity of observations and good intercalibration. 	GONG, SOON, SOHO, the SDO, the Solar Terrestrial Relations Observatory (STEREO), PRoject for On-Board Autonomy-2 (PROBA-2), and others,, X-ray spectrograph at GEO		
Solar Coronagraph images	Space Weather: <ul style="list-style-type: none"> Provision of Solar Corona images should be estimated as poor. A particular concern in that area is to assure the continuity of coronagraph data for the estimation of CME initiation parameters, which have a profound impact on Space Weather forecasting capabilities. The key ground-based systems designed for science should develop a real-time mode for space weather applications and become coordinated at a worldwide level to ensure the continuity of observations and good intercalibration. 	Large Angle and Spectrometric Coronagraph (LASCO) on-board the SOLar Heliosphere Orbiter, Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument on-board the STEREO, Solar coronagraph and radio spectrograph at L1		

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
Solar wind bulk velocity, density and temperature	Space Weather: <ul style="list-style-type: none"> Unfortunately, due to the differences in instrumentation, the bulk solar wind parameters provided by these two satellites sometimes exhibit large differences. The bulk solar wind parameters (except IMF) are also available (not in real time) from SOHO (located at L1 point), and from WIND research missions. Current situation with data provision on solar wind bulk parameters and IMF can be estimated as marginal. 	ACE (Advanced Composition Explorer), DSCOVR (Deep Space Climate Observatory, NOAA), Solar wind, in situ plasma, energetic particles and magnetic field at L1		
Solar energetic particles fluxes	Space Weather: <ul style="list-style-type: none"> Unfortunately, DSCOVR, does not have energetic particle instruments. High-energy electron measurements at L1 are not currently routinely available. Thus, current availability of data on solar energetic particles from measurements in solar wind should be defined as poor. 	ACE, SOHO (NASA/ESA), and WIND (NASA), Off-L1 position the energetic particles are measured by one of STEREO satellites, Solar wind, in situ plasma, energetic particles and magnetic field at L1		
Heliospheric images	Space Weather: <ul style="list-style-type: none"> One of the satellites has recently ceased supplying observations. Provision of data should be estimated as poor. 	STEREO, Solar coronagraph and heliospheric imagery, both on and off the Earth-Sun line (for example, at L5)		
Electron differential directional flux (GEO, MEO, LEO)	Space Weather: <ul style="list-style-type: none"> Coverage of low-energy electrons (< 100 keV) is poor, as is availability of data. Increasing the number of locations in GEO and LEO where these electrons are measured and making the 			

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	data available in real time is required. Increased availability of high-energy electron measurements at both GEO and LEO is also needed, as is increased availability of high-energy electrons at LEO. Additional electron measurements in HEO orbits would improve the ability to specify the electron flux levels throughout the magnetosphere. Marginal.			
Cosmic ray neutron flux (surface-based)	Space Weather: <ul style="list-style-type: none"> only a limited number of sites provide high quality data in real time. Improving the real-time data quality and the incorporation of these data in global models could contribute to better estimates of radiation levels on aircraft. Marginal. 	Ground-based neutron monitors and muon detectors,		
Radiation dose rate (aircraft-based)	Space Weather: <ul style="list-style-type: none"> Radiation dose rate measurements are not routinely available on aircraft. A baseline should be established for these measurements that could be used to develop initial service capabilities (including verification of models) and later to refine measurement requirements. Poor. 			
Total Electron Content (TEC)	Space Weather: <ul style="list-style-type: none"> The situation is worse with data availability above oceans, for which the space-based GNSS observations are a feasible way to bridge the gaps. The International GNSS Service (IGS) provides ground GNSS data from a network of globally distributed sites, including GPS and GLONASS, and in future could be extended to incorporate BeiDou (formerly named COMPASS), GALILEO and other GNSS. Overall for ground GNSS receivers data provision is Acceptable in some regions (e.g. in US, Japan, Europe) but Poor globally (problems particularly in the timeliness). The horizontal resolution and coverage of GNSS-RO observations will be improved with the launch of COSMIC-II GNSS-RO constellation (2017–2020), with estimated latency about 45 min. This is within the threshold but is still poor compared to the goal. Thus, estimation of observations provided by GNSS-RO is Poor (problems particularly in the timeliness). 	GNSS radio occultation (basic constellation), GNSS radio occultation; additional constellation for enhanced atmospheric/ionospheric soundings (including polarimetric), including LEO-LEO radio occultation for additional frequencies optimized for atmospheric sounding,		

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
Scintillation (S4 and $\sigma\phi$)	Space Weather: <ul style="list-style-type: none"> For scintillation measurements, there is a need in increasing the number of ground-based GNSS scintillation receivers, particularly in polar and equatorial regions where the phenomena most often occur, in order to achieve more homogeneous coverage and to satisfy the requirements. Innovative solutions should be searched to cover the ocean regions to support off-shore activities. Up to now, the data provision should be defined as Poor. 			
foEs	Space Weather: <ul style="list-style-type: none"> Data provision for monitoring the above characteristics of F and E-regions of ionosphere can be regarded as Acceptable in some regions (e.g. in Mid-Europe) but Poor globally (problems in the timeliness). 			
D-region absorption	Space Weather: <ul style="list-style-type: none"> Overall, the availability of D-region absorption observations is Poor. Additional availability and data timeliness, particularly from scientific riometer, would improve ionospheric specification in extreme conditions. 			
Temperature (space)	Space Weather: <ul style="list-style-type: none"> Gap Assessment: Lower Thermosphere Temperature: Marginal – OSIRIS data are available, but they do not cover whole vertical range and have poor timeliness. Gap Assessment: Upper Thermosphere Temperature: Poor – Only a few sparse FPI observations are available. Poor timeliness. 	OSIRIS satellite instrument, FPI		
Atmospheric Density	Space Weather: <ul style="list-style-type: none"> Gap Assessment: Lower thermosphere Density – Less than Marginal / Marginal – SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness. Gap Assessment: Upper thermosphere Density – Marginal – Swarm meets most of the requirement, apart from timeliness and vertical resolution. The latter could be addressed by the introduction of new missions like DANDE and the GRACE follow- 			

Variable	Application Area And Gaps	Available Technology To Address The Gaps	Emerging Technologies	Comment/Recommendations (Cost, Complementarity Of Technologies, Capacity Development Aspect, GBON Development, etc.)
	on SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness.			
Horizontal Wind	Space Weather: <ul style="list-style-type: none"> Gap Assessment: Lower thermosphere Wind – Poor – No current observations. Awaiting ICON mission in 2017. Gap Assessment: Upper thermosphere Wind – Poor – Only a few sparse FPI observations. Poor timeliness. Accelerometer winds have too large errors to be useful. 			
Ground-based observations of geomagnetic field	Space Weather: <ul style="list-style-type: none"> The requirement of spatial distribution (100 km) in several areas is not met based on current non-uniformity in the locations of the INTERMAGNET geomagnetic observations around the globe. They are most dense in Europe and the least dense in Africa, South America and the Asian part of Russia. Other collaborative networks of the ground magnetometers do not satisfy the requirements on more parameters than INTERMAGNET. INTERMAGNET data satisfy the goal requirements of observing cycle (1 sec) and uncertainty (0.1 nT). At the same time, the INTERMAGNET data transmission is within 72 hours of acquisition, thus, threshold timeliness of 60 min is not met. In general, the data availability, sampling rate and quality of the ground-based geomagnetic data should be regarded as marginal to (in some places) good, while the timeliness is still poor. 			
Space-based observations (LEO, GEO) of geomagnetic field	Space Weather: <ul style="list-style-type: none"> the requirements for observations of the geomagnetic field at GEO and LEO orbits can be regarded as met at level of marginal with the horizontal resolution goal on GEO and LEO are not met as well as timeliness for LEO. But, as has being pointed out, these locations do not represent the overall status of the dynamical magnetosphere, especially at high latitudes of the magnetosphere, (which in the future might be filled by high inclination HEO mission). Thus, the overall spatial coverage and the temporal resolution of the global scale magnetospheric magnetic field data and needs to be improved and in its current state should be classified as poor. 			

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ANNEX 3**KEY ACTIONS OF THE IMPLEMENTATION PLAN FOR THE EVOLUTION OF GLOBAL OBSERVING SYSTEMS (EGOS-IP) TO BE CARRIED OUT BY MEMBERS**

Annex of Resolution 40 (Cg-18)

Members are encouraged to focus on the key EGOS-IP (see EGOS-IP document in WMO languages: [EN](#), [ES](#), [FR](#), [RU](#), [ZH](#)) actions listed in the table below, and to provide feedback on how they are implemented at the national level. However, the remaining actions are also important and need to be addressed by the identified actors in the EGOS-IP.

Action No.	Action	Performance Indicator
C3	WIS Standards – Ensure all operators producing observations adhere to the WIS standards.	Extent to which WIS standards are applied.
C4	Users consultation – Careful preparation is required before introducing new (or changing existing) observing systems. The impact needs to be assessed through prior and ongoing consultation with data users and the wider user community. Also, data users need to be provided with guidance on data reception/acquisition, processing and analysis infrastructure, the provision of proxy data, and the provision of education and training programmes.	Extent to which user community concerns are captured.
C7	“Change management” procedures – Ensure time continuity and overlap of key components of the observing system and their data records, in accordance with user requirements, through appropriate change management procedures.	Continuity and consistency of data records.
C8	Data sharing principles – For WMO and co-sponsored observing systems, ensure continued adherence to WMO data sharing principles irrespective of origin of data, including data provided by commercial entities.	Continued availability of all essential observational data to all WMO Members.
C12	Radio frequencies – Ensure a continuous monitoring of the radio frequencies which are needed for the different components of WIGOS, in order to make sure they are available and have the required level of protection. Provide any new information regarding new application or equipment using radio frequency.	Observation frequency bands available/not available with required level of protection.
G2	Hourly data exchange – Ensure, as far as possible, a global exchange of hourly data which are used in global applications, optimized to balance user requirements against technical and financial limitations.	The standard monitoring indicators used in global NWP.
G4	WIGOS Standards – Ensure exchange of observations from atmosphere, ocean, terrestrial observing system, according to the WIGOS standards. If needed, organize different levels of pre-processed observations in order to satisfy different user requirements.	Statistics on the data made available to each application.

Action No.	Action	Performance Indicator
G7	Radiosondes in data-sparse areas – Expand radiosonde stations, or re-activate silent radiosonde stations, in the data-sparse areas of Regions I, II and III which have the poorest data coverage. Make all possible effort to avoid closing existing stations in these data-sparse areas, where even a very small number of radiosonde stations can provide an essential benefit to all the users.	The standard monitoring indicators used in NWP.
G13	Radiosonde data availability – Identify radiosonde stations that make regular measurements (including radiosondes operated during campaigns only), but for which data are not transmitted in real time. Take actions to make data available.	A number of the above radiosonde stations providing data to GTS, plus standard monitoring indicators on radiosonde data availability and timeliness.
G14	HR Radiosonde data – Ensure a timely distribution of radiosonde measurements at high vertical resolution, together with position and time information for each datum, and other associated metadata.	Number of radiosonde sites providing the high-resolution profiles.
G17	Regional remote-sensing profiling stations – Develop networks of remote-sensing profiling stations on the regional scale in order to complement the radiosonde and aircraft observing systems, mainly on the basis of regional, national and local user requirements (although part of the measured data will be used globally).	Number of profiling stations providing quality-assessed data in real time to WIS/GTS.
G18	Processing & exchange of profiler data – Ensure, as far as possible, the required processing and the exchange of profiler data for local, regional and global use. When profiler data can be produced more frequently than 1 hour, a data set containing only hourly observations can be exchanged globally following the WIS principles.	Number of profiling stations exchanged globally.
G40	Metadata & representativeness of special stations – Ensure, as far as possible in real time, exchange of observations, relevant metadata, including a measure of representativeness made by surface-based stations serving specific applications (road transport, aviation, agricultural meteorology, urban meteorology, etc.).	A percentage of observations from the above stations exchanged regionally and globally in real time.
G45	Dual polarization radars – Increase the deployment, calibration and use of dual polarization radars in those regions where it is beneficial.	Data coverage obtained from this type of radar for each region.
G47	Weather radars for developing countries & DRR – For areas in developing countries which are sensitive to storms and floods, a special effort has to be made to establish and maintain weather radar stations.	Number of operational weather radar stations in the above areas.

ANNEX 4**OVERVIEW ON GBON REQUIREMENTS (SHALL/SHOULD)**

(based on GBON provisions in WIGOS Manual, WMO-No. 1160, 2021 Edition)

	SHALL					SHOULD			
Network Type	Variables	Horizontal Resolution	Temporal Resolution	Vertical Resolution	Data Exchange	Horizontal Resolution	Variables²⁰	Temporal Resolution	Vertical Resolution
Land Surface Stations	<ul style="list-style-type: none"> • Atmospheric Pressure • Air temperature • Humidity • Horizontal wind • Precipitation • Snow depth (where applicable) 	200 km	Hourly	-	Globally Real time / Near-Real-time	< 100 km	<ul style="list-style-type: none"> • Atmospheric Pressure • Air temperature • Humidity • Horizontal wind • Precipitation • Snow depth • & further available observations 	<= hourly	-
Upper-Air Stations over land	<ul style="list-style-type: none"> • Temperature • Humidity • Horizontal wind 	Up to 30 hPa or higher: 500 km	2x / day or more frequent	100 m	Globally Real time / Near-Real time	Up to 30 hPa: 200 km or higher Subset: Up to 10 hPa or higher: 1000 km or higher	<ul style="list-style-type: none"> • Temperature • Humidity • Horizontal wind • & further available observations 	Up to 30 hPa: 2/day or more frequent Up to 10 hPa or higher: 1/d or more frequent	100 m
Upper-Air Stations over ocean	<ul style="list-style-type: none"> • Temperature • Humidity • Horizontal wind 	Up to 30 hPa or higher: 1000 km	2x / day or more frequent	100 m					

²⁰ Are indicated within square brackets these variables which should be reported whenever the observations are available.

	SHALL					SHOULD			
Network Type	Variables	Horizontal Resolution	Temporal Resolution	Vertical Resolution	Data Exchange	Horizontal Resolution	Variables ²⁰	Temporal Resolution	Vertical Resolution
Marine Surface Stations	<ul style="list-style-type: none"> • Atmospheric Pressure • Sea-surface temperature 	500 km	Hourly		Globally Real time / Near-Real time				
Aircraft meteorological Observation Ascents/descents					Globally Real time / Near-Real time		<ul style="list-style-type: none"> • Temperature • [Humidity] • Horizontal winds • & further available observations 	Hourly or more frequent	300 m or higher
Aircraft meteorological Observation Level flight					Globally Real time / Near-Real time	<= 100 km	<ul style="list-style-type: none"> • Temperature • [Humidity] • Horizontal winds • & further available observations 		
Remote-sensing profiler					Globally Real time / Near-Real time		<ul style="list-style-type: none"> • [Temperature] • [Humidity] • Horizontal winds • & further available observations 	Hourly	100 m or higher

INTEGRATED URBAN SERVICES (IUS) FOR WIGOS HIGH LEVEL GUIDANCE

Introduction

By 2050, 80% of the world's population will be in urban centres (ICLEI, 2020). If well-planned and well-managed, urbanization can be a powerful tool for sustainable development for both developing and developed countries. The United Sustainable Development Goals (SDG 11) and the UN New URBAN Agenda represents a shared vision for a better, resilient and more sustainable and healthy future for cities (UN, 2016; UN 2019). The WMO has responded by promoting the concept of Integrated Urban Services (Cg-17, resolution 68; Cg-18, resolution 32 and 61; EC-68, Decision 15; EC-69, Decision 41; EC-70, Decision 7, Annex 1 and 2; WMO Strategic Plan 2020–2023).

The objective of this document is to articulate the high-level monitoring and observation requirements and priorities of IUS as a part of the WIGOS 2040-High Level Guide for NMHS to implement in next 5 years (2021–2025).

As there are concurrent activities in providing details and guidance on Integrated Urban Services, IUS (Study Group on Integrated Urban Services (SG-URB), 2021), the perspectives summarized here use both existing and draft documents as well as reviewed by SG-URB and other experts. The guidance provided by experts on IUS will evolve and needs to be formalized but there is general agreement on the views and priorities expressed in this document.

IUS is not an existing WIGOS Application Area (AA) though it is closely linked to the narrower applications area "Providing Atmospheric Composition information to support services in urban and populated areas" which is limited to air quality forecasting. Given the distinctive nature and issues of urban observations (e.g. variety, variable surface, height, virtual location (multi-location), high spatial and temporal resolution and timeliness, low latency, required partnerships, data quality, representativeness, integration and significant metadata issues) and its direct use by users and decision makers in early warning decisions, consideration of a new WIGOS AA to capture IUS monitoring may be needed. Given its inclusion in this WIGOS High Level Guidance document and also based on the discussion with SG-URB, the analysis of gaps and priorities are presented here assuming that observations in support of the Integrated Urban Services can be considered as distinct AA and that formalization of goals, objectives, scope and requirements will follow in the fullness of time.

Integrated Urban Services Concept

Need for urban services: The density of people, the diversity of the urban environment (e.g., building density, building heights, surface, permeability, anthropogenic emissions), the concentration of critical artificial infrastructures (e.g., power, telecommunications, roads, sewers) create an enhanced sensitivity to hazards due to weather, climate, air quality and hydrology. The impact of hazards is inter-related and there is a cascading non-linear far-reaching downstream domino effect (WMO, 2019; WMO, 2021, ICLEI, C40). The needs for urban services and underlying infrastructure are driven not only by the short-term hazards' preparedness needs but the long-term planning and adaptation requirements.

Urban planning for healthy cities (air quality, ecology, quality of life, resiliency), considering climate change, is multi-faceted and include considerations of re-designing cities (green spaces, blue or water spaces), urban structures (green roofs, building materials, water sources for heat storage or cooling processes), ecology/biodiversity (plant life, species, flora, fauna) and quality of life (efficient transportation, clean air, clean water, greenhouse gases).

Conurbation areas are so large that hazards and associated warnings/impacts in one location may not affect other locations and emergency services (deployment of rescue teams in

flooding in low lying areas and strong wind conditions, emergency hospital admissions, preparation and appropriate staffing) as well as day-to-day services.

Need for Integration: These multi-faceted issues require specific, consistent and accurate high-resolution information and integration of services for both strategic long-term decadal planning and for tactical emergency response and recovery. Integration is also needed across domains to most efficiently utilize resources to support observational infrastructure. The weather, climate, environment and water services require common meteorological data, exchange of service specific data to enable new capabilities at high spatial resolution, efficiently and without duplication. Interoperability (standards, exchange formats, data access, metadata) is fundamental as well as knowledge of processing differences, timeliness, data access and latency. The high-density spatial resolution, the specificity of and cost of urban observations requires specialized expertise that can only be achieved by partnerships and integration. Integration is essential and critical to seamless prediction, Earth System Modelling, value chain, rapid research to operations and operations to services technology transfer elements of the WMO Strategic and Operating Plan 2020–2023 (Brunet et al., 2015; Grimmond et al., 2015; WMO-HIW, 2021; Golding, 2021).

Scope of IUS: The Integrated Urban Services concept has been formulated by WMO (WMO, 2019 (G1); WMO, 2020 (G2); Grimmond et al., 2020; Ren and McGregor, 2021; SG-URB, 2021) and includes the following domains:

- (a) Weather – hazardous warnings (more specific), emergency services, extra heat;
- (b) Climate – building codes, urban design, climate change (greenhouse gases, WMO-IG3IS, 2018);
- (c) Water – Sewer Management, Urban Flooding (Coastal, river);
- (d) Environment²¹ – atmospheric composition as well as health, ecology (insect, flora and fauna), water quality and others

Methods of Integration: Methodology developed by WMO includes several different methods of integration:

- (a) Integration at service level;
- (b) Integration at product /post-processing level;
- (c) Integration at modelling level;
- (d) Integration at observation level

Integration of observational infrastructure is the most relevant aspect of the Integrated Urban Services for this particular statement. Depending on the specific service and usage, urban observations will have different processing, siting and density requirements that need to be considered when integrating diverse sources of observations and this must be included in the metadata (e.g., time averaging, accuracy and precision, coverage; WMO-WIGOS, 2021). IUS requires information/data/metadata to flow or be integrated all along the value chain (Golding, 2021; WMO-HIW, 2021)) for use/interpretation by decision-support systems (e.g. data and product visualization systems that may include “big data” analytics processing; will also include domain experts) and decision makers (e.g. mayors of cities). Hence, integrated products that

²¹ Note that in this document “urban environment” refers to the physical characteristics of the city, the distribution of buildings, green and blue space, building density and heights, permeability of the surfaces, etc. whereas “environment services” refers to the air and water quality, ecology, biota of the city.

support these services could be created using individual sensors, (e.g. time series of individual gauge for areal precipitation estimation), or diverse monitoring networks of either homogeneous (e.g., precipitation maps from rain gauges; or radar) or heterogeneous (e.g., precipitation maps from gauges, radar and satellite) observation technologies. The processing may be very sophisticated and may include the use of numerical weather models (e.g. reanalysis).

Heritage

WMO Initiatives: WMO Congress/Executive Council has approved the concept and requested the development of guidance materials on IUS.

- (a) Congress approves IUS concept (Resolution 68, CG 17, 2015; Decision 15, EC 68, 2016; Decision 41, EC 69, 2017);
- (b) WMO Strategic and Operating plan 2020–2023;
- (c) Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services, Volume I: Concepts and Methodology has been formally approved and accepted (2019);
- (d) Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services, Volume II: Demonstration Cities has been formally approved and accepted (2021);
- (e) Guidance on Urban Heat Island is in development (release 2022);
- (f) Study Group on Integrated Urban Services (SG-URB) was formed (2020);
- (g) Good Practices on high resolution modelling for IUS is under development by SG-URB;
- (h) Good Practice for the observational based evaluation of urban GHG emissions (WMO-IG3IS, 2021)

Existing WMO guidance materials are available:

- (a) Initial Guidance on Urban Observations (WMO, 2006)
- (b) Guidance materials on AQ, Water, NWP, CIMO documents (WMO, 2018)

Other

- (a) National Research Council, US, 2012;
- (b) HIW (Golding, 2021);
- (c) Healthy Cities Book (Ren and McGregor, 2021)

Role/Mandate of Cities: Urban services/warnings are generally the mandate of cities who have organized themselves (with national and global support) to address local urban sustainability issues and play a significant role is setting requirements, priorities and actions.

- (a) The ICLEI – Local Governments for Sustainability, formed in 1990, with support from the United Nation, was formed as an NGO to provide technical assistance to local governments to support sustainability goals.

- (b) C40, formed in 2005, is a group of 97 megacities committed to take bold climate action for healthy and sustainable future.
- (c) Global Covenant of Mayors

Role of NMHS: A key message of guidance on Integrated Urban Services was that NMHS are well positioned and expected to lead the development of IUS (Rogers, 2013; C40, 2020) because of:

- (a) capacity, particularly in high-resolution urban scale modelling (from global, to regional, local and microscales including dispersion modelling for chemical, biological, radiological or nuclear and explosives (CBRNE) hazards)
- (b) capability, existing air, climate, environment and water mandates at the global, national scale as well as existing pathways for the communication of warnings.
- (c) heritage, role in multi-hazard early warning systems, disaster risk reduction and climate change
- (d) authoritative voice, recognized expert and lead in warning provisions and essential role in decision-making processes

IUS and Observations: At the same time, WMO is providing guidance on the future of the global observation system through the WIGOS 2040 Vision of the Global Observation System (W2040-Vision). The WIGOS Vision concepts are consistent with those of IUS, in particular:

- (a) Integrated observing systems;
- (b) Observations from non-traditional sensors and platforms;
- (c) Data management and access;
- (d) High impact and seamless services;
- (e) Focus on meta data; and
- (f) partnerships.

Issues, among others, include:

- (a) Focus on non-traditional observation sources and inclusion of "reference" stations in network design;
- (b) Analysis of heterogeneous sensors/networks of observations for quality control;
- (c) Focus on local/micro observations and representativeness at various scales;
- (d) Non-meteorological data for high impact verification

Background/State of the Art

- (a) IUS are affected by global and regional weather and climate scale systems such as climate change, synoptic and extratropical systems as well as hurricanes/typhoons. Cities are influenced the processes at all scales and hence, **guidance for global or regional observations are relevant for IUS observations.**

- (b) There are **local (scale of the city or conurbation to neighbourhoods), micro (city blocks) and obstacle (individual buildings) scale** processes and impacts. Conurbations are sufficiently large that hazards affect one location but perhaps not another and hazards initiate or occur in a location far from where it has an impact. With new observation capability, improved observation density, modelling and targeted decision-making, IUS from local, micro or obstacle will be evolving.
- (c) While there is a close association of spatial and temporal scales for weather, there are IUS applications (e.g. urban planning) where information at microspatial scales is needed on longer (climate) temporal scales. For weather and air quality applications, the **3D dimensional** nature of the various urban canopy layers (~100 m to ~2 km) plays significant roles in the process characterization and numeric modelling. Atmospheric chemical processes and distribution of constituents vary at even finer vertical scales (WMO-UHI, 2022; SG-URB, 2021).
- (d) Urban services are generally under the mandate of municipalities supported by regional (state) and national governments. **Urban services already exist**, and this is most often done at the “service level” where disparate information and expertise from a variety of sources is combined manually for decision makers as in civil emergency management operations. Another example of current urban services is in the establishment of building/construction codes from climate data (using long time series of weather information). At the same time there is an obvious gap in the integrated of such services provided by different organizations.
- (e) Traditional climate services rely on observations from a **rural site** (often an airport) and **adapted or interpreted for urban** sites/environments using statistical relationships from “30-year normals”. However, urban planners require micro (and perhaps obstacle) scale weather, air quality and water predictions under climate change and urban development scenarios (Amorin et al., 2018). Oftentimes, urban observations that can be directly used in support of Integrated Urban Services are missing or conducted in a scattered way by different organizations.
- (f) Regardless of the level of integration, **service level integration will always be part of the “final mile”** given the complexity and knowledge required to interpret the disparate information and to develop trust by decision makers (e.g. mayors). Observations are directly needed for verification of the produced products and to enable trust all along the value chain.
- (g) In general, the **urban environment is not well represented** in the current generation of operational NWP even where global or regional models (for weather and climate forecasting) have grid resolution on the kilometre scale (typically 2–4 km). Cities are simply represented or not at all (i.e., treated as rural) in such models. One of the chief benefits of the higher resolution models is that it captures the large scale (~O(100 km)) processes better (more accurate structures and better prediction of intensities) which in itself improves urban prediction as it predicts the rural environment better. IUS requires sub-kilometre scale models to resolve urban environment variations and processes. Some models run at 2 and 3 m scales.
- (h) **Data assimilation for high resolution** numerical weather prediction is still in research and development stage. Progress in the scientific understanding of urban processes (surface exchange) and their parameterization is further needed. Current urban models (and services) are initiated via global or regional models where global and regional observations are assimilated. Hence, (i) improvements of the monitoring network at global and regional scales will benefit IUS and (ii) network

design of urban observing networks for NWP initiation is a future priority. It should be noted that new generation of AI based parameterization and assimilation schemes are in rapid development and progress may greatly accelerate this development.

- (i) The **high-resolution microscale capability of the urban models** and expected observations are defining current and future capabilities of IUS. For examples, urban designers require knowledge of the urban environment at microscales to combine green (**trees**, parks, gardens) and blue (sources of water for heating/cooling; sinks of effluent for sewer management systems for sustainability) areas for healthy urban designs (building and factory location; Weston, 2021). Survey of urban numerical models indicate that hecto-metric scale models ($\sim O(100)$ m) are common in research and pre-operations, as well as geospatial models that go with resolution down to tens of metres. Urban design for air ventilation is at the street canyon scale (Ng, 2009; Ren et al., 2018).
- (j) The first step in urban modelling is the representation of the **initial and boundary conditions** (the urban environment) at the local, micro and obstacle scale. Depending on the sophistication of the urban applications (e.g. climate), it may be sufficient to identify "**Local Climate Zones**" (Stewart and Oke, 2012) to translate rural into urban weather/climate observations or model output (local scale).
- (k) However, the **representation of the urban environment** in high resolution (or order hundreds of metres and less) **urbanized limited area models** requires a higher level of detail where urban structures such as buildings, their height and density, the surface impermeability, micro/obstacle heating or emission sources such as highways, industrial factories and backyard cooking (and hence human activity such as work and traffic patterns, use of air conditioners, backyard cooking) are represented (Ching et al., 2018).
- (l) The **urban environment evolves** over time with highways, industrial plants, buildings being constructed and low lying flood-prone areas (underpasses) and where water ways and flood plains are situated being changed into used areas. Given the constantly changing environment, the data and environment metadata describing it require frequent updates and enhancements over current practices.
- (m) Interpretation of the observation requires knowledge of the environment that it represents (i.e., Local Climate Zones (LCZ) or micro urban environments). Fetch length and even wind speed and direction affect the interpretation. Therefore, **urban meta data is critical to interpret the observation and should include information about urban environment as well as site representativeness.**
- (n) In the existing decision-support systems, particularly in the age of "big data" analytics/Artificial Intelligence, **products derived from observations are required and treated as data** for downstream processing and support of services. For example, precipitation may be processed, derived or quality controlled from multiple sensors (gauges, radar, satellite, crowdsourced or from reanalysis) and the original observation source may be irrelevant.
- (o) **Development and demonstration** projects, test beds and other research projects enhance and accelerate the **research to operations** and **operations to services** and **services to decision-making** technology transfer processes following and supporting Long-Term Strategic Goals of the WMO.

- (a) **One size does not fit all.** The observation/monitoring needs will evolve following the requirements and applications of Integrated Urban Services and they will be specific to each conurbation. Geography will play a great role in IUS design but to first order this is mainly already covered by the global (and regional) climate observing systems. Having said that, there are commonalities amongst cities for local/microscale services for weather and air quality hazards, to address climate change impacts, local floods and urban planning requiring higher resolution observations.
- (b) **Essential IUS Variables:** There is a wide variety of variables that need to be measured. Basic meteorological information (e.g. temperature, wind, precipitation) is common to all IUS domains. Domain specific observations such as fluxes, emissions, water levels and other parameters may also be needed by other domains such as water quantity/levels in urban basins/sewers for calibration, verification or impact estimation. Multisector observations will enable coupling of models, development of new science and new and better services. This may include user success metrics (e.g. hospital admissions or epidemiological data) to properly evaluate the impact of IUS.
- (c) **IUS Siting:** There are existing principles for network design and guidelines for metadata (WMO-WIGOS, 2021; WIGOS, 2019). However, urban observations are fundamentally **different** from rural observations due to: (i) sensors comprising an urban station may be displaced both horizontally and/or vertically, (ii) the underlying surface is variable and (iii) height of the observation particularly relative to the three-dimensional nature of the urban canopy. Previous guidance on urban observations that focused on urban climate (local scale, and the subsequent development of the Local Climate Zone concept) indicated that sensors comprising a "station" may be physically displaced. Temperature may be measured in one location, but the wind may be measured several buildings away to escape obstacle flow effects. Observations on rooftops were discouraged for urban climate services but are needed if they are considered critical components of the heat island or are part of the physics of the urban modelling (SG-URB, PA15). Wind may be collected at a different location and/or at different heights above ground within the urban boundary layer (urban canopy layer, the roughness sublayer, the inertial sub-layer, UHI 2021).
- (d) **Need for dense observations:** High resolution observations are needed for a variety of reasons: from developing scientific understanding, parameterization of processes in models, developing climatological/statistical relationships (require long-term monitoring), for microscale nowcasts and early warning preparation (timeliness/low latency, high spatial/temporal resolution, maintaining situational awareness, warning preparation), setting initial and boundary condition for models, for validation (checking model/product processing assumptions are correct), use by downstream decision-making systems (e.g., use in "big data"/"AI" systems) and verification (checking predictions are correct to develop trust) in the decision-making process. For high impact warnings, the verification data should also include metrics and parameters related to the impact of the event (e.g. flood height, area, hospital admissions, ecological parameters). These latter data may not be readily available to the scientific community but will be needed to demonstrate success of the services and their cost-benefits.
- (e) **Integrated Urban Observation Network Gap.** Few NMHS have urban stations whilst many environment agencies have deployed high quality air quality stations with meteorological sensors; some **municipalities** have deployed compact weather station networks and atmospheric composition sensors; most rivers as well as some sewer system in urban areas are gauged; research, demonstration projects and test beds have deployed networks of remote-sensing and in situ technologies (radar,

lidar, ceilometer); and mobile vehicles (cars or bicycles) have meteorological or atmospheric composition sensors (Google, 2021) when combined can provide basic and reference tier observations. Crowdsourcing technologies include cell phone microwave towers, vehicle technologies (temperature; precipitation detectors for wiper activation; lidars, radars and cameras for driver assistance), mobile phone (temperature, pressure, UV), crowdsourcing applications (weather reports, twitter activity, Instagram) can provide comprehensive tier observation along the value chain for high impact IUS verification (Elmore et al., 2014; Smith et al., 2015; McNicholas and Mass, 2021). As IUS service increases, there will be an expectation of higher skill and this will require the additional monitoring of additional confounding factors (e.g. debris accumulation in sewers) where new technologies are to be developed. Through partnerships, the **creation of integrated urban observation networks**, will enable new capabilities, increase capacity, reduce duplication and costs of urban observations.

- (f) **Urban Environment Information Gap:** For climatology applications, rural observations (and predictions) are used in a statistical manner for urban applications. The most common use is to estimate the temperature increase due to the urban heat island effect at the local or city scale where a quasi-Gaussian spatial impact is postulated. For local scales, initial **guidance** has been available that provide instrument and site requirements in an urban environment (WMO, 2006; WMO, 2019). For siting, representativeness is encapsulated in fetch considerations requiring uniformity of the urban environment on the scale of 500 m or more. Recently, using the concept of Local Climate Zone classification (e.g. building height, density, surface type) and assuming universality, urban monitoring observations can be cross-applied to reduce the urban network monitoring requirements (Stewart and Oke, 2012). For urban models and services, microscale urban environment details are needed as in severe weather, flooding or air quality warnings or where sources of water are part of green-blue design concepts and implementation. Knowledge of the **urban environment**, to properly interpret of urban observations and networks is **fundamental for all IUS and is therefore the first gap to address**. The World Urban Data and Access Portal (WUDAPT) is an international community-based effort to capture both the local and microscale urban environments (Ching et al., 2018).
- (g) **Reference Station Gap:** Given the breadth of issues including heterogeneity of the sensors, observation types, processing **and** other quality management issues, reference stations are needed to calibrate or quality control the IUS underlying data. Both rural and urban stations in applicable Local Climate Zone, (or other classification scheme) or in emission zones need to be established as part of the network design. This is a significant gap.
- (h) **Urban Metadata Gap:** As the observations need to satisfy multiple uses, the **metadata** must include sufficient information to support the use of the observation (interpretation to "fit the application"). The urban environment is one aspect that must be captured as observations will be affected by obstacles and microscale structures (WMO 2006). As the urban environment undergoes constant renewal, annual update of this in the metadata was recommended (WMO, 2006; Grimmond and Ward, 2021; Muller et al., 2013). The specification of urban observation metadata standard is needed.
- (i) **Data Management Gap:** Knowledge of available data, data exchange mechanisms, data formats, signal/data processing **algorithms** and quality control are recognized issues requiring leadership, technical capabilities and demonstrated mutual benefits before partnerships can flourish. Effective data exchange would require that privacy and intellectual property rights are respected. Data sharing among the providers of the individual components of the observing system is a

major gap. Management of the metadata is critical. **IUS demonstration projects, test beds and knowledge exchange are needed.** Newly adopted WMO open data policy may act as a lever for the improved urban observational data exchange and harmonization of the data exchange formats and protocols.

- (j) **Gap Assessment:** The examples of the fully implemented integrated service do exist, in particular in small city-states (Baklanov et al., 2020), though there are substantial gaps in IUS provision worldwide.

IUO Priorities

- (a) The highest priority and fundamental to all IUS applications is **information about the urban environment** (fabric, texture, building height, surface permeability). It is particularly important to: (i) interpreting urban observations for their representativeness and (ii) observation network design. This has been conceptualized for urban climate services at the local scale as LCZ. Microscale urban services with greater variability will require higher resolution information about the urban environment. Establishment and adoption of common classification standards at various scales will enable the transferability of results and accurate assessment of risk and impacts thereby reducing duplication and costs.
- (b) The second highest priority is to **establish IUS reference station(s)**. Given the differences with rural measurement requirements (siting, surface and height variability, essential variables), IUS reference station(s) are needed to support (calibrate, interpret) the WIGOS Tier concept of basic, reference and comprehensive networks. In many cases, urban stations often do not exist and IUS are crudely based on simple heat island concepts and in this simple situation, the distinction between basic and reference stations may be moot or based on comprehensiveness of the suite of variables measured. Different levels of sophistication may be deployed: (i) a single reference station representing the entire conurbation will provide a basic evidenced based IUS, (ii) reference stations per representative LCZ, (iii) reference stations for each LCZ in the conurbation.
- (c) The third priority is to **develop and demonstrate the IUS observing network concepts** to (i) accelerate their development, (ii) establish and test standards, particularly with respect to metadata, (iii) demonstrate IUS benefits and impacts to Members, (iv) instigate and initiate partnerships and test beds, data exchange and access, (v) accelerate development and demonstration of comprehensive networks including crowdsourcing, new technologies, information extraction and quality control processes, and (vi) provide capacity training and building opportunities for members amongst others. Coordinated demonstration projects with different service requirements and partnerships are needed to test the universality of proposed standards and processes and partnership, integration and IUS development modalities.

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ANNEX 6**ATMOSPHERIC COMPOSITION VARIABLES IN SUPPORT OF MONITORING AND FORECASTING APPLICATIONS**

The following variables were identified as priority:

Forecasting Atmospheric Composition (F)

- (a) All global NWP variables (e.g. planetary boundary layer (PBL) + Tropopause height)
- (b) Aerosols (aerosol mass, size distribution (or at least mass at three fraction sizes: 1, 2.5 and 10 micron), speciation and chemical composition, AOD at multiple wavelengths, Aerosol Absorption Optical Depth (AAOD), water content, ratio of mass to AOD, vertical distribution of extinction).
- (c) Total ozone, profile ozone, surface ozone, NO, NO₂ (surface, column, profile), PAN, HNO₃, NH₃, CO, VOC (isoprene, terpenes, alcohols, aldehydes, ketones, alkanes, alkenes, alkynes, aromatics), SO₂ (surface and column), CH₄, CO₂, N₂O, HCHO, HOx, Clx, ClO, BrO, OCIO, ClONO₂, HDO, CFCs, HCFCs, HFCs, Rn, SF₆.
- (d) Others: actinic flux, fire radiative power, land proxies, lightning, dry and wet deposition, pollen (key species), OCS.

Monitoring Atmospheric Composition (M)

- (a) All global NWP variables (e.g. PBL + tropopause height) and other meteorological/climate variables (e.g. SST, deep ocean temperature, solar variability, albedo, land use, soil moisture, precipitation, sea-ice cover, snow cover, polar stratospheric clouds (PSC) occurrence).
- (b) Aerosols (aerosol mass, number, size/surface distribution (1, 2.5, 10 micron), speciation and chemical composition, AOD at multiple wavelengths, AAOD, water content, ratio of mass to AOD, vertical distribution of extinction), stratospheric aerosol backscatter coefficient, PSC composition, concentration of metals, chemical composition of PM (sulphate, nitrate, ammonium, BC, OC, OM, dust, sea salt, BS, SOA) aerosol index, refractive index, precipitation chemistry composition, Hg, persistent organic pollutants (POPs), primary biological particles.
- (c) Total ozone, profile ozone, surface ozone, NO, NO₂ (surface, column, profile), PAN, HNO₃, NH₃, CO, VOC (isoprene, terpenes, alcohols, aldehydes, ketones, alkanes, alkenes, alkynes, aromatics), SO₂ (surface, column), CH₄, CO₂, N₂O, N₂O₅, NO₃, HCHO, HOx, Cly, ClO, BrO, OCIO, ClONO₂, HDO, CFCs, HCFCs, HFCs, halons, CH₃Br, CH₃Cl, BrONO₂, Rn, SF₆, glyoxal, methyl chloroform, H₂O, H₂O₂, H₂, O₂/N₂ ratio, dimethyl sulphide (DMS), methanesulphonic acid (MSA), OCS.
- (d) Isotopes of CO₂, CH₄, N₂O, CO, (D, ¹³C, ¹⁴C, ¹⁷O, ¹⁸O, ¹⁵N) also in the aerosol phase.
- (e) Actinic flux, fire radiative power, land proxies, lightning, dry and wet deposition, pollen (key species), ocean colour, chlorophyll-A, Leaf Area Index (LAI), Photosynthetically Active Radiation (PAR), fraction of PAR (fPAR), fluorescence, vegetation maps, land use maps, burned areas, night light, fire counts, wet lands, ship routes, forest inventory, biomass density, crop lands.

It should be noted that this list of variables rather represents a wish list and guidance is provided by the GAW Programme only on the limited number of the listed variables. User requirements in the OSCAR database are also document only for the subset of these variables that have the primary importance.

ACRONYMS

ABO	Aircraft-Based Observations
AMDAR	Aircraft Meteorological Data Relay
AMV	Atmospheric Motion Vectors
ARGO	Profiling Float programme
ATM	Air Traffic Management
CAMS	Copernicus Atmosphere Monitoring Service
CGCM	Coupled General Circulation Model
CGMS	Coordination Group for Meteorological Satellites
CSI	Country Support Initiative
DRR	Disaster Risk Reduction
ECV	Essential Climate Variable
EGOS-IP	Implementation Plan for the Evolution of the Global Observing Systems
EUMETNET	European Meteorological Services Network
FSOI	Forecast Sensitivity-based Observation Impact
GAW	Global Atmospheric Watch
GBON	Global Basic Observing Network
GCOS	Global Climate Observing System (WMO, IOC of UNESCO, ISC, UN Environment)
GCW	Global Cryosphere Watch
GDPFS	Global Data Processing and Forecasting System
GEMS	Geostationary Environment Monitoring Spectrometer
GHG	Greenhouse Gases
GNSS	Global Navigation Satellite System
GOS	Global Observing System
GOOS	Global Ocean Observing System (IOC of UNESCO, WMO, ISC, UN Environment)
GRUAN	GCOS Reference Upper-Air Network
GSRN	GCOS Surface Reference Network
GTS	WMO Global Telecommunications System
GURME	GAW Urban Research Meteorology and Environment
ICAO	International Civil Aviation Organization
INFCOM	WMO Commission for Observations, Infrastructure and Information Systems
IMOP	Instruments and Methods of Observation Programme
IPET-OSDE	former Commission for Basic Systems Inter Programme Expert Team on Observing System Design and Evolution
IR	Infrared
JET-EOSDE	INFCOM Joint Expert Team on Earth Observing System Design and Evolution
LDC	Least Developed Country
NMHS	National Meteorological and Hydrological Service
NRT	Near-Real-Time
NWP	Numerical Weather Prediction
MOS	Model Output Statistics
MW	Microwave
ODAS	Ocean Data Assimilation System

OPAG-IOS	former Commission for Basic Systems Open Programme Area Group on Integrated Observing Systems
OSCAR	Observing System Capability Analysis and Review Tool
OSE	Observing System Experiments
PoC	Point of Contact
PWPP	Plan for the WIGOS Pre-operational Phase 2016–2019
RO	Radio Occultation
RRR	Rolling Review of Requirements
RWC	Regional WIGOS Centre
SC-MINT	INFCOM Standing Committee on Measurements, Instrumentation and Traceability
SC-ON	INFCOM Standing Committee on Earth Observing Systems and Monitoring Networks
SDG	Sustainable Development Goal of the UN
SERCOM	WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications
SG-DIP	INFCOM Study Group on Data Issues and Policies
SIC	Sea-ice Concentration
SIDS	Small Island Developing States
SIT	Sea-ice Thickness
SLA	Sea-level Anomaly
SOFF	Systematic Observations Financing Facility
SoG	Statement of Guidance
SOP	Special Observing Period
SST	Sea-Surface Temperature
SSLP	Sub-Seasonal to Longer Predictions
SWE	Snow Water equivalent (the water content obtained from melting accumulated snow)
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
TRL	Technical Readiness Level
UAS	Uncrewed Aircraft System
VSRF	Very Short-Range Forecasting
WAFS	World Area Forecasting System
WDQMS	WIGOS Data Quality Monitoring System
WHOS	WMO Hydrological Observing System
WICAP	WMO-IATA Collaborative AMDAR Programme
WIGOS	WMO Integrated Global Observing System
WIR	WIGOS Information Resource
WIS	WMO Information System
WUDAPT	World Urban Database and Access Portal Tools
WWW	World Weather Watch
YOPP	Year of Polar Prediction