Global Demonstration Campaign for Evaluating the Use of Uncrewed Aircraft Systems in Operational Meteorology

White Paper

2023 edition

WEATHER CLIMATE WATER

WORLD
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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at https://public.wmo.int/en/meteoterm.

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EXECUTIVE SUMMARY

The lower atmosphere, including the boundary layer, plays a critical role in energy and moisture exchange between the surface and the free atmosphere. In addition, shallow, small-scale flow features and low-level gradients in temperature, winds and humidity often determine impactful local meteorology such as where fog forms, thunderstorms initiate, precipitation changes phase or air quality is affected. However, atmospheric modellers and weather forecasters have identified the boundary layer as a domain that is undersampled and which therefore represents a significant gap in the global observing system.

The expected growth in commercial applications of small low-flying uncrewed aircraft systems (UASs), coupled with current efforts to develop fully autonomous launch, land and recharge operations for routine atmospheric sensing by UASs, indicates there is great potential for such new observing systems to fill the observational gap. Studies have shown that observations obtained with commercial passenger and transport airlines improve weather forecasts. Other, recent and more limited studies indicate that UAS observations may have a significant positive impact on the skill of regional and high-resolution forecast model predictions.

Based on the growth of UAS commerce and the potential benefits of small UAS observations for National Meteorological and Hydrological Services, the WMO Joint Expert Team on Aircraft-Based Observing Systems has begun to assess the maturity of UAS sensing technologies. This White Paper provides an overview of the current level of readiness of UASs to routinely provide observational data to support National Meteorological and Hydrological Services around the world and as a contribution to the WMO Integrated Global Observing System.

The current status of UAS technology and UAS ability to fill gaps in the WMO Integrated Global Observing System is discussed, along with previous and current efforts related to their technological advancement and operational integration. The benefit of operational UAS programmes in improving weather services through data assimilation and timely monitoring of rapidly changing conditions to improve short-term predictions is explored.

The paper also discusses the required areas of technological development and standardization of UAS operational and data management procedures needed for integrating UASs into the operational weather monitoring domain. This includes various considerations that will affect UAS implementation to support operational meteorology such as potential cost, standardization of data collection, formats, testbeds, required level of autonomy and regulatory hurdles.

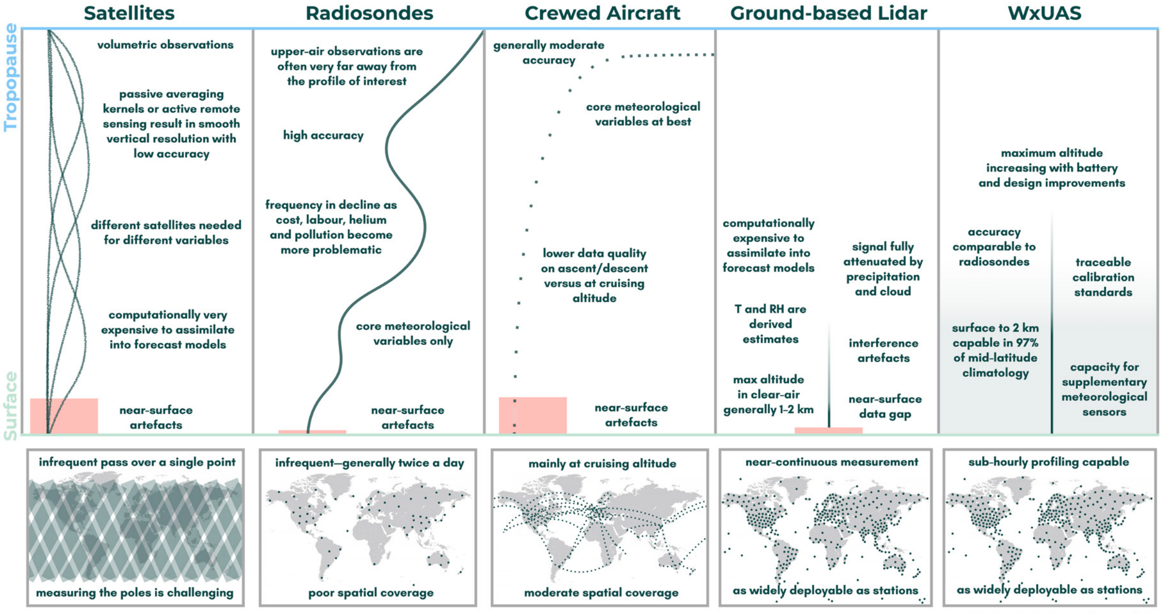
Recommendations are made in relation to these requirements for further UAS and related operational development, including the need for demonstration of the technology and its capability, for which WMO is taking a lead role in coordinating the UAS Demonstration Campaign in 2024.

1. INTRODUCTION

In the lower atmosphere, there is a significant in situ observational gap that encompasses the surface layer, atmospheric boundary layer and lower free troposphere (National Research Council, 2009; Geerts et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2018; NOAA, 2020). This observational gap is most acute in remote locations and is generally greater in developing regions of the world (*Guidelines on High-resolution Numerical Weather Prediction* (WMO-No. 1311)).

Reducing gaps in the observation of thermodynamic and kinematic properties of the lower atmosphere is critical for achieving more skilful mesoscale predictions of high-impact weather (Dong et al., 2011; Stensrud et al., 2013). This is becoming all the more important as climate shifts result in increased frequency of weather extremes such as torrential rains, which are driven by processes that occur at much finer spatio-temporal scales than currently captured by conventional, operational observing systems.

Figure 1 demonstrates how uncrewed aircraft systems (UASs), used to observe atmospheric variables (termed "wxUAS" hereafter), have the potential to fill gaps in the global observing system.



Courtesy of Dr. Ben S. Pickering, Menapia Ltd.

Figure 1. The global observing system, with a focus on the observation types that provide vertical profile information

Notes: The upper portion shows the vertical characteristics of each observation type, along with comments on their accuracy and characteristics. The lower portion represents the coverage of each observation type on a global scale, based on observations received operationally by the European Centre for Medium-Range Weather Forecasts. RH = relative humidity; T = temperature.
Source: Ben S. Pickering, Menapia Ltd

1.1 Development of weather-sensing uncrewed aircraft systems

In the 1990s, UASs – also known as drones, unmanned aircraft systems and remotely piloted/controlled aircraft – began to emerge as a new observing system for atmospheric science (Holland et al., 1992).

In 1998, a small UAS called an aerosonde made the first fully autonomous transit of the North Atlantic (Holland et al., 2001). This UAS with a combustion engine was specifically designed for meteorological applications.

Since then, multiple aerosonde deployments across a range of environmental conditions have demonstrated that wxUASs could be deployed to collect targeted observations in remote locations, to conduct continuous profiling to capture rapidly evolving atmospheric conditions, or to perform horizontal mapping patterns to remotely sense surface characteristics.

This new class of aircraft provided a relatively economical solution for tackling the "dull, dirty, dangerous" missions (Curry et al., 2004) needed to improve understanding of the lower atmosphere and to routinely monitor conditions where observations are lacking. However, while pushing the envelope of in-flight autonomy, National Meteorological and Hydrological Services (NMHSs) considered the aerosonde not completely suited for operational use due to several limitations. These included their inability to achieve full (take-off to landing) autonomy, their operational expense (including maintenance and upkeep, fuel costs, and crew resource requirements) and the limitations dictated by airspace regulations.

Over the last 15 years, UASs have evolved from being primarily fuel powered to being primarily battery operated, which has had many advantages. The move from fuel to battery and the advent of multirotor airframes and more efficient motors have greatly simplified and reduced the cost of aircraft maintenance. Since the introduction of battery-powered UASs, the number of research groups focused on developing environmental-sensing UASs has flourished around the world (Pinto et al., 2022).

The capabilities of UASs are already considerable and growing rapidly across a vast range of applications. Application areas include: entertainment (such as in light shows), surveillance and reconnaissance, cargo delivery, infrastructure inspection, public safety, security, wildlife monitoring and environmental sensing. Such diversity of applications, coupled with a drive for their use by the public, means the technology is rapidly advancing. However, the regulatory aspects of their use are struggling to keep pace with the technology developments.

Small wxUASs have the potential to revolutionize the collection of meteorological observations in the lower atmosphere for use in regional high-resolution numerical weather prediction (NWP) models. Larger long-duration, high-altitude wxUASs, with the ability to release dropsondes, could collect observations of value to regional and global models. Observations from both systems would likely have a significant positive impact on the skill of NWP at a range of scales (*Workshop on Use of Unmanned Aerial Vehicles (UAV) for Operational Meteorology*).

From the WMO international perspective, an observing system could be considered operational when the observations are available on the WMO Information System (WIS), and when these observations can meet the requirements for one or more meteorological, hydrological or climatological application areas.

The WMO Integrated Global Observing System (WIGOS) provides a standardized framework for all observing systems, and enables the provision and availability of observations based on the requirements of the 14 application areas of WMO. The requirements for observations are established and maintained through the WMO Rolling Review of Requirements process. A particular challenge to WMO Members is to determine how best to implement wxUASs efficiently and effectively while overcoming the challenges of meeting airspace regulatory requirements and the limited resources available to NMHSs.

1.2 **Objectives and structure of this White Paper**

This paper builds on recommendations made at the WMO Workshop on Use of Unmanned (note that the term "unmanned" is now "uncrewed") Aerial Vehicles (UAS) for Operational Meteorology, from 2 to 4 July 2019 in Toulouse, France.

Its purpose is to discuss key factors influencing the widespread adoption of wxUASs as an operational observing system by NMHSs around the world. It expands on the work of Pinto et al. (2021), which discusses the potential for small wxUASs in operational meteorology, by providing additional details on the various considerations and requirements for utilizing wxUASs in operational meteorology.

A description of the observational gaps that wxUASs could fill is first provided from modelling and forecasting perspectives. This is followed by a summary of how UASs and wxUASs have evolved over the past few decades to potentially become new environmentally friendly systems for collecting weather observations in support of operational meteorology. This discussion includes a description of recent field demonstrations that continue to add evidence for the efficacy of this new weather sensing technology.

Then, the requirements for wxUAS observations are discussed and areas of further development for more widespread use of wxUAS in operational meteorology are outlined. Moreover, potential pathways for more routine operational use of wxUASs are presented. Plans for a global demonstration project are then discussed, followed by a summary of the paper. Finally, a set of recommendations for future activities are presented. These recommendations are provided to encourage potential wxUAS operators and the operational community to continue to work together to advance the use of wxUASs in operational meteorology.

2. OBSERVATIONAL GAPS AND REQUIREMENTS

There are significant gaps in the availability of in situ observations in the lower atmosphere, as discussed above and outlined in the work of Pinto et al. (2021). These observational gaps affect operational meteorology by contributing to model prediction uncertainties (particularly at regional scales) and by limiting the awareness of operational weather forecast providers of the current state of and recent trends in the atmosphere. Both issues are even more relevant in remote areas and in regions characterized by complex terrain or other surface heterogeneities that are difficult to capture explicitly with NWP.

The requirements for improved, accurate and timely measurements of the lower atmosphere with enhanced spatio-temporal coverage will be driven by operational meteorologists and regional NWP models that need better measurements on the evolution of the atmosphere to make more acute forecasts and predictions. WxUASs offer the potential for filling these critical gaps in the current operational observing infrastructure around the world.

2.1 From a modelling perspective

The skill of NWP is fundamentally limited by the accuracy of the initial state of the model, followed by the sophistication and accuracy of the model physics from which the initial state is stepped forward over time. Therefore, reducing gaps in the observation of thermodynamic and kinematic properties of the lower atmosphere is critical for achieving more skilful mesoscale predictions of high-impact weather. For example, the National Oceanic and Atmospheric Administration (NOAA) goal of developing a Warn-on-Forecast capability (Stensrud et al., 2009, 2013) hinges on improved observation of the lower atmosphere at spatial and temporal scales relevant for accurately predicting hazardous severe weather at very fine scales.

Temporal and spatial gaps in existing observing systems contribute to model forecast uncertainty (Dong et al., 2011; James and Benjamin, 2017; James et al., 2020). In fact, the full potential of regional NWP models will not be realized until spatio-temporal sampling of the lower atmosphere is comparable to a model's effective resolution (Dabberdt et al., 2005).

Moreover, the need for increased coverage of observations has become increasingly important as the number of extreme weather events increases due to the impacts of climate change. For example, extreme precipitation events often result from convective processes that are driven by thermodynamic and kinematic processes in the lower atmosphere. Such processes occur at spatial and temporal scales that are not currently resolved by conventional observing systems.

In addition, as society and commercial sectors increasingly require hyperlocal weather information, the need for increased observation at very fine scales will continue to grow. Emerging modes of aerial transportation, including UASs and electric vertical take-off and landing vehicles, are being developed to support urban air mobility. They will require increasingly precise (localized) and accurate weather guidance products to support their safe and efficient operation as an alternative mode of transportation. These new entrants could also collect measurements of the lower atmosphere, which would improve observational coverage to help meet next-generation weather prediction needs.

2.2 From an operational forecasting perspective

Operational meteorologists have pointed to the need for increased observation of the lower atmosphere as being critical for improving short-term (less than 24 hours) forecast guidance products (Houston et al., 2020, 2021). Surveys of operational meteorologists in the United States of America have indicated a need for increased sampling of remote environmental locations during periods of rapidly changing conditions (such as evolution of temperature and moisture, and wind profiles in the pre-convective environment) to improve their short-term forecast products (Houston et al., 2021).

Moreover, the dearth of lower-atmospheric observations is especially significant in developing regions of the world. This makes it particularly challenging for NWP models and NMHS meteorologists to produce accurate short-term forecasts of high-impact weather events like severe thunderstorms (Woodhams et al., 2018) and dust storms (Wang, 2015).

In addition to helping address the above, wxUASs could also be used to fill some other potential services provided by NMHSs. These include the acquisition of more detailed surveys of severe thunderstorm impacts (Wagner et al., 2019), coastal storm impacts on erosion (Kaamin et al., 2016), inland water body flood monitoring (Imam et al., 2020) and volcanic plume monitoring (Schellenberg et al., 2019). While these applications should also be considered by NMHSs, this White Paper will focus specifically on the potential for wxUASs to obtain meteorological observations for assimilation in NWP models and to aid in operational short-term weather forecasting.

3. DEVELOPMENTS AND DEMONSTRATION OF CAPABILITY

Over the past few years, the environmental-sensing capabilities of UASs have continued to evolve to fill gaps in existing observational networks. WxUASs are now capable of collecting routine observations of the lower atmosphere to extend existing observing system networks, as described by Chilson et al. (2019) and demonstrated by Leuenberger et al. (2020).

The flexible nature of UASs can facilitate their use in ways that other observing systems are not capable of. For example, wxUASs may be deployed to collect targeted observations in relatively data-sparse areas of interest that may require more intensive local observation and monitoring to improve the prediction of high-impact weather (Koch et al., 2018). Small wxUASs can also be transported by larger aircraft and deployed in regions where in situ observations are otherwise too dangerous to make. For instance, NOAA has demonstrated this type of deployment strategy, whereby wxUASs were launched from a NOAA P3 hurricane hunter aircraft to collect observations within the boundary layers in the eyewalls of hurricanes (Cione et al., 2020).

These attributes, coupled with decreasing costs of UAS production, operation and maintenance and their reusability, are making wxUASs more economically viable for use by NMHSs around the world to fill observational data voids (McFarquhar et al., 2020).

It is therefore evident that UASs have the potential to provide a useful supplementary platform for in situ measurements, adding value to and complementing existing operational sounding and remote-sensing systems. They especially have the potential to reduce the data gap in the lower atmosphere by enabling increased spatio-temporal sampling at scales comparable to the effective resolution of regional mesoscale models. In addition to making standardized, routine observations, some high-altitude systems could be used to collect targeted observations for specific weather phenomena, such as in areas deemed conducive for tropical cyclone development. UASs are also well suited to collecting measurements in remote or dangerous locations such as for monitoring volcanic ash, forest fires and other natural or human-made hazards (for example, chemical spills).

3.1 Recent advances in power and control

Fixed-wing and multirotor UASs are now primarily powered by batteries rather than by combustion engines. The evolution of battery technology has supported this key advancement, which continues to increase power to weight ratios and safety over time (Deng, 2015; Gandoman et al., 2019). Coupling the new battery technology with solar recharging makes this new sensing system an environmentally friendly alternative to other observing systems that require more energy to deploy. In addition, the batteries used to power UASs can be recharged many times during the battery lifetime before the battery materials are ultimately recycled.

The novel innovation in any new battery technology is making the chemistry stable, such that safety is tolerable and the power performance lasts many charge cycles. Due partly to the demand for electrification of transport industries to meet net zero targets, several promising new chemistries have now demonstrated laboratory energy densities multiple times higher than those currently available on the market (Evers and Nazar, 2013; Rahman et al., 2014; Shen et al., 2018; Zhao et al., 2020; Knight, 2021). However, their stability requires improvement before they can be useful.

At the same time, autopilots have evolved to become highly reliable and economical, with off-the-shelf control software costing less than US$ 250. In addition, UASs have been simplified with stable flight controllers and programmable flight planning tools such that a single person can perform all duties required to support an extended period of UAS operations. For example, United States Federal Aviation Administration (FAA) waivers have been obtained, allowing a single pilot to fly up to 500 UASs at a time (Liptak and McCormick, 2017).

3.2 Recent advances in sensing technology

Sensors and their integration onto wxUASs are a function of platform type. Key considerations for integrating sensors into UAS fuselages include the need to shield sensors from solar radiation, insulate them or aspirate them, to avoid heat generated by UASs from the motors and the batteries, or aerodynamic effects such as compressional warming from the propeller modified airstreams (Greene et al. 2018, 2019). Unlike multirotor UASs, which pull air down from above with prop wash, fixed-wing platforms allow for measurement of the environment that has been potentially less modified by the platform itself.

Trends within the sensor market are towards miniaturization of components, which is useful for the application of wxUASs. Typically, the trade-offs with miniaturized sensors are accuracy and response time, but improvements are also steadfast in this regard. While most wxUASs use lightweight and fast response time sensors, there are several approaches being used specifically for how these sensors are mounted upon wxUASs. These include using different locations on the airframe relative to the potential sources of bias.

The CopterSonde wxUAS, a quad-copter developed at the University of Oklahoma, includes a radiation shield and internal fan that aspirates the sensor with environmental air flow (see Figure 2). Custom flight controller software ensures the platform orients the sensor vent opening into the wind to provide the sensors with the least-disturbed airflow (Greene et al., 2019). Bell et al. (2020) demonstrated the accuracy of the CopterSonde to be within 0.7°C of radiosonde data obtained with the Vaisala RS92 sensor for temperature and dewpoint. They also found that for wind speeds greater than 4 m s^{-1}, the CopterSonde-sensed wind observations agreed with radiosonde observations of wind speed and direction to within 0.6 m s^{-1} and 4°, respectively. The agreement was reduced at lower wind speeds, in part because the CopterSonde requires winds strong enough to tilt the aircraft.

Figure 2. CopterSonde wxUAS developed at the University of Oklahoma

Source: Tyler Bell, University of Oklahoma/NOAA

The Menapia Ltd wxUAS, called MetSprite (see Figure 3), is also a quad-copter design. It uses propellers to aspirate a sensor pod located under the UAS arms using the two-thirds radius optimization (Greene et al., 2018, 2019). This relatively new entrant to the wxUAS market is designed for automatic profiling from a ground charging pad. It also has easy integration of third-party sensors due to the on-board communication ports, power supply and customizable housings (such as underarm sensors, top-mounted sensors and boom poles) obtained using three-dimensional (3D) printing.

Based on 30 year radiosonde climatology, the MetSprite wxUAS (maximum speed of 28 m s^{-1}) could reach an altitude of 2 km above mean sea level approximately 97% of the time when deployed as a routine operational tool (Pickering and Mooney, 2023). Verification of the MetSprite core observations (pressure, temperature, humidity and 3D wind) is ongoing, in partnership with the Royal Netherlands Meteorological Institute. The first operational deployment of MetSprite is occurring from June to August 2023 on the Wessex Convection project (Barrett et al., 2021).

Figure 3. MetSprite wxUAS developed by Menapia Ltd

Source: Ben S. Pickering, Menapia Ltd

The latest Meteomatics AG MeteoDrone MM-670 (hexacopter with six propellers, see Figure 4) design places the meteorological sensors protruding out of the side of the UAS main body, between two propellers and slightly above the height of the propellers. The radiation shield consists of a single white plastic wall spaced widely around the sensors with an open top and bottom for the air to pass through. The MeteoDrone pictured is recharging automatically on the Meteobase, which enables continuous profiling over multiple days without human intervention.

Hervo et al. (2022) describe a 6 month validation campaign of the MeteoDrone, using 97 night-time flights synchronized with radiosondes. Using the Observing Systems Capability Analysis and Review (OSCAR) criteria (OSCAR Application Areas), temperature observations were considered “breakthrough” (root mean square error (RMSE) = 0.68 K), the humidity observations were considered “threshold” (RMSE = 8.3%) and the horizontal wind estimates were considered “threshold” (RMSE = 3.12 m s^{-1}). Notably, the measurements improved during the campaign, such that temperature became “goal” (RMSE < 0.5 K) and humidity became “breakthrough” (RMSE < 5%). The effect of solar radiation is not included since the wxUAS profiles were conducted at night in compliance with the airspace approval that Meteomatics AG has obtained in Switzerland.

Figure 4. Meteomatics MeteoDrone MM-670 automatically recharging on the Meteobase

Source: Matthias Piot, Meteomatics

For wind sensing on multirotor wxUASs, several approaches have been taken that fall primarily into two categories. The first is to mount a traditional sensor outside the flow field induced by the UAS propellers (Shimura et al., 2018; Thielicke et al., 2021). Thielicke et al. (2021) found that to avoid disturbances produced by the propellers on measurements obtained with a 3D sonic anemometer, the instrument should be placed 2.5 times the diameter of the propellers above the height of the propellers. The second wxUAS wind-sensing category is to use the wxUAS itself as a wind sensor through the forces exerted upon the platform. Within this category of inertial wind sensing, multiple approaches have been implemented, with varying accuracies reached (Allison et al., 2020; Tian et al., 2021; Meier et al., 2022; Wildmann and Wetz, 2022). Approaches differ for fixed-wing wxUASs, where pitot tubes and multihole probes, combined with inertial measurements, are more common (Elston et al., 2015; Rautenberg et al., 2018).

In addition, sensor calibration is critical to remove biases and sensor drift, and to identify sensor failure. Routine, automated calibration methods, whereby sensor data are compared with a reference standard, must be included in any operational wxUAS observing system (Chilson et al., 2019) – the same as any meteorological observing instrument. Additional studies are needed to intercompare wxUAS observations with those obtained using towers, radiosondes or other remote-sensing systems to assess atmospheric sensing issues that may be realized only during flight (Barbieri et al., 2019; Bell et al., 2020; Hervo et al., 2022).

3.3 Demonstration of the capability

While there have been a few demonstrations focused on use of wxUASs in an operational environment (Koch et al., 2018; Cione et al., 2020), these campaigns have been limited in scope and duration. Longer duration demonstrations are needed to assess the utility of wxUASs in an operational environment, to develop protocols, requirements and standards, and to evaluate observation accuracies. Long-term demonstrations at testbeds and other sites are also critical for performing detailed data impact assessments to quantify how wxUAS observations improve model skill and also if wxUAS observations can be used effectively by weather forecasters in developing their guidance products. These impact studies are required as part of a cost–benefit analysis.

Testbeds can be used to further demonstrate wxUAS capabilities in a safe environment, while working with regulators to streamline procedures for obtaining permissions for wxUAS operations. They enable the establishment of connections between wxUAS operators and modelling centres. They also facilitate interactions among wxUAS developers, commercial UAS operators, operational meteorologists and other stakeholders. Within these testbeds, experiments can be designed to tackle hurdles in moving wxUASs into operational use by NMHSs.

Testbeds can be used as a stepping stone for the development and demonstration of new sensing technologies and for determining how they can be used to support NMHS weather forecasters, as well as to improve weather prediction models via data assimilation. They can also be used to develop cost-sharing approaches that can be evaluated in a real-world environment. For example, the cost of collecting and transmitting weather data can be weighed against the added value of improved situational awareness among UAS operators as well as the impact of these data on short-term weather forecasts needed to support commercial UAS operations. Likewise, the cost of maintaining and operating a small fleet of wxUASs by NMHSs can be weighed against the value of increased lead time in the prediction of severe or high-impact weather or improved air quality forecasts.

Cione et al. (2020) describe an operational testbed designed to support short-term hurricane intensity forecasting and hurricane boundary layer research. In this, an air-launched wxUAS, called the Coyote, was deployed from a NOAA P3 aircraft through the dropsonde launch tube. This wxUAS collected measurements of 3D winds, temperature, pressure and humidity in the eyewall of a hurricane. Observations were transmitted in near real time from the Coyote wxUAS to the NOAA P3 aircraft to the NOAA National Hurricane Center (NHC) for use by operational forecasters. While the utility of this new observing system was promising, there were shortfalls with data quality and data transmission outages that limited the assessment of operational forecasting impacts.

The NOAA Air Resources Laboratory Atmospheric Turbulence and Diffusion Division in Oak Ridge, Tennessee, has been demonstrating routine wxUAS operations in boundary layer research and operational meteorology. Observations obtained with a wxUAS are being transmitted to the Morristown, Tennessee, Weather Forecast Office (WFO), to aid forecasters in generating short-term forecasts in near real time. At the time of writing, over 350 flights have been performed to support forecasters at the Morristown WFO, with multiple flights being performed on a given day to temporally resolve the diurnal transition periods and to obtain observations needed to improve severe thunderstorm and winter precipitation type predictions. Forecasters have reported that the wxUAS observations have been used to develop forecast products and augment their decision support services.

Several wxUAS demonstrations are being conducted or are planned throughout the world over the next few years. For example, a recently concluded FAA-funded project called Frequent *in situ* Observations above Ground for Modeling and Advanced Prediction of fog used wxUASs to collect observations to improve fog prediction at a major airport in the United States. This demonstration campaign, which took place during the winter and summer of 2022, required close coordination among wxUAS operators, airport managers, FAA and a local WFO.

Campaigns are also planned to develop and demonstrate weather-aware UAS traffic management systems (Kopardekar, 2014). Understanding and planning for conditions hazardous to commercial UAS operations will be critical for their safe and efficient integration into national airspace (Roseman and Argrow, 2020; Thibbotuwawa et al., 2020).

For example, Oklahoma State University is leading a team of universities and private partners to develop a weather-aware UAS traffic management system. In this testbed, wxUASs, possibly along with commercial UASs, will collect and transmit observations of the lower atmosphere that will inform other UASs operating nearby of winds and potential UAS hazards. These same data will be made available for assimilation into experimental NWP models, to evaluate the impact of these observations on the accuracy of low-level winds, turbulence and UAS weather hazard guidance.

WxUAS campaigns have also been conducted in Europe. For instance, a 6 month long demonstration campaign in Switzerland, which ended in June 2022, focused on evaluating the performance and reliability of wxUASs in strong winds and icing conditions, which included night-time flights up to 1 500 m above ground level (AGL). WxUAS observations will be compared with conventional radiosonde observations as, well as measurements from remote sensors (wind lidar, Raman lidar and radiometers). The wxUAS observations will also be assimilated by MeteoSwiss, to evaluate their impact on NWP skill.

In Finland, the Finnish Meteorological Institute (FMI) has been operating a testbed since mid-2020, with one or two profiles every hour during the day, measuring temperature, relative humidity and pressure. The testbed site is also a radiosonde sounding station, and data are validated against the twice daily operational radiosonde launches. This dataset will soon be used in observing system experiment (OSE) trials by Météo-France in collaboration with FMI. One aim is to test the transfer of data to an operational data centre, and ensure the data format is suitable for data assimilation (DA).

Denmark has also established a UAS research testbed. Its vision is to combine the efforts of a unique testing facility to accelerate drone innovation in Denmark and internationally. It is one of the only test centres in Europe that provides a beyond visual line of sight (BVLOS) airspace ready to use over sea without interference from other aviation.

4. REQUIREMENTS AND IMPROVEMENTS NEEDED FOR INTEGRATION INTO OPERATIONAL METEOROLOGY

4.1 Development of technology

This section discusses several of the key aspects of wxUAS technology and operation that require further development, improvement and/or demonstration before being considered for integration into WIGOS. The key aspects to be considered include:

- Accuracy of key variables and impact of data
- Cost
- Flyability
- Automation and reliability
- Environmental impact, safety and societal acceptance
- Airspace integration and security

Each of these considerations is examined below, with an analysis of the requirements and current status, and highlighting areas where improvements may be needed.

4.1.1 *Accuracy of key variables and impact of data*

4.1.1.1 Requirements

Primary requirements for wxUASs to be useful for operational meteorology are that they collect accurate measurements of at least temperature, pressure and humidity in the lower atmosphere and that they can make these observations available in a timely manner. Coincident measurements/estimates of the horizontal wind would also be valuable. In addition, wxUAS observations should be comparable in accuracy to those collected with the WMO Aircraft Meteorological Data Relay (AMDAR) observing system and should strive to be as accurate as those obtained with radiosondes.

4.1.1.2 Current status and improvements needed

Recent intercomparisons of wxUAS observations with other observing systems have indicated that the accuracies of temperature, pressure, wind and relative humidity from wxUASs are comparable to those obtained with towers, radiosondes and other remote-sensing platforms (Barberi et al., 2019; Bell et al., 2020; Hervo et al., 2022). However, work is still needed to establish standards for accuracy and data quality for each new entrant wxUAS. In addition, there will be a need to establish requirements for sampling rates and data latency.

4.1.1.3 Model impact studies

The value of wxUASs in improving the skill of weather predictions can be assessed using OSEs and observing system simulation experiments (OSSEs). Such methods utilize variational, ensemble-based or hybrid systems to determine the influence of a particular observing system on predictive skill. Hoffman and Atlas (2016) give detailed reviews of OSSEs and OSEs. As wxUAS observations will generally be confined to the lower atmosphere, while at the same time providing potentially dense coverage, the benefit of wxUAS observations should be quantified using regional mesoscale predictions systems (Snyder and Zhang, 2003; Sobash and Stensrud, 2013).

Preliminary studies have used regional OSSEs to demonstrate potential skill gains associated with augmentation of the Oklahoma Mesonet with wxUAS profiling for predicting localized serve thunderstorms (Moore, 2018), as summarized by Chilson et al. (2019). The utility of wxUAS observations has been demonstrated in modelling studies across a range of environment conditions including fog prediction (Leuenberger et al., 2020), low-level meso-gamma scale flow patterns (sea breeze and oceanic boundary layers; Jonassen et al., 2012; Flagg et al., 2018), terrain-driven flows (Jensen et al., 2021), convection initiation (Moore, 2018; Jensen et al., 2022) and hurricane intensity (Cione et al., 2020).

Some studies have demonstrated that wxUAS DA can improve the skill of impactful weather condition forecasting using mesoscale weather prediction models. An OSE by Leuenberger et al. (2020) showed that the assimilation of wxUAS observations improved the short-term prediction of radiation fog events. Jensen et al. (2021, 2022) demonstrated that wxUAS DA dramatically reduced large biases in the analyses of low- and mid-level moisture and winds that were critical in predicting the timing and location of thunderstorms and subsequent outflows.

Figures 5 and 6 show examples of the impact of wxUAS DA on improving the representation of the pre-convective environment and storm prediction. Here, several distributed profiling wxUASs reduced biases in temperature and moisture, which made the atmosphere more conducive for the development of convective storms. These findings are consistent with the results of Moore (2018) and Chilson et al. (2019), which demonstrated the value of wxUAS DA in predicting thunderstorm evolution. Moore (2018) and Jensen et al. (2022) demonstrated the value of targeted profiling using wxUASs to improve the timing and location of storm initiation and subsequent evolution over that possible with conventional observations alone.

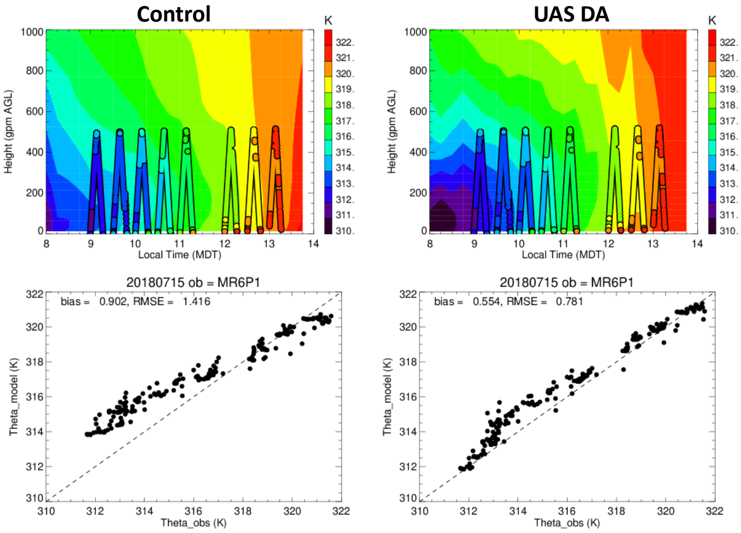


Figure 5. Time–height cross-sections of ensemble mean analyses of potential temperature obtained with: (left) control run (only surface observations assimilated) and (right) wxUAS DA run as compared with independent wxUAS observations (colour filled circles) collected in the centre of the San Luis Valley of Colorado before convection initiation. Corresponding scatterplots quantify the time–height comparisons illustrating improvements in bias and RMSE.

Notes: Assimilation experiments were performed using the Weather Research and Forecasting Model and Ensemble Adjustment Kalman Filter (EAKF) DA from the National Center for Atmospheric Research Data Assimilation Research Testbed (Anderson, 2001). gpm = geopotential metres; MDT = mountain daylight time.

While these results demonstrate the potential for wxUAS DA in NWP and hint at some of the requirements for data accuracy and sampling strategies, a great deal of work is needed to assess the effectiveness of wxUAS DA across a range of challenging forecast problems. In addition, strategies for implementation of wxUASs within an operational environment need to be developed via close coordination with NMHSs and operational forecast offices (Houston et al., 2020).

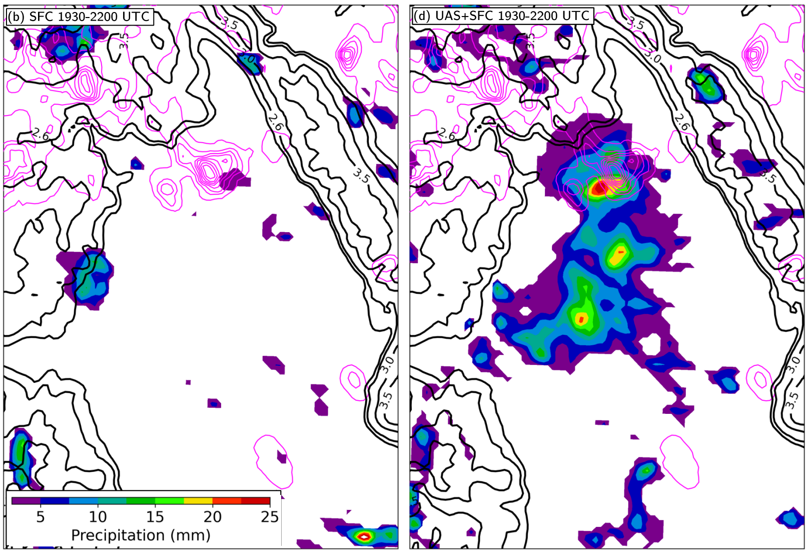


Figure 6. Comparison of 3 hourly accumulated precipitation (mm) from the National Centers for Environmental Protection, Stage IV gauge corrected radar estimates (magenta contours) and from 3 hour predictions (colour fill) that were initialized with analyses generated obtained using EAKF DA of (left) surface observations and (right) surface plus wxUAS observations

Source: Anders Jensen, Global Systems Laboratory, NOAA

4.1.2 ***Cost***

4.1.2.1 Requirements

The decision to adopt wxUASs as an operational capability will depend on a comparison of the cost of the new observing system and the potential societal benefits of improved weather prediction afforded by the new observations. For example, many studies have been conducted to demonstrate the value of commercial airline observations on weather prediction and, more specifically, on improving the safety and efficiency of the aviation industry, before AMDAR became operational (Peterson et al., 2015).

In the future, the potential market value of commercial UAS operations is expected to eventually exceed US$ 100 billion (Nath, 2020). In the United States, FAA expects commercial UAS registrations to increase by 33% over the next 3–5 years (FAA, 2023). While this growth is contributing to the drive to improve UAS technology and to driving down production costs, these airspace users will require forecasts of low-level winds and weather that are more accurate and finer scaled than those that exist today – an area in which wxUASs are expected to add the most skill to NWP.

4.1.2.2 Current status and improvements needed

WxUASs offer reusable profiling. This is a significant improvement to sustainability and cost-effectiveness for boundary layer profiling compared with single-use radiosondes. While wxUASs comprise a larger mass of materials, these can last from months to years of operation before needing replacement. For example, an initial 3D Mesonet deployment will likely involve a vertically profiling multirotor wxUAS profiling for 10 minutes (approximately 2 km altitude to capture the full planetary boundary layer (PBL)) every 90 minutes. Using such values, the operational lifespan of wxUAS components can be estimated.

The professional UAS industry is still maturing, with a fast pace of innovation. The range of lifespans for different components is therefore broad, and depends on the quality of the engineering and conditions during use. Typically, lithium-ion batteries have a 300–2 000 charge cycle (2–12 months), propellers have a 100–1 000 flight hour lifespan (1–12 months), brushless UAS motors have a 150–5 000 hour lifespan (2–60 months), vibration-isolated electronics have a multi-year lifespan, and carbon fibre arms and casings have a decadal lifespan. Furthermore, most components are highly recyclable at end-of-life, and contain valuable materials that motivate recycling.

The component lifetime estimates above suggest that a network of profiling wxUASs could be operated with, at worst, a monthly maintenance schedule. This is cost-effective in human labour compared to other boundary layer observing systems. Long term, it is feasible that maintenance could be performed on a similar schedule to that of sensor recalibration (typically 6–12 months).

The cost of wxUASs has decreased dramatically due to massive investments in developing UAS technologies in recent years by private industry, governments and academia (Belton, 2015). With the continued expansion of commercial UAS operations, the cost of acquiring components to build wxUASs has declined markedly in the past decade, particularly with respect to battery cells and the motors employed at UAS size scales. Nonetheless, the cost of purchasing a fully autonomous wxUAS, including an automated recharging system, is of the order of at least US$ 100 000, with operations and maintenance adding about US$ 20 000 per year. These compare favourably to the cost of radiosonde launches (including materials and labour), estimated at approximately US$ 300 per launch or roughly US$ 200 000 per year per site (depending on the operational programme and the number of special or non-routine launches made).

However, radiosondes can reach altitudes of 35 km AGL, which is far beyond the capabilities of current wxUASs. Vertically profiling wxUASs should therefore be seen as having the potential to become a supplementary component of the upper-air observing system. WxUASs will likely justify at most a reduction in the frequency of radiosondes rather than their replacement, since a single wxUAS site can profile the rapidly evolving PBL and mid-troposphere 12–24 times a day operationally.

The costs of an automated, vertically profiling wxUASs also compare favourably to those of operational wind lidar profilers (of the order of US$ 100 000 per year) and Raman lidar (US$ 100 000–500 000 upfront, US$ 10 000–50 000 annually; Leuenberger et al., 2020). However, these are both remote-sensing systems that are subject to heavy signal attenuation by precipitation, or by cloud in the case of lidar, and all exhibit signal artefacts. Additionally, data from such systems are challenging to assimilate into NWP since a DA forward operator must simulate their radiative characteristics.

4.1.3 ***Flyability***

4.1.3.1 **Requirements**

A critical requirement of operational wxUASs is to be able to reliably fly in most meteorological conditions where they will be deployed. This is referred to as the flyability.

WxUASs are dynamic systems that must actively use energy to reach desirable measurement locations within the atmosphere. Depending on the tolerances and abilities of wxUAS, these desirable locations may not be reached due to high winds, icing, precipitation and other adverse weather conditions (for example, lightning). The benefits to NWP of a wxUAS (and therefore the justifiable cost) are directly related to how frequently the useful measurement locations can be reached. Assuming permission can be obtained to operate BVLOS within and above cloud layers, the most significant limitations to unhindered autonomous profiling of the lower atmosphere include in-flight icing (such as snow, supercooled liquid cloud drops and freezing precipitation) and excessive winds.

4.1.3.2 Current status and improvements needed

While reliability describes the failure rates of the hardware, flyability describes the success rates of wxUASs reaching mission-driven altitudes and locations given its nominal operating capabilities. Maximum horizontal speed and the ability to withstand icing conditions have been shown to be the predominant controls of wxUAS flyability. For example, Pickering and Mooney (2023) showed with a 30 year radiosonde climatology that in the mid-latitudes, a vertically profiling wxUAS with a de-icing capability and a maximum horizontal speed of 28 m s^{-1} would reach 2 km AGL 97% of the time. The 50th percentile maximum altitude was shown to range from 3.2 km to 3.7 km across six different climate regimes while including realistic operational logic such as a safety reserve battery and overcharging avoidance. Improvements are needed to expand the range of icing conditions that can be flown through to increase flyability at altitudes above 3.2 km.

4.1.4 *Automation and reliability*

4.1.4.1 Requirements

To gain widespread use by NMHSs, wxUASs must be relatively easy to use and maintain, and thus will require a high level of automation. They will also need to demonstrate reliability, with expected uptimes in excess of 95%, as a requirement of operational safety and economic efficiency of data collection.

A key area of focus for determining the overall reliability of an automatic wxUAS is assessing its operational performance in weather conditions that adversely affect launch, landing and recharge. The reliability of the automated landing system will likely have a lower wind tolerance than the wind restrictions of 28 m s^{-1} used to determine flyability in section 4.1.3.2. This is due to additional uncertainties that are introduced by boundary layer turbulence and the requirement for more precise in-flight conformity associated with landing in a small target area. Therefore, wxUAS inertia and stability, and, critically, the design of the landing enclosure (which can enhance turbulence if not properly designed) are important considerations to maximize overall reliability of the fully automated system.

4.1.4.2 Current status and improvements needed

Most wxUASs are now fully autonomous once in flight, with recent efforts demonstrating fully autonomous operation from launch to recovery (Leuenberger et al., 2020). Although leading private companies have demonstrated automation through the entire profiling process using multirotor aircraft (Hervo et al., 2022), additional long-term demonstrations of these technologies are needed.

UASs continue to improve safety features by including parachute deployments or other means to mitigate catastrophic failures. Progress towards full widespread autonomous wxUAS flight is being made. This will allow one pilot to control many wxUASs from a central location (Jacob et al., 2020). The medical supply delivery industry in some countries is already demonstrating such one-to-many flight monitoring, as evidenced by the recent success of Zipline in Ghana, Nigeria and Rwanda (Gangwal, 2019; Chin, 2023). In other countries where airspace access is more restricted, such advances will require additional oversight and testing, first in local testbeds environments before widespread adoption. This allows for rigorous evaluation under a range of environmental conditions and more complex airspace (Mitchell et al., 2020).

4.1.5 *Environmental impact, safety and societal acceptance*

4.1.5.1 Requirements

A factor that must be addressed in making wxUASs more acceptable for widespread operational use in meteorology is to ensure and assure the public and airspace regulators that such vehicles are safe to operate and pose no threat to public safety and privacy.

UASs, and, in particular, automated, remotely operated UASs, are a relatively new technology that many people have yet to be exposed to or fully understand. Operations away from population centres are unlikely to cause significant concern; however, UAS flights conducted near homes and over people raise legitimate safety concerns. UAS operators will need to demonstrate that the risk of a UAS failure leading to injury or property damage is negligible.

Another issue of concern is environmental noise and the potential for scene clutter (visual annoyance).

4.1.5.2 Current status and improvements needed

The small dimensions of wxUASs make them unlikely to cause harm to human life or property in the event of loss of control (Barr et al., 2017). However, a low incident rate is still critical for reducing cost of operations and to support positive public perception. A simple step towards societal acceptance for collecting observations in more populated areas might be to use consistent non-threatening colours that would make wxUASs readily identifiable by the general public.

Privacy issues are already being considered by regulators and will likely need further refinement, particularly for UAS operations in highly populated areas. Outreach will be a useful approach to educate the public and will enhance the rate of acceptance of routine wxUASs.

Work also continues to make motors and propellors quieter. In an operational setting, all efforts should be made to perform wxUAS missions in areas that are far removed from populated areas, in order to minimize the effects of noise.

WxUASs are reusable over a potentially long lifespan. They therefore have a small environmental impact that can be further reduced as improvements to batteries are made and integrated into assembly. Since wxUASs are recoverable, their batteries can first be reused as stationary energy storage, and then at end-of-life be recycled with recovery rates exceeding 90% (rates improving rapidly due to the economic value of battery materials). The motors and electronics also contain valuable materials and have the potential to be recycled. In addition, the casings, particularly if 3D printed, can also be recycled, albeit unprofitably.

The recyclability of wxUASs is thus a stark improvement over conventional radiosonde systems, which, while theoretically reusable if recovered, are almost never found and reused. For example, in the United States, it was estimated that only about 18% of the material from radiosondes was reused (Dabberdt et al., 2002). This non-recoverability results in pollution of the environment with radiosonde materials such as lines, circuit boards and batteries.

Finally, it will be important to optimize the time intervals and costs of maintenance, while also ensuring all critical systems have preventative maintenance in place to eliminate, as far as possible, the risk of catastrophic or severe failure. System safety needs to be publicly demonstrated in case of catastrophic system failure. Great strides have been made to prove mitigation strategies by commercial wxUAS developers, which have demonstrated effective parachutes that automatically deploy when a system failure is detected.

4.1.6 *Airspace integration and security*

4.1.6.1 Requirements

For wxUASs to achieve their optimal potential as an observing system for supporting the needs of operational meteorology, they will need to be able to routinely fly much higher than currently permitted in general airspace. For maximum effectiveness, wxUASs will need to operate up to at least 1 000 m AGL (Chilson et al., 2019) and through cloud layers, which is considered to be BVLOS.

Aspects of national security will also need to be considered. For example, wxUASs will need to identify themselves electronically to other air users and air traffic management systems using various methods of remote identification.

4.1.6.2 Current status and improvements needed

Past restrictions on the accessibility of airspace for land-based flights have been a challenge for operators during research campaigns (Houston et al., 2012). However, in recent years, UAS and wxUAS flights over land areas have become commonplace, and links to operational meteorology are starting to develop.

Current regulations in the United States and Europe require UASs to be flown within unaided visual line of sight (VLOS) and below 120 m. These regulations pose a severe constraint for the use of wxUASs in operational meteorology. Exceptions to VLOS and the 120 m AGL rules can be obtained in Europe and the United States, but for limited time periods and specifically identified locations only.

In the United States, this is done by obtaining a certificate of authorization from FAA. In Europe, starting in 2021, a waiver that will permit BVLOS called a predefined risk assessment (PDRA-01) may be obtained from the European Union Aviation Safety Agency. On a case-by-case basis, wxUASs have already been granted permission to fly up to 2 km AGL in the United States and up to 6 km AGL in Europe. However, to maximize the potential of wxUASs for operational meteorology, the process for obtaining these waivers needs to be streamlined and standardized.

To demonstrate that BVLOS operation of wxUASs can be safely and effectively integrated within airspace regulations, more studies like CASCADE (David et al., 2021) are required. There also needs to be some consideration given to BVLOS operations in class G airspace, below 120 m. It is critical to formulate procedure and practices within this airspace. This is a crowded and unregulated area, where wxUASs would need to be able to automatically avoid other UASs, gliders, helicopters, privately piloted aircraft, towers, buildings and other obstacles.

To obtain the future required, less-restricted airspace access, wxUASs will almost certainly need to provide the necessary interfaces, communications and reliable autonomy to operate safely with other traffic (such as the FAA UAS Traffic Management System Pilot Program; Garret-Glasser, 2020; FAA, 2022). Importantly, in relation to this aspect, wxUASs are a predictable intrusion into existing crewed airspace, making it straightforward to inform airspace regulators of their locations at all times.

WxUASs also have a minimal ground risk area that can be controlled, providing an ideal first platform for automated, high-altitude UASs to gain societal acceptance.

Furthermore, wxUAS contributions to societal and aviation safety through observing wind jets and icing conditions should be a positive consideration when decisions are made on airspace integration for wxUASs. The benefits of flying wxUASs operationally into crewed airspace may outweigh the slight risk increase to other aircraft, and aviation safety may be improved overall by the existence of wxUASs.

4.2 Development of data integration into meteorological applications

The utility of wxUASs for collecting research quality datasets within the lower atmosphere is well established (Houston et al., 2012; Elston et al., 2015; Vömel et al., 2017; Bärfuss et al., 2018; de Boer et al., 2018, 2020; Chilson et al., 2019; Lee et al., 2019; Bailey et al., 2020; Frew et al., 2020; Kral et al., 2020; Lee and Buban, 2020).

WxUASs have great potential to meet the requirements and fill observations gaps in support of a range of NMHS applications. However, the use of wxUASs in operational meteorology has thus far been limited, despite the advances and indications of their utility. To integrate wxUASs into the global observing network (WIGOS) and to facilitate the use of wxUAS observations by meteorologists and modelling centres around the world, several areas of development and demonstration, as outlined below, will be needed.

4.2.1 *Data representation*

4.2.1.1 Requirements

Establishment of a common data format for wxUAS observations is critical for the widespread adoption of these systems within operational meteorology. Standardization of the wxUAS observation data format, which includes information on how data are collected and the quality of data (metadata), is required before operational modelling centres and NMHSs can effectively utilize the new observations.

Data formats are most effectively governed by national and international organizing bodies, which require close international coordination among data providers and users. For new data formats to be adopted as recognized WMO standards, relevant experts will need to: (1) develop and agree on the wxUAS data and metadata model; (2) define, test and document the data representation format; (3) complete the WMO process for adoption of new data representation standards and (4) promote and facilitate use and availability of the data format by UAS operators and data users. Additionally, consideration needs to be given to the development and availability of converters between standards in the case that more than one is adopted.

4.2.1.2 Current status and improvements needed

There is currently no internationally recognized standard data format for wxUAS meteorological measurements. A netCDF (network common data form) standard specifically for wxUASs, and which is climate and forecast (CF) compliant, has been developed and shared with participating wxUAS operators.

These activities have been discussed in the United States within ASTM, focused on developing standards for supporting routine UAS operations (ASTM, n.d.). Similarly in Europe, the PROBE Cost Action UAS task team is working to develop standards for application of wxUASs in operational meteorology (PROBE Cost Action, n.d.). Another aim of the PROBE UAS task team is to engage industry and potential wxUAS data users in the discussion around data quality and operational requirements.

Such efforts can be most efficiently and effectively accomplished through the development and use of testbeds, followed by wider demonstration of the operational capability in coordinated campaigns. Widespread adoption of the new internationally agreed standard is required to enable operational use by modelling centres and NMHSs. Also needed is the development of a converter to translate between operationally accepted data formats such as the Binary Universal Form for the Representation (BUFR) of meteorological data.

4.2.2 ***Data availability and delivery to users***

4.2.2.1 **Requirements**

That the data must be reliably made available in near real time is critical to the usability of wxUAS observations for operational meteorology. To be of most benefit to NMHS forecasters and to serve as input to regional mesoscale prediction models, this means observations must be available within roughly an hour of collection (Houston et al., 2020). For use in global models, data latency of up to 3 hours may be acceptable, depending on the DA cycling period and the period between forecast updates.

Making the data widely available for access (in a timely manner) by all potential users will increase the likelihood that NWP centres or private companies can justify the effort to monitor, assimilate and evaluate this new source of measurements from wxUASs.

Also critical to data availability is the integration of communications technology to support routine transmission of wxUAS observations while in flight or immediately after flight for dissemination on WIS.

4.2.2.2 **Current status and improvements needed**

Much of the efforts relating to data representation and data availability need end-to-end demonstrations to establish linkages among the wxUAS development efforts, operational meteorologists and modelling centres. This will facilitate evaluation of the potential benefits of more widespread implementation of wxUASs.

To minimize data latency, additional development efforts are needed to establish routine air-to-ground communications. One method for doing this might be through Automatic Dependent Surveillance–Broadcast (ADS-B). Over the next few years in Europe every UAS over 0.25 kg must have an e-signature and have the capability to transmit the required metadata (height/course/speed). Every UAS over 0.9 kg will have to carry an ADS-B transponder and could potentially transmit weather data automatically. These transmission requirements could be exploited to provide a means of transmitting meteorological data along with other required fields.

This approach will require on-board data processing (such as averaging and quality control) to reduce data rates. The transmission of these data will also require close coordination among wxUAS operators and the corresponding regulatory bodies as data transmission standards are developed and adopted.

4.2.3 ***Technical regulations and guidance***

4.2.3.1 **Requirements**

Part of the process of integration of observing systems into any operational framework is to establish and document standards. These should ensure observations are fit for purpose and meet the requirements for interoperability so as to meet the needs for a range of applications.

Within the WMO WIGOS regulatory framework, this means the development and integration of a range of standards and best practices into WMO technical manuals and guidance materials, including those aspects covered herein.

4.2.3.2 **Current status and improvements needed**

WxUASs are not currently integrated into WIGOS as an operational component system. Therefore, there will need to be a concerted effort within the WMO technical framework to develop and document the necessary standards and best practices to support NMHSs and other third-party data providers in establishing operational practices and procedures and in their provision of wxUAS data. This work can be undertaken in a parallel and phased approach, along with the necessary technological and airspace regulatory development required.

4.2.4 *Integration into user applications*

4.2.4.1 Requirements

Integration into user applications will require interactions between wxUAS operators and data users. The data users will need to determine whether or not the wxUAS observations will have a significant impact within their application areas. This will require benefits assessment studies that can be applied to any application area including the impact of wxUAS observations on the skill of NWP.

Pilot studies have hinted at the potential benefit of wxUAS observations in operational meteorology and other related applications. However, wide-scale and long-term provision of wxUAS observations in standardized formats is needed to facilitate integration into existing operational modelling systems, displays and decision support tools before their full utility can be realized and quantified.

4.2.4.2 Current status and improvements needed

Thus far, the integration of wxUAS observations into existing systems has been relatively ad hoc. It has revolved around small-scale pilot studies and larger, yet limited, field campaigns in which integration of wxUAS observations into models and other applications has been done offline. In addition, attempts to standardize data formats and metadata across wxUAS platforms have not been completely successful owing to the lack of published and internationally agreed-upon data formats.

Standardization of data formats, provision of data to potential users in real time and broader-scale demonstrations are needed to facilitate the integration of wxUAS observations into modelling systems and other user applications.

Direct linkages between wxUAS operations and end users during a large-scale demonstration campaign (modelling centres and meteorologists) are needed.

Furthermore, an assessment of the potential benefit of wxUAS observations in relation to their cost will be required to determine whether or not this new observational capability should be fully adopted.

4.3 Pathways towards routine operational use

There are several potential pathways for establishing wxUASs in support of operational meteorology. One pathway already being evaluated is the use of wxUASs to conduct targeted sampling of areas where high-impact weather is expected to develop. Such efforts may be funded by national centres or private companies.

For example, NOAA has studied the potential for using wxUASs to gather observations within tropical cyclones to aid in short-term predictions of storm intensity. Data collected from expendable Coyote glider dropsondes released from NOAA P3 aircraft have been supplied to NHC in near real time, and have been used to evaluate model simulations (Cione et al., 2016, 2020). Frew et al. (2020) have demonstrated the potential for using wxUASs to perform targeted sampling of precursor and surrounding environmental conditions to aid the prediction of supercell storm severity. In addition, Leuenberger et al. (2020) have demonstrated using targeted-in-time wxUAS observations to aid in the model predictions of river valley and radiation fog.

Another pathway to operations that has been proposed is to co-locate wxUAS profiling sites with existing surface observing networks (Chilson et al., 2019). This type of implementation takes advantage of existing infrastructure to extend surface layer observations into the boundary layer and above, depending on regulatory permissions. This 3D Mesonet concept requires launch-to-land-to-recharge automation, robust and reliable airspace deconfliction systems that include detect-and-avoid capabilities so systems can fly to BVLOS altitudes, and one-pilot-to-many UAS flight operations. Each of these aspects of an autonomous network of profiling wxUASs is maturing and entering into the deployment and evaluation stage.

There are networks of surface observing stations in many parts of the world that could be leveraged to follow this approach. These include the National Weather Service's Automated Surface Observing System in the United States and the Met Office's Automatic Weather Station network in the United Kingdom of Great Britain and Northern Ireland, among many others. NMHSs, local governments and/or the private sector generally finance and operate Mesonets. Depending on resources and funding mechanisms, there may be opportunities for cost sharing that can help build out wxUAS observing capabilities. As wxUASs become more reliable and easier to maintain, they will become more cost-effective than radiosondes (particularly in the face of global hydrogen and helium shortages, which have increased radiosonde costs worldwide).

Another pathway to operations would be to leverage the established global network of radiosonde sites by using wxUASs to fill temporal gaps between radiosonde launches. Such operations could be targeted for times and periods when additional profiling would be expected to improve prediction of high-impact weather. At these sites, there is existing airspace clearance to launch balloons carrying radiosondes at specified times each day. This could possibly be expanded and extended to the use of wxUASs. This approach could be potentially easier to implement initially than the 3D Mesonet idea since radiosonde launch sites already have some level of flight clearance and are typically situated in areas away from commercial flight paths. Supplementing the twice daily radiosonde launches with hourly or more frequent wxUAS profiles would be beneficial to NWP, particularly if wxUAS observations are made when rapidly changing conditions are expected.

Observations could also be obtained from UASs whose primary mission may be a commercial application like medical supply delivery or traffic surveillance. This method of data collection is referred to as "opportunistic", akin to data collected from citizen weather stations (Nipen et al., 2020), weather data collected by road vehicles and inferring weather conditions via traffic cameras.

Access to observations from commercial UASs could greatly increase the coverage of observations in data-sparse regions of the lower atmosphere. In fact, Robinson et al. (2020) posit that perhaps all emerging modes of autonomous aerial transportation should be required to report standard atmospheric variables to be allowed entry into regulated airspace. However, access to these datasets will be challenging owing to potentially proprietary considerations such as frequency and location of operations. It may also be challenging to obtain information regarding observational error and biases, calibration methods (or lack thereof) and details/consistency of sensor package mounting on commercial UASs, which could affect the utility of the observations they collect.

Nonetheless, some commercial operators may find there is additional value by providing accurate quality-controlled observations to modelling centres to improve weather predictions. Such an approach has been taken in the past for AMDAR weather observations that are now routinely collected by commercial aircraft and downlinked in real time for use by NWP modelling centres (Benjamin et al., 2010; Peterson, 2016).

Finally, there will be opportunities for data sharing and developing new cost models to determine the value of UAS-based weather observations in the private sector. These models will vary around the world. For example, in the United States, government-supported weather data are typically available for free, while in Europe, governments typically charge private industry for access to weather data. Agreements will likely need to be developed once the value of weather data collected by commercial entities is better quantified. At the same time, data-sharing agreements may be highly desirable since the new observations could lead to improved weather prediction, resulting in a win–win solution for all stakeholders involved.

5. PLANS FOR A GLOBAL DEMONSTRATION

Before wxUASs can be widely implemented for use in operational meteorology, there are many aspects of implementing wxUASs operationally that need to be evaluated and advanced. To support this advance towards operational integration of wxUASs, it has been proposed to undertake a large-scale, internationally coordinated global demonstration campaign.

The WMO UAS Demonstration Campaign (UAS-DC) would facilitate a large-scale cost–benefit analysis of wxUAS capabilities, analysis of performance characteristics and measurement of the impact of wxUAS observations on weather prediction (UAS Demonstration Campaign). The campaign is expected to be based on the establishment and use of wxUAS testbeds and other approved sites, to demonstrate their capacity to routinely provide observations of key meteorological variables over a suitable period of time.

Such a demonstration of wxUAS performance, along with analysis of observational data accuracy and impact on numerical model skill, could provide input to a business case to help NMHSs determine where wxUASs add the most value, assist manufacturers in tailoring their products, and also allow data users to prepare for the availability of such data in the future. Based on the outcomes of the campaign, WMO and NMHSs would better understand whether wxUASs could serve as an additional operational component of WIGOS under the Global Basic Observing Network (GBON).

Under its Commission for Observation, Infrastructure and Information Systems, WMO is developing plans to coordinate a global wxUAS demonstration campaign during 2024 (UAS Demonstration Campaign). The aims are to:

1. Demonstrate the current capabilities of a range of wxUASs and to measure their capacity to contribute to meeting operational requirements for upper-air observations and the filling of observational gaps of WIGOS GBON and/or the Regional Basic Observing Network;

2. Demonstrate the capacity of wxUASs and their data-processing systems to provide data in an interoperable format ready for use by relevant applications and forecast systems;

3. Measure, analyse and report on the impacts of wxUAS observations on relevant WMO application areas and forecast systems;

4. Determine more generally and report on areas of development needed for wxUASs to adequately meet requirements to efficiently, economically and environmentally responsibly contribute operationally to WIGOS;

5. Determine and make recommendations relating to regulatory conditions imposed on wxUASs that affect their ability to contribute to WIGOS.

The campaign is planned for a 6 month period from March to August 2024. This period was chosen to allow for adequate planning time and resourcing while at the same time overlapping with the 2024 Paris Olympics in July/August. This event is expected to include a major European focus on demonstrating the latest observing systems and modelling capabilities.

UAS-DC will consist of at least two special observing periods (SOPs) of 1 month duration, during which time wxUAS operators will make best efforts to undertake a more intense observing cycle at a greater number of sites. These SOPs are expected to take place towards the middle and end of the campaign, possibly one in May and the other in August 2024. Throughout the campaign, operators will be encouraged to collect and provide multiple profiles each day, and to provide the data in a standardized format in near real time for dissemination on WIS so they are available for utilization by research and operational modelling centres.

It is expected that participating wxUAS operators will collect, at a minimum, observations of temperature, pressure and humidity. The provision of wind measurements is also highly desirable. Participants will need to adopt the standardized data format (described below and on the UAS-DC website), and also provide relevant metadata and information on data quality.

A key aspect of UAS-DC will be the collection of observations in areas and at times of the day so as to fill observational data gaps. This might include, for example, conducting profiles at a radiosonde site between sounding launch times or to provide observations where radiosonde launches have been discontinued due to helium shortages or other issues.

Operators would also be encouraged to conduct profiles in remote locations or in areas of complex topography where subsynoptic variability in the atmosphere may be important for improving the initial conditions for mesoscale modelling systems. Operators could also collect targeted observations in areas where rapidly evolving conditions are anticipated to either support weather forecasters and/or for use in improving the initial conditions for regional weather prediction systems.

The establishment of a wxUAS data representation standard is a critical component and outcome of UAS-DC. Through discussions with wxUAS operators and data users, it was decided to initially focus on the development of a CF-compliant netCDF data representation format to be used by operators. A first data format description has been proposed and is described on the UAS-DC website (UAS Demonstration Campaign UAS Data Representation Standards). This data format will facilitate ease of use by the general atmospheric science community and can easily be converted to other formats such as WMO BUFR, which is currently used by operational modelling centres around the world.

An important consideration for the campaign and as an outcome will be improved access by wxUASs to additional airspace, to enable vertical profiling through at least the first 2 km of the atmosphere and beyond. There has been some progress working with regulators to enable flights of up to 6 km at some locations and in special circumstances through the acquisition of waivers. However, national-level coordination with regulators will be required. An expected outcome of the campaign will be to better understand how to work with airspace regulators and the benefits that might be realized through improved access to the airspace under the relevant international and national regulatory frameworks.

Participant data users will be engaged to use and test the impact of the wxUAS data generated by the campaign, during and after the event, and within operational and developmental NWP systems and applications. Based on this interaction, data user participants will be able to assist in analysing and improving the operational aspects of wxUASs and the quality of the data produced.

The compilation and provision by the campaign participants of reports during and after the campaign observing period will be of critical importance to the campaign and its desired output and outcomes. Such participant reports will be used to:

- Adjust and improve the campaign parameters and requirements during the campaign, as necessary, and in the interests of improving observational outputs and data use

- Measure, assess and report on the impact of wxUAS observations by data users

- Contribute to the final reports to be produced by WMO after the campaign is completed

- Analyse the capabilities of wxUASs to contribute observations to WIGOS and GBON and make related recommendations for future actions

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

It is evident that wxUASs have a current and developing future role in the operational and research domains of meteorological, hydrological and climatological science and monitoring. There will be opportunities for NMHSs to form partnerships with private sector organizations, entities and individuals to obtain meteorological data from wxUASs and other commercial UASs that incidentally collect high-quality weather observations.

In addition to the wider incorporation of wxUASs into the observing systems of NMHSs, it is likely that the private sector will play a role in implementing wxUASs that could also be used by NMHSs. The private sector may implement wxUASs specifically for environmental monitoring, or within some other commercial application (for example, medical supply delivery) in which environmental observations are collected and transmitted either voluntarily or as a paid service.

As UASs continue to expand in their usage and range of applications, it will be important for meteorological services to seek potential partnerships where meteorological observations can be provided at a reasonable cost. As many modern meteorological applications have requirements for high-density observational networks, this emerging new opportunity for meteorological data could help fill the current observational gap. For example, there are opportunities in the expanding industry of delivery drones that could potentially provide large volumes of weather observations under a suitable cost-sharing model.

The management of data obtained or provided under such partnerships requires consideration of a range of issues, including data transmission, quality control, security, privacy and storage. WMO is considering how to facilitate and coordinate the advancement of such partnerships through UAS-DC and the development of standards and mechanisms for data collection and sharing.

With the cost of wxUAS operations and maintenance continuing to decline and as UASs incorporate the use of “greener” technologies, the economics of using wxUASs to observe the lower atmosphere on an operational basis are increasingly compelling. In the near future and likely within the next decade, observations collected with wxUASs will provide new information to aid forecasters in developing short-term predictions of high-impact weather by providing observations in data-sparse regions and between radiosonde soundings.

These observations will likely also be a key driver in advancing the accuracy of mesoscale analyses and weather prediction by helping to fill observational data gaps. As with any new observing system, wxUASs will need to continue to gain acceptance by the scientific community, modelling centres, operational meteorologists and society in general through research activities, publications, testbed demonstrations and public outreach.

6.2 Recommendations

6.2.1 *Provide support for the WMO Uncrewed Aircraft System Demonstration Campaign*

The focus of UAS-DC is on demonstrating the capacity for wxUASs to meet the vision for their future role in WIGOS. This campaign is already fostering collaboration among stakeholders around the world. However, its success is critically linked to wide participation by wxUAS operators and by potential users of these new observations. WMO calls upon wxUAS and environmental data user scientific communities to support this endeavour.

6.2.2 *Foster wider adoption by National Meteorological and Hydrological Services for operational deployment in observing systems*

WxUASs have the ability to fill a significant gap in the global observing system. They can significantly increase sampling of the lower atmosphere to serve the development of short-term weather and water guidance products. They can also provide higher spatio-temporal resolution of the thermodynamic and kinematic structure of the lower atmosphere. NMHSs are encouraged to investigate ways in which wxUASs can be integrated into their observing systems, based on partnerships with suppliers, academic research and research supported by government agencies and third-party operators.

6.2.3 *Further evaluate and develop technology towards improved operational efficiency and capability*

As with any new observing system, the technology needs to be thoroughly reviewed and accepted by the scientific and operational communities. For this to occur, the capabilities and efficiencies of UASs need to be well demonstrated and proven through ongoing research and demonstration campaigns, such as WMO UAS-DC. WxUAS developers, vendors and operators should use the results to improve wxUAS technology to meet technical and functional requirements for their rapid integration into WIGOS.

6.2.4 *Continue evaluation of observational data by the user community*

Significant global efforts have been made to evaluate wxUASs for improved understanding of land–atmosphere interactions and severe storm dynamics, and, more recently, to improve the initial conditions and short-term model predictions of winds and high-impact weather. These studies expand the range of conditions under which wxUASs have been applied, and have demonstrated the potential benefit to operational meteorology.

With the near-future availability of a WMO wxUAS data exchange standard, NWP and other data user communities are encouraged to analyse wxUAS observations and their impact on environmental modelling and other applications. These impacts should be reported in peer-reviewed literature, trade articles and other technical documents.

6.2.5 *Encourage wider deployment in existing and new testbeds and campaigns*

The development of wxUAS research testbeds is critical for demonstrating wxUAS technologies and potential benefits to operational meteorology and NWP. NMHSs and partner research institutions are encouraged to make wider use of wxUASs in new and existing testbeds and to develop and obtain the required permissions for their deployment.

6.2.6 *Promote increased and less-restricted access to airspace of the lower troposphere for research campaigns and meteorological operations*

Ultimately, the future utilization of wxUASs in operational environmental monitoring programmes requires airspace regulators to accommodate their access to airspace in the lower atmosphere (nominally up to 2 km AGL). This increased accessibility to the lower atmosphere will be highly dependent on UAS operator ability to demonstrate achievement of safety standards and an ability to meet any other regulatory requirements developed by airspace regulators.

Airspace regulators are encouraged to work with NMHSs, research agencies, wxUAS vendors and operators, and relevant governmental agencies to develop and communicate improved and less-restricted regulatory conditions for wxUASs to be tested and implemented within operational observing programmes.

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