AeM SERIES No. 5

Long-term Plan for Aeronautical Meteorology

Commission for Aeronautical Meteorology

WEATHER CLIMATE WATER

WORLD
METEOROLOGICAL
ORGANIZATION

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Welcome

The World Meteorological Organization (WMO) attaches a high priority to the advancement of scientific and technical methods and practices to support the provision of meteorological service for international air navigation to ensure worldwide, reliable provision of high quality, timely and cost-effective meteorological service to aviation users. The development and implementation of the long-term plan for aeronautical meteorology (LTP-AeM) can provide a framework upon which aeronautical meteorological service providers (AMSPs) of WMO Members in particular, and the broader meteorology and aviation communities in general, can plan a progressive transformation from a conventional "product-centric" approach to a modern "information-centric" approach to service provision for aviation through to 2030 and beyond.

Today, there is an urgent need for filling gaps remaining between the developed and developing world for the provision of high-quality meteorological services to aviation users. Members are seeking to either provide or seek assistance so that no country is left behind. Twinning and mentoring programmes, where appropriate, should be actively pursued and embraced to close often longstanding capability gaps and improve services.

In addition, a majority of the national meteorological and hydrological services of WMO Member States and Territories engage in the provision of meteorological services for aviation as do a significant number of providers from the private sector. The worldwide provision of such services can be seen as a model of where the global weather enterprise is working effectively around the clock to supply aviation users with a range of meteorological products and services, data and information which, in terms of international air navigation, conform to the high standards set by ICAO and WMO.

WMO and the International Civil Aviation Organization (ICAO) have a long and productive history of coordination and cooperation dating back to more than 60 years which addresses both the aeronautical requirements and the capabilities necessary to fulfil the requirements. However, much has changed since the WMO and ICAO were established back in the 1950s, not only in the context of the scientific and technological advances but also in the context of how aviation has grown and evolved into an increasingly and inherently safe and efficient interconnected global system (a system of systems) where more than 100,000 commercial flights carrying more than 10 million passengers are taking to the sky each day. These already remarkable figures are expected to double over the next 15 years as consumer demand for air travel continues to grow and where the aviation industry is looking to become more efficient, more environmentally responsible and even safer.

In order to meet this demand and faced by the challenges of a changing climate, the needs and expectations of the aviation industry will evolve rapidly over the coming decade and our scientific and technical meteorological methods and practices will have to do likewise if WMO and its Members are to remain credible and relevant on this international stage.

Through the activities of its constituent bodies and programmes, WMO will continue to work in close collaboration with ICAO and other partners to develop the next generation of high quality meteorological data and information services based on the application of the best science and technology. The scope and pace of change now being called for will require a community effort involving eminent experts from world-leading scientific research institutes, universities and other academia, public and private sector meteorological service providers, aviation users and the wider industry itself. Together we can achieve great things.

(P. Taalas)
Secretary-General

Foreword

Meteorological conditions, including hazardous phenomena, know no boundaries and aviation users need seamless, consistent prediction of these events. High quality, well-coordinated, consistent and understandable meteorological information for operations at airports and across airspaces is a clear need from the aviation community. We must put high-quality, value-added meteorological services in the hands of the end-users to fully meet their needs and expectations.

Quality services can only be fulfilled with a holistic approach, so we cannot neglect any of the aspects that underpin authoritative, credible and fit-for-purpose services. While aeronautical meteorology is ahead of many other disciplines in the competency and qualification of its personnel, this is an area that requires ongoing maintenance and continuous improvement. Likewise, the implementation of rigorous quality management has seen greater adoption, but progress and continual improvement must continue.

We must also sustain, improve and adapt the observations and observing systems that not only underpin the services we provide but also the numerical modelling and prediction tools upon which we depend. Likewise, aircraft-based observations and access to this data by meteorological service providers and the international research community is of growing importance.

In short, to realize the efficiencies needed to support global aviation of the future, our knowledge and skill in aeronautical meteorology will need to continue to mature. While advances in the underpinning science, the observations, the modelling and the forecasting are necessary to realize this growth, they are not sufficient in isolation. We must also consider how this information is to be delivered and used. Our meteorological information and decision support services can only realize their ultimate value when well-integrated in the decision-making processes of the aviation end-users. We cannot neglect the impacts of climate change and variability either, as we've already seen extreme weather events affecting flight operations.

Of course, capacity development, the sharing of best practices and the supply of guidance material by WMO will continue to be required to help bridge the existing or evolving gaps amongst Members. The need for accelerated transition from research-to-operations and science-to-services based on collaborative efforts and appropriate data-sharing practices are essential as well.

WMO and ICAO will continue their close collaboration on the evolution of aeronautical meteorology including the activities of the ICAO Meteorology Panel, ICAO's Global Air Navigation Plan (GANP) and its aviation system block upgrades (ASBU) methodology, the evolution of ICAO Annex 3, and the development of a new PANS-MET. Information management will enable faster access to quality-controlled and cost-effective exchange of meteorological data. We must recognize the global weather enterprise as well, appreciating the growing role of the private sector in our business and the opportunities that this presents. As aeronautical meteorological service providers, we must be constructively and actively engaged in this process. If not, opportunity will pass us by.

The long-term plan for aeronautical meteorology presented here, will outline how we, as WMO Members, should be looking to move forward to meet the evolving needs of the aviation industry into the 2030s and beyond. The aeronautical meteorology community will not look the same as it does today in 10 years; that is a reality that is upon us and it is up to us to make sure we remain a valuable partner in the future landscape of service provision.

(I. Lisk)
President, WMO Commission for
Aeronautical Meteorology

Executive Summary

The long-term plan for aeronautical meteorology (LTP-AeM) is intended to provide a framework upon which aeronautical meteorological service providers (AMSPs) of WMO Members in particular, and the broader meteorology and aviation communities in general, can plan a progressive transformation from a conventional "product-centric" approach to a modern "information-centric" approach to service provision for aviation through to 2030 and beyond.

The LTP-AeM pays due regard to sector-wide air transport progress envisaged over the coming decade or more and is complementary to the Global Air Navigation Plan (GANP) of the International Civil Aviation Organization (ICAO). This complementarity is necessary to ensure that as ICAO's vision for a globally interoperable, harmonized air traffic management system of the future becomes fully realized developments on the WMO side can and will occur in unison. The LTP-AeM offers a long-term vision, a rolling strategy that will assist WMO, its Members and partners ensure that aeronautical meteorological service provision evolves in a manner that harnesses scientific and technological advancement, both on the service providers' side and the aeronautical users' side.

The LTP-AeM considers the implications that a projected increased growth in air traffic and a changing climate will have not only on aviation users' needs for meteorological information services but also on the actual meteorological service provision that is to be supplied nationally, regionally and globally.

Taken as a whole, if appropriately implemented and adequately resourced, the developments outlined in the LTP-AeM offer the potential to better serve the needs and expectations of international civil aviation over the next decade and beyond and thereby ensure that WMO and its Members remain as integral, credible and relevant components within the implementation of ICAO's GANP.

It is important to recognize that aviation, like meteorology, is a continually evolving sector, one that advances through scientific and technological progress and other factors such as the public's continuing (growing) appetite to travel domestically and internationally by air. With each new edition of ICAO's GANP/ASBU, issued once every 3 years, comes the potential for changes to the existing or future requirements for aeronautical meteorological service. It is essential therefore that the LTP-AeM responds to the evolutionary path that aviation has already embarked upon and that it is maintained through periodic review and update by the relevant WMO constituent bodies.

WMO and Aeronautical Meteorology

In terms of aeronautical meteorology, the primary responsibilities of WMO, as determined by the World Meteorological Congress, are as follows:

1. ***To contribute****, in close collaboration with ICAO, to furthering the international standardization of meteorological service provision to international air navigation and provide assistance to Members to achieve compliance with those standards.*

2. ***To promote and facilitate****, in collaboration with relevant WMO bodies, the international sharing of implementation experience, exchange of technology and research uptake, including appropriate pilot projects, to meet evolving user requirements for aeronautical meteorological information and services.*

3. ***To participate****, in close collaboration with ICAO and other relevant stakeholders, in the development of enhanced aeronautical meteorological services in support of the future Air Traffic Management system.*

4. ***To coordinate*** *development of guidance, training material and learning opportunities in collaboration with other WMO bodies and ICAO, to ensure Members' compliance with the competency and qualification requirements for aeronautical meteorological personnel.*

5. ***To review and respond*** *to Members' aeronautical meteorology prioritized needs and support capacity development activities, in cooperation with regional associations, aimed at enhancing the delivery of quality aeronautical meteorological services, especially by developing and least developed Members.*

6. ***To promote*** *good governance and efficiency, in cooperation with ICAO, regional bodies and Members, including enhanced regional and sub-regional cooperation in aeronautical meteorological service delivery and development of related cost-recovery mechanisms.*

7. ***To maintain*** *existing and develop further partnerships with relevant aviation user and stakeholder organizations and collaborate on issues related to aeronautical meteorology.*

1. Drivers for change

Meteorology is an evolving science, continually advancing our understanding of the world's weather, water and climate system and their impacts on society. In a similar way, aviation is an evolving industry, continually advancing the way in which it keeps up with consumer demand through improved sectoral efficiency while at the same time maintaining aviation's number one priority, namely safety, and minimizing the impact of aviation on the environment.

Aeronautical meteorological services contribute directly to the safety, regularity and efficiency of aviation operations, both on the ground and in the air, and are now also playing an increasing role in informing environmental considerations. It should also be recognized that meteorology is just one of many domains which aeronautical users – operators, flight crew members, air traffic services units, search and rescue services units, airport managements and others – have to contend with on a daily basis.

Aircraft themselves are also becoming an increasingly important platform for the in-situ observation of a range of meteorological parameters, including wind, temperature and humidity, which are directly contributing to improved numerical weather prediction performance through data assimilation. WMO is working with partners including the International Air Transport Association (IATA) to increase the scope and availability of aircraft-based observations, both in terms of the observed parameters and the airlines participating in programmes such as AMDAR[1].

Despite much progress and many advances over the years on both sides, meteorology and aviation continue to be somewhat limited by the continued application of legacy approaches to service provision. While some countries, particularly those that are more developed, have been able to push the boundaries of what is possible in terms of service provision, other countries, particularly those that are lesser developed, have at times been unable to keep up with the pace of change. Deficiencies in aeronautical meteorological service provision have persisted in many parts of the world for many years despite capacity development and other related efforts by WMO, ICAO and other partners. Deficiencies can be and occasionally are overcome, however progress can often be slow resulting in inefficiencies and, in the worst case, safety concerns within the growing aviation industry. Making changes to regulations that have national or international consequences can also, often, take time.

While there will be challenges and obstacles to be overcome, there are opportunities to eradicate system inefficiencies and deficiencies, to improve effectiveness (including cost effectiveness) thereby better serving the aviation users' needs and expectations long into the future.

Aeronautical meteorological service provision is highly reliant on the supplier/consumer, provider/user relationship. Over the past two decades in particular the introduction of quality management systems (QMS) for the provision of meteorological services for international air navigation has placed special emphasis on ensuring that high-quality products and services are developed with the customer's needs and expectations 'front and

[1] Aircraft Meteorological Data Relay (AMDAR) is a programme initiated by WMO and its Members with aviation partners as a sub-system of the WMO Integrated Global Observing System.

centre' and that they are supplied at a price that the customer can afford. Often this places unique demands on the AMSP to demonstrate how a particular product or service can and will add value, how and where there is a cost-benefit to be gained from its development and ultimately its operational introduction.

Aeronautical meteorology is critical to the safe and sustainable operation of the global aviation system. This is underscored by the headline 'book-value' to aviation: the gross benefit of aeronautical meteorology to airlines is in the vicinity of US$ 20 to 30 Billion[2] annually.

The loss of that gross benefit would be experienced in the form of increased fuel burn, increased flight times, increased maintenance costs, shorter aircraft life, loss of airspace capacity, reduced certainty in service delivery, increased air navigation and airport costs, increased weather-related incidents and accidents, and so on.

Given the net profit for global aviation in 2017 was US$ 38 Billion on a turnover of US$ 787 Billion[3], it is clear that the removal or dysfunction of aeronautical meteorology would create significant financial problems for some airline operations. The wider social cost of such dysfunction would likely be orders of magnitude greater, considering that the annual global gross domestic product (GDP) contribution of aviation is over US$ 2.7 Trillion[4].

The social costs would include the downstream reduced employment effects of a marginal aviation industry, reduction in trade and reduced GDP, reduction in social connection for people, reduction in emergency capabilities, potential harm to property and people, and the loss of lives.

Hence, the effects that could be expected in the event of the loss or degradation of aeronautical meteorological services, in summary, are the increase in safety risk and financial risk in airline operations, and an increase in wider negative social effects.

Compared to these marked economic and social costs and values, the much smaller estimated annual global cost of aeronautical meteorology is a good investment, estimated at around US$ 1.5Billion[5]. As such, this leaves ample financial capacity for increased management and development capacity in global aeronautical meteorology.

So, as air traffic growth continues to defy recessionary cycles, doubling once every 15 years as it has done since the mid-1970s, with more-and-more aircraft in our skies as each year passes, connecting more-and-more communities worldwide, this is placing and will continue to place increased demand on the available airspace and on the optimal use of that airspace – whether at the aerodrome, in the terminal area or en-route – to ensure that it remains safe to operate within. Indeed, as conveyed in ICAO's GANP (5th Edition, 2016), "*growth under certain circumstances can be a double-edged sword. Though a sure sign of increased living standards, social mobility and generalized prosperity on the one hand, unmanaged air*

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[2] Noted at the 2017 World Meteorological Organization (WMO) Aeronautical Meteorology Scientific Conference, held in Toulouse, France (https://library.wmo.int/opac/doc_num.php?explnum_id=4554). The estimates are based on UK work in 2012 and applying an update extrapolation methodology based on RPK data.

[3] From *IATA Economic Performance of The Airline Industry*, Mid-year Report 2018 (https://www.iata.org/publications/economics/Reports)

[4] From Aviation Benefits Beyond Borders, 2014 data (https://aviationbenefits.org/economic-growth/value-to-the-economy)

[5] From *Improving Meteorological Information for Air Transport*, Jaakko Nuottokari, Finnish Meteorological Institute, 2017 (ISBN 978-952-336-032-7)

traffic growth can also lead to increased safety risks in those circumstances when it outpaces the regulatory and infrastructure developments needed to support it".

The foreseen growth in air traffic through to 2030 and beyond is placing and will continue to place increased demand on AMSPs to come up with new, innovative solutions and potentially new business models that ensure the customers' needs and expectations can be fulfilled in an appropriate and wholly sustainable manner. Advances in science and technology are already making it possible to realize solutions which, just a few years ago, may have been considered inconceivable.

Yet, even with the meteorology community's improved ability to observe and predict the weather through scientific and technological advances, and to communicate these more readily through advances in communications technology, it is concerning to note that, in the early 21st century, meteorological conditions continue to be a significant factor in aviation incidents and accidents around the world.

And it is not simply the foreseen growth in air traffic or the continued influence of the weather in aviation incidents and accidents that is driving the need for change within the sector; the earth's climate is changing too. As the effects of climate change and variability on aviation operations become better understood, better communicated and ultimately experienced by users through the increased occurrence of extreme weather events, the need to ensure that aviation adapts to and mitigates the hazards posed by a changing climate through new and improved meteorological information services can be envisaged.

The only way that aviation is going to be able to grow as it intends, and adapt as it will need to adapt under a changing climate scenario, is if both communities, aviation and meteorology, pull together to address the challenges and harness the opportunities.

Additionally, a changing landscape of service provision is already being realized within the aeronautical meteorology community. Whereas in the past it was the traditional realm of an NMHS in the public sector to serve, *de facto*, as the sole AMSP of a country, today the situation is quite different. Private sector enterprise and other commercial entities as well as air traffic service organizations and others are now an embedded part of the aviation meteorology supply chain. This is a situation that is unlikely to change given free market conditions that prevail in many countries. It is reasonable to assume, therefore, that the global weather enterprise is here to stay. This then, evidently requires the NMHSs to have sufficient situational awareness of the changing business environment around them, nationally and internationally, and sufficient ability and agility to adapt to change, whenever and wherever it may be needed, establishing new business models and forging new partnerships to ensure a continuing and thriving role in aeronautical meteorological service provision.

Collectively, all of the foregoing factors are considered sufficient reason for change. Undoubtedly, over the coming years, other influencing factors and drivers for change will have a bearing on developments. So, it is important for all concerned to be open to and embracing of change.

One-size is unlikely to fit all and the role of the standardization bodies

Within ICAO's GANP it is emphasized that it is *not* the case that all States will need to implement *every* module within its ASBU methodology. The GANP makes clear that ICAO will be working with its Member States to help them determine exactly which capabilities they should each have in place based on their unique operational requirements. These operational requirements will be based upon many factors associated with existing and foreseen aviation operations nationally, regionally and globally.

This philosophy that one-size is unlikely to fit all – and does not necessarily need to fit all – can and does apply equally here in the context of this long-term plan. Aeronautical requirements for meteorological service will, in some instances, vary from one country to the next or from one region to the next as they do today. Identifying and responding to the varying requirements will continue to place great emphasis on the key standardization roles played by WMO and ICAO and their constituent bodies.

There will be a need for alignment between the aeronautical requirements and the meteorological capabilities and a consistent application by all stakeholders. Standardized meteorological coding practices, applied worldwide by service providers at a national level, is just one example of many that will facilitate a globally interoperable, harmonized air traffic management system of the future.

A multi-hazard operating environment demands a seamless model of service provision

Aeronautical meteorology is a discipline that addresses a broad range of phenomena on varying spatial and temporal scales. Some phenomena are beneficial to flight (e.g. tail winds resulting from a jetstream can have a marked influence on reducing flight times) while others are hazardous to flight (e.g. the very same jetstream can have clear air turbulence associated with it posing safety risks to the aircraft and its occupants). Wind, temperature, visibility, present weather, cloud (type, horizontal and vertical extent), pressure, icing and turbulence are just some of the many meteorological phenomena of long-standing and continuing interest to aviation, from both safety and efficiency perspectives.

In the past several decades interest has turned also to other phenomena not traditionally classed as ‘meteorological’ but that nonetheless can be influenced by the prevailing meteorological conditions, such as clouds of volcanic ash and sulphur dioxide, and releases of radioactive materials and other toxic chemicals into the atmosphere.

The ability to observe and forecast these meteorological and non-meteorological phenomena can often vary since they rely on the maturity of the underpinning science and the implementation of appropriate available technologies.

The troposphere[6] where the bulk of aviation activities are currently conducted is, by its very nature, a multi-hazard environment. These hazards can be posed by the meteorological/environmental conditions within the troposphere itself (e.g. the presence of cumulonimbus clouds yielding the risk to aviation of severe icing, turbulence and hail) or they may be as a result of other non-meteorological/non-environmental factors (e.g. airspace congestion in one area caused by airspace restrictions elsewhere). Aeronautical users on the ground and in the air have multiple considerations to contend with when planning and conducting their operations, and the observed and forecast meteorological conditions is just one of these considerations.

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[6] WMO-No. 182, *International Meteorological Vocabulary*, defines the troposphere as the “*lowest part of the terrestrial atmosphere, extending from the surface up to a height varying from about 9 km at the poles to about 17 km at the equator, in which the temperature decreases fairly uniformly with height*”.

Despite the certainty and uncertainty, a common situational awareness of all the meteorological hazards, on all the required spatial and temporal scales that users require, demands a seamless approach to service delivery[7], thereby ensuring that all the available information (including meteorological information) can be integrated into the safety risk assessments and collaborative decision-making processes of concerned aeronautical users.

For seamless service delivery to be achieved, on a worldwide basis and in the timescales conceived by this long-term plan, traditional approaches to aeronautical meteorological service provision on a country-to-country or FIR-to-FIR[8] basis will have to be reviewed and reformed, with an increased prominence, potentially, of a regionalized and/or globalized service delivery approach.

Evolving user requirements and capabilities

As the air traffic growth and the evolution of the air traffic management system are continuous processes, it is conceivable that other as yet unforeseen or unrealized aeronautical requirements for meteorological information will emerge over the lifetime of this long-term plan for which the meteorological community will need to be prepared to respond. The meteorological community has, for example, been recently made aware of emerging user needs for high altitude ice crystals information. Aviation's embarkation into commercial human space flight could be another example of one such area that may require advanced products and services to support going forwards.

A further consideration that the meteorological community needs to be ready to respond to is the evolving on-board capabilities of the new generation of aircraft. The ability of modern aircraft to have meteorological information uplinked direct to the cockpit (be it on the ground or in the air) is already a reality for some operators through the use of electronic flight bags or other similar technologies. These advances are being made possible through continued advances in communication technologies.

Moreover, advances in communications technologies are already shaping how the current and next generation of flight crew are being trained, how they operate and how they expect to receive information relevant to their flight, including meteorological information.

The legacy approaches to flight briefings and to the supply and use of flight documentation are already being challenged and reformed in some quarters in light of what is already possible from a technological perspective. This trend can only be expected to continue.

And, as alluded to previously, the increasing in-situ observing capabilities of aircraft are yielding direct benefits for the meteorological community in terms of numerical weather prediction performance and, in turn, more accurate, more reliable forecasts for aviation users.

In an ICAO Meteorology Panel (METP) 'White Paper' of 2018 titled '*Future Aeronautical Meteorological Information Service Delivery*' (hereinafter referred to as the ICAO White Paper), the emerging user needs are explored in more detail. The emerging user needs do not treat meteorological observations and forecasts in isolation but instead address the ways in which this information is to be harmonized and delivered in an integrated manner.

[7] In this context 'seamless' is intended to mean a smooth and continuous model of service delivery, one that devoid of any apparent gaps or spaces between one component and another.
[8] Flight information region (of ICAO).

As outlined in the ICAO White Paper, foreseen improvements are required in respect of the (meteorological) observations, forecasts, advisories and warnings to meet emerging user needs focussed around:

- enhanced meteorological information with global coverage for flight planning and en-route operations;
- enhanced 4-dimensional information for meteorological hazards of any type; and
- enhanced high-resolution 4-dimensional meteorological information for airport and terminal area operations.

The specific meteorological focus areas for which continued and improved services, including effective user communication strategies, are needed include:

- High Altitude Ice Crystals (HAIC)[9] and airframe icing;
- All forms of turbulence;
- Significant convection;
- Detection and prediction of low-level wind shear and wake vortex;
- Low visibility including fog;
- Space weather;
- Atmospheric aerosols including volcanic ash and potentially other gases;
- Observing methods (in-situ and remote sensing) and use of observations, including those from aircraft, other airborne platforms and from space;
- Nowcasting and probabilistic forecasts; and
- Seasonal (3-6 months ahead) forecasting.

In addition, and as identified in the AeroMetSci-2017 recommendations outlined above, the climate change and variability impacts on aviation is an emerging area for which new information services will be required to meet aviation's emerging needs. Greater maturity and clarity in these requirements will naturally progress as this subject becomes better understood.

Integration and interoperability

The observed and forecast meteorological conditions are an embedded component of the multitude of decisions that are made by aeronautical users on a day-to-day, hour-by-hour and minute-by-minute basis. Information on the observed and forecast meteorological conditions will, together with other aviation-relevant information, be an integral part of the future data-rich system-wide information management (SWIM) environment that will underpin global air traffic management. Users with authorized access to the SWIM environment will interact with meteorological information like never before in order to make informed decisions. These interactions may be machine-to-machine or a human-and-machine mix depending on the operational application.

[9] Sometimes referred to as 'High Ice Water Content' (HIWC).

There must be interoperability of the information within SWIM as well as an interoperability of the information of other systems that feed SWIM. For example, meteorological information within the WMO Information System (WIS) that is to be used to support the needs of aviation users will require that WIS and SWIM be interoperable to enable the data exchanges to take place, seamlessly.

Improved and enhanced observational, forecast, advisory and warning information will need to be able to be fully integrated into the globally interoperable ATM system. SWIM-based MET information exchange is a prerequisite to ensure that enhanced situational awareness is obtained. Decision-making support for strategic, pre-tactical and tactical ATM decisions can be provided, and concepts such as collaborative decision-making (CDM) and trajectory-based operations (TBO) can be supported.

As captured in the ICAO White Paper, the following must be considered in the full integration of MET information into the decision making process:

- in-cockpit and on-board MET capabilities;
- terminal area and impact-based forecast;
- en-route hazards information systems;
- translation of MET information for impact and risk assessment;
- Collaborative Decision-Making (CDM);
- air traffic flow management (ATFM) and network management,
- trajectory-based operations (TBO);
- flight planning and user-preferred routing; and
- MET information for climate-optimized trajectories (e.g. preferred routing based on jet stream patterns).

Borderless, harmonized service provision and phenomenon-based service provision

Phenomenon-based service provision, sometimes referred to as the borderless service provision concept, is envisioned in the ICAO White Paper as a concept that will need to reach its completion by 2030.

The concept of phenomenon-based service provision hinges on four considerations:

- the four dimensions of the MET phenomena;
- the required quality of services (QoS) for the associated information that needs to be provided around these phenomena;
- the required aeronautical MET capabilities including the state of the science to provide this information; and
- satisfactory arrangements to be put in place for governance and cost recovery.

Ultimately, the aim is to develop a framework of globally-consistent, high quality services that "*enables all stakeholders to use information issued by a regional or global function, as authoritative for all associated decision making*". Additionally, the ICAO White Paper notes that "*all of these functions (must) develop into a unified global system that is in a position to provide services directly to the end-user communities*' – specifically, that "*end-users* *increasingly take their guidance products directly*" as they "*are more convenient to use and are recognized by national authorities for use by airlines; recognising that this practice is beyond the scope of the current Annex 3 provisions*".

To adjust to the evolving service delivery paradigm, AMSPs must work to develop partnerships or pursue active and constructive relationships in these service models. Those AMSP who cannot meet the expected level of service may see an erosion or elimination of their responsibility in the provision of services for international air navigation. Even for AMSPs capable of meeting the expected level of service, consolidation of service provision may lead to the reduction of responsibility in some areas.

2. The role of science and technology

Responding to aviation users' needs and expectations will require improvements across the entire meteorological science to services delivery chain. The science underpinning the modelling and forecasting that provides the basis of these services must continue to improve. Likewise, the observations and the application of the observations underpinning forecasts and warnings will need to improve as well. These improvements must be transformed into improved services, not only with respect to the quality, accuracy, lead time and timeliness of the information that is required, but also with respect to the way this information is delivered and integrated into decision making processes.

Scientific and technological advancement

In many cases, full realization of services that fully meet the existing and emerging aeronautical requirements for meteorological service will only be realized through advancements in the underlying science and technology. In 2017, an Aeronautical Meteorology Scientific Conference (AeroMetSci-2017) conducted by WMO formulated recommendations for three key areas of science and research developments over the next 15 years in support of aviation[10]. The recommendations were as follows:

1) In the context of science underpinning aeronautical meteorological (MET) **observations, forecasts, advisories and warnings**, the conference recommended that:

- Research activities demand improved access to data, especially aircraft-based observations (ABO) to support validation, verification and calibration as part of a continuous improvement drive;
- Research efforts should be conducted in collaboration with users to ensure their needs are addressed;
- The transition from research to operations following validation should be accelerated and well communicated;
- Conveying uncertainty is required to inform risk management, but remains a challenge that needs further research and guidance; and
- MET hazards and their impacts on aviation should be more clearly defined and articulated.

2) In the context of **integration, use cases, fitness for purpose and service delivery**, the conference recommended that:

- Close collaboration within and across MET and air traffic management (ATM) communities should be actively encouraged as a prerequisite of impact assessment and an enabler to future global interoperability and harmonization;
- Establishing ATM users' requirements should be a prerequisite for tailored, fit-for purpose MET solutions;
- MET information must be translatable into ATM impacts to enable full integration in the strategic planning, pre-tactical and tactical decision-making phases;

[10] The proceedings of AeroMetSci-2017 are available as WMO AeM SERIES No. 2.

- Probabilistic methodologies with proper verification and calibration should be applied to better convey to users where and to what extent inherent forecast uncertainties exist;
- Blending MET parameters through ensemble approaches that yield a higher quality, more usable forecast should be further pursued but with an acknowledgement of the potential masking of extremes;
- Machine-learning such as artificial intelligence could be pursued to optimize MET support to ATM in the era of 'Big Data';
- Design of systems for delivering harmonized MET information to pilots and other stakeholders should further consider the need for standardization and collaborative decision-making (CDM);
- An increasingly automated ATM operating environment will require supporting MET educational programmes for end-users; and
- The research-to-operations process for prioritized MET products and services reaching maturity should be expedited.

3) In the context of **climate change and variability on aviation** and associated science requirements, the conference recommended that:

- The potential impacts of climate change and variability on aviation operations on the ground and in the air, downscaled to the local level, must be well researched and communicated;
- The mitigation of extreme weather events and the adaptation to a changing climate demands a multidisciplinary effort involving both the physical and the social sciences. Furthermore, all stakeholders in meteorology and aviation must work together, including through WMO and ICAO, to build consensus on robust, sustainable global solutions;
- Responding to climate variability will require a high degree of flexibility on the aviation users' side. While the incidence of high-impact extreme weather events is expected to increase, they will be infrequent relative to the norm. The foreseen continued growth of aviation worldwide in a changing climate scenario may present new challenges as demand for airspace capacity increases;
- Improved availability of and access to high-quality in-situ observations of meteorological parameters, including water vapour, is a key enabler to improving climate prediction model capabilities. The preservation of such data is essential for validating and calibrating climate predictions; and
- A changing climate scenario may render some of today's aerodrome, airspace and airframe design and operation standards inadequate in the years or decades to come. Using past climatological records alone as an indicator of future climate at an airport, say, may be insufficient given the (current) rate at which the world's climate is changing (warming).

The foregoing recommendations can and will guide scientific and technological advancement in support of aviation over the coming years although these advancements must be planned and implemented based on the highly organized principles of project management best practice.

3. Performance improvement: WMO's role

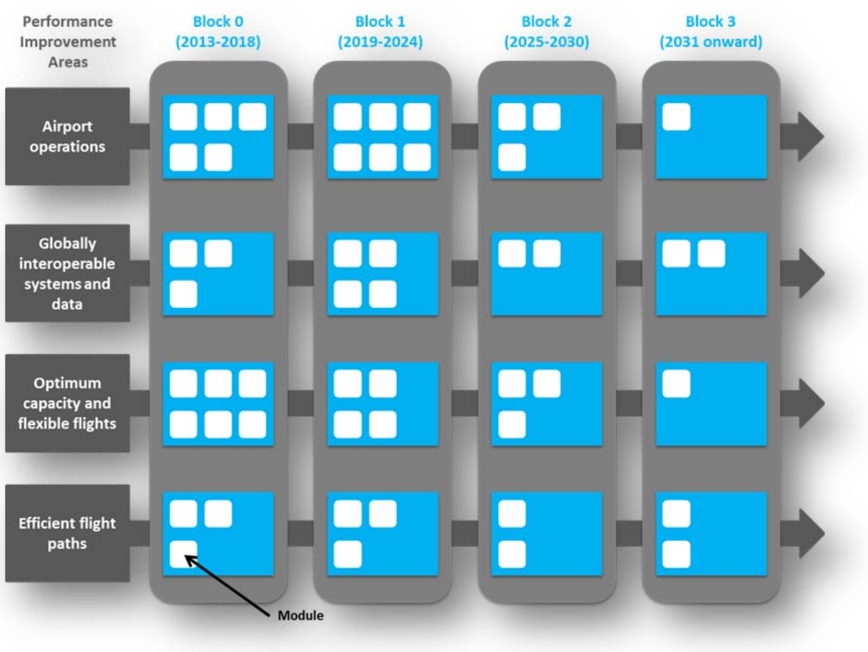
Before determining WMO's long-term plan for aeronautical meteorology, it is essential to consider how the aviation industry envisages change taking place over the coming years, and the aeronautical meteorological service advances that are necessary or desirable to ensure optimal service delivery.

ICAO GANP and its ASBU methodology

The ICAO GANP and its ASBU methodology, alluded to in the previous sections, provide a rolling, 15-year strategic methodology for air transport progress which leverages existing technologies and anticipates future developments based on State/industry agreed operational objectives as civil aviation continues to grow, with a projected doubling of air traffic by the 2030s. The latest (fifth) edition of the GANP covers the period from 2016 to 2030 and describes enhancements in the aeronautical meteorology domain which, together with other domains, are considered necessary or desirable to achieve tangible air navigation capacity and efficiency performance improvements, including a reduced impact of aviation on the environment, while sustaining aviation's number one priority: safety.

The strategic methodology for air transport progress described in the GANP has a direct bearing on an evolving aeronautical meteorological service provision, since existing and foreseen requirements of aeronautical users are (where there is a demonstrable capacity and efficiency gain, safety and/or environmental benefit) to be fulfilled through the standardized technical methods and practices of aeronautical meteorological service providers.

The ASBU methodology within the GANP puts forward a systems-engineering approach based on a series of performance improvement areas, blocks (time steps) and modules. The graphic below illustrates the ASBU methodology:



Each ASBU Block [vertical] refers to the target availability timelines for a group or groupings of operational improvements (essentially technologies and procedures) [horizontal] that will eventually realize a globally interoperable, harmonized air traffic management system of the future. The technologies and procedures for each Block have been organized into unique ASBU modules [squares] which have been determined and are cross-referenced based on the specific performance improvement area to which they relate. State regulatory authorities and other concerned with international civil aviation operations need only consider, adopt and implement the modules appropriate to their operational need.

In many instances, module 'threads' are associated with a specific performance improvement area. For example, an ASBU module in the Airport Operations performance improvement area of ASBU Block 2 (2025-2030), say, may require certain technologies and/or procedures to be available in ASBU Block 1 (2019-2024). Put another way, it is not possible to realize B unless A has already happened. Therefore, there will be a thread linking the module in Block 1 with its related (consequential) module in Block 2. Every module of the ASBU methodology serves to progress towards one of the target performance improvement areas.

Each module within ICAO's ASBU methodology can be traced to standards-making and other related activities being undertaken or planned to be undertaken at a global level within the various ICAO constituent bodies, including the Meteorology Panel and its working groups. Furthermore, it offers ICAO's planning and implementation groups at a regional level (the PIRGs) the ability to determine, often well in advance, whether a particular technology or procedure will need to be introduced within the region based on the region-specific requirements. This foresight offers those charged with developing new standards and those charged with implementing new standards – from regulators, service providers and users' perspectives – with a far greater degree of predictability and an ability to efficiently and effectively manage resources than might otherwise be the case. This is particularly true for those situations where there is a high degree of complexity associated with introducing new technologies or procedures, such as onboard avionics and flight operations which often need to be planned several years or more in advance.

The systems-engineering approach adopted by ICAO to realize performance improvements within the global aviation system is a model which WMO and its Members have a vested interest in. Many WMO Members serve as aeronautical meteorological service providers through the activities of their NMHS or other entities. To meet the needed service improvements, and closely aligned with and reflected in its strategic and operating plans, WMO will strive to better enable Members to fulfill their prevailing aeronautical meteorology obligations and to respond to the emerging challenges and opportunities outlined above.

WMO long-term planning for aeronautical meteorology

WMO and its Members efforts to respond to the air transport modernization conveyed in the ICAO GANP and its ASBU methodology will require necessary and appropriate standards-making activities, new and improved guidance, targeted capacity development activities and other outreach by WMO.

A long-term planning approach for aeronautical meteorology will be applied by WMO across the following thematic areas:

1) Education, training and competency of personnel providing meteorological service for international air navigation

a) Development of updated aeronautical meteorological personnel standards and supporting guidance and training material in response to changing models of service delivery; and
b) Development of updated and new guidance material to support the application and use of enhanced meteorological information.

2) Aeronautical meteorological information services and governance

a) Governance and guidance – Working closely with the ICAO MET Panel to support and influence the development of information and data exchange policies, quality management system standards, cost recovery principles and best practices; and
b) Information and services – Working closely with the ICAO MET Panel to support the integration of meteorological information into air traffic management systems and decision-support, including transition of new capabilities into operational and impact-based services.

3) Aeronautical meteorological hazards science

Promotion, coordination and advocacy of scientific and technological research and innovation to improve the monitoring and forecasting of aviation hazards in support of improved impact-based decision-support services, through advances in:

- Verification, validation and calibration tools and techniques;
- Utilization of ground-based and aircraft-based observations;
- Satellite and other remote sensing applications;
- Numerical weather prediction modelling and nowcasting, machine-learning and artificial intelligence applications; and
- Probabilistic and other forecasting techniques.
- Analysis of the climatological variation of the atmosphere (seasonal and inter-annual characteristics) resulting in changes in the location and/or intensity of jet streams, aviation hazards such as icing, turbulence and convection, and extreme weather events downscaled to the local level where required;
- Analysis of the impact of climatological variation of the atmosphere on:
  - airport operations and airspace management/optimization; and
  - airframe design.

For each four-year WMO financial period, the WMO will establish long-term goals, strategic objectives and other identifiers within its strategic and operating plans. These plans, particularly the operating plan, convey what is to be done, why it is to be done, by when and by whom. And, as importantly, the budgetary aspects associated with undertaking the activities are detailed in the operating plan. It is to be expected that WMO's activities in aeronautical meteorology will respect the WMO strategic and operating plans as well as other similar plans of ICAO and other partner organizations. Therefore, the foregoing list of thematic areas will evolve over time.

The constituent bodies of WMO – including technical commissions, regional associations and their subsidiary bodies – are the entities responsible for leading the required activities with the support of experts from WMO Members and partner organizations/agencies. The following section provides strategic guidance for Members in support of the evolution of aeronautical meteorological service provision.

4. Strategic guidance for Members

Ultimately, Members of WMO must determine exactly which capabilities they should have in place and by when based on their local circumstances and their users' operational requirements. Each Member should work to define country-specific milestones and developments to meet the needs applicable to their situation. Notwithstanding, the following performance improvement areas can serve as overarching guidance for the development and implementation of national implementation plans:

Foundational elements

The foundational elements that underpin authoritative aeronautical meteorological services include a rigorous quality management system (QMS) as well as adherence to the competency and qualification requirements for personnel engaged in the provision of aeronautical meteorological services. While great progress has been made across the WMO community in the compliance with these ICAO-mandated requirements, deficiencies remain in some countries. Both now and in the longer term, compliance must be achieved and maintained across these core foundational elements for AMSPs to remain viable as authoritative service providers to international civil aviation.

Improved observations including ABO

As noted in chapter 2, improvements and, in some cases, paradigm shifts are needed to meet the aviation users' needs and expectations for enhanced meteorological service provision. Specifically, longer term gains are required in the following areas:

- **Sustainment and/or improvement of the basic observing network** – AMSPs must ensure that their basic infrastructure to support the observing network is developed and maintained. Rigorous and defensible cost recovery mechanisms, where applicable and needed, should account not only for the development and installation of observational infrastructure but also for the ongoing operation and maintenance of these systems and associated life cycle costs.

- **Increased availability and application of aircraft-based observations (ABO)** – ABO is an important input to numerical weather prediction, providing valuable in-situ observational data of meteorological parameters, particularly over traditionally data-sparse or remote areas. Success in expanding ABO programmes comes through the demonstration of their value and building relationships with partner airlines through mutually-beneficial relationships. Members should pursue this wherever practicable.

Improved forecasts including impact-based forecasts to support risk-based decision-making

The expected increases in air traffic and associated constraints on available airspace will require significant improvement in the efficiency of flight planning which, in turn, will require better integration of high quality meteorological information and data. Specifically, aeronautical meteorological service providers will have to better support ATM decision-making needs for strategic, pre-tactical and tactical meteorological information, including through the provision of probabilistic and impact-based forecasts. This will, in particular, be the case in larger terminal areas where the need for the interpretation and integration of the meteorological information into risk-based decision-making processes is especially high.

As more real-time or near-real-time meteorological information is uplinked directly to the cockpit – while the aircraft is on the ground and in the air – there will also be a growing demand for more frequently updated meteorological information of higher spatial and temporal resolution, therefore a need for enhanced forecasting methods and systems.

Improved gate-to-gate services

As outlined in the AeroMetSci-2017 recommendations in Section 2, scientific and technological advancement will be needed across the entire service delivery chain to fully meet emerging aviation needs from gate to gate. Members must invest, as and where necessary, in the realization of these advancements. These investments must span the entire service delivery chain including the underpinning science, associated modelling, and the accelerated transfer of that science to operations. Members should use defensible economic benefit analyses in securing and defending their national investments in these areas.

Improved cost recovery

The provision of aeronautical meteorological service for international civil aviation is often funded through a cost recovery system mechanisms based on the ICAO's key charging principles and associated guidance, including ICAO Docs 9082 and 9161. WMO meanwhile provides guidance to its Members on cost recovery arrangements within WMO-No. 904, *Guide to aeronautical meteorological service cost recovery: principles and guidance*.

Fair and transparent cost recovery is of critical importance for sustained success in aeronautical meteorological service provision. In many cases where AMSPs struggle to fully meet service requirements today, the underlying cost recovery models are identified as being deficient or entirely absent. Members with inadequate cost recovery should seek to improve or introduce cost recovery practices consistent with ICAO and WMO guidance as they evolve.

Seamless information delivery, collaborative decision making (CDM) and impact-based services

As outlined above, the future of aeronautical meteorological service provision demands substantial changes in both the delivery of and access to meteorological data as well as changes in how that information is integrated seamlessly into decision-making processes.

It is clear that aeronautical meteorological services only realize their full value when well integrated into the decision-making processes of the end users. Members should, therefore, work with all concerned stakeholders to ensure that their impact-based services are fit-for-purpose and integrated into the aviation decision-making processes. Additionally, the importance of healthy, collaborative relationship with the relevant civil aviation authority (or authorities) cannot be understated. Aeronautical meteorological services cannot be produced or delivered in isolation. Members are encouraged to improve the value of the services they provide through these principles.

Increased efficiency including partnership and collaboration, adding value where most appropriate

To remain competitive, AMSPs should embrace opportunities, wherever necessary, within the global weather enterprise (GWE). Relationships with the private sector and academia should be embraced as mutually-beneficial opportunities rather than viewed as representing an organizational risk. AMSPs are encouraged to be an active and collaborative partner within the GWE, otherwise they run the risk of being left behind as the GWE grows and matures around them.

Where gaps remain between the developed and developing world, Members should seek to either provide assistance or seek assistance so that no country is left behind. Twinning and mentoring programmes, where appropriate, should be actively pursued and embraced to close often longstanding capability gaps and improve services.

Additionally, the evolution of meteorological service provision has resulted in challenges for many Members in maintaining end-to-end programmes given the complexity of the weather enterprise and the significant investment required to maintain the state-of-the-art capabilities. Collaboration in observations as well as numerical weather prediction should, therefore, be pursued wherever appropriate. Members should also emphasize and capitalize on their added value in the service delivery chain, particularly in the ultimate delivery to end users and stakeholders where local knowledge and relationships are of critical importance.

5. Conclusion

There are many changes on the horizon in aeronautical meteorological service provision. These changes manifest in the form of challenges to be overcome and opportunities to be capitalized upon.

Through close collaboration with ICAO and other partners, the sustainment of WMO's active role in aeronautical meteorology and the investment and efforts of WMO Members are essential to ensure that the aeronautical meteorology service provider community can meet the needs and expectations of the aviation user community, thereby ensuring safe, efficient and environmentally responsible flight operations now and into the future.

Members are strongly encouraged to be proactive in addressing the existing and foreseen changes, as the pace of change in the aviation industry is such that time is of the essence in achieving common goals.

Aeronautical meteorological services remain an important element in many NMHSs. These NMHSs should realize that there are risks and opportunities in the changing landscape of this service area. Innovation, particularly in the context of meteorological science and technology, is necessary and required. A failure to innovate represents a real organizational risk.

As described in the LTP-AeM, WMO continues to have a significant role to play in the development and evolution of the future global air traffic management systems. It is important therefore that WMO Members analyse and consider the issues outlined in the LTP-AeM in order to better mitigate the risks, embrace the challenges and, together, ensure that the best aeronautical meteorological science, technology and expertise is used to drive the aviation industry's meteorological information needs into the 2030s and beyond.

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