The Status and Future of Small Uncrewed Aircraft Systems (UAS) in Operational Meteorology

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Capsule

Small weather-sensing Uncrewed Aircraft Systems are becoming reliable and accurate enough to be considered as a cost-effective solution for filling observational gaps that could enhance National Meteorological and Hydrological Services around the world.

Abstract

The boundary layer plays a critical role in regulating energy and moisture exchange between the surface and the free atmosphere. However, the boundary layer and lower atmosphere (including shallow flow features and horizontal gradients that influence local weather) are not sampled at time and space scales needed to improve mesoscale analyses that are used to drive short-term model predictions of impactful weather. These data gaps are exasperated in remote and less developed parts of the world where relatively cheap observational capabilities could help immensely. The continued development of small, weather-sensing Uncrewed Aircraft Systems (UAS), coupled with the emergence of an entirely new commercial sector focused on UAS applications, has created novel opportunities for partially filling this observational gap. This article provides an overview of the current level of readiness of small UAS for routinely sensing the lower atmosphere in support of National Meteorological and Hydrological Services (NMHS) around the world. The potential benefits of UAS observations in operational weather forecasting and numerical weather prediction are discussed, as are key considerations that will need to be addressed before their widespread adoption. Finally, potential pathways for implementation of weather-sensing UAS into operations, which hinge on their successful demonstration within collaborative, multi-agency-sponsored testbeds, are suggested.

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A significant *in situ* observational gap resides in the lower atmosphere which encompasses the surface layer, atmospheric boundary layer and lower free troposphere (National Research Council 2009; National Academies of Sciences, Engineering, and Medicine 2018; Geerts et al. 2018; NOAA 2020). This observational gap is most acute in remote locations and is further exacerbated in less developed regions of the world (WMO 2018). A schematic representation of this *in situ* observation gap is shown in Figure 1. While surface meteorological stations including airport-based observing stations and mesonets provide good spatio-temporal near-surface coverage over land areas in developed countries, radiosondes are launched just twice daily and are generally spaced over 300 km apart. Thus, radiosondes alone greatly under-sample mesoscale and diurnal variability of the atmosphere. While aircraft-based observations (which may be obtained via AMDAR, TAMDAR, ADS-B, Mode S) can capture diurnal variations of the lower atmosphere (Zhang et al. 2019), these observations are confined to arrival and departure ascent/descent legs at major airports and have reduced temporal coverage overnight.

Radar networks and satellite observations help to fill these *in situ* observational gaps, but these remote-sensing platforms also have limitations. Doppler weather radar networks (e.g., U.S. NEXRAD) require the presence of scatterers (bugs, precipitation) for sensing velocities, provide limited thermodynamic information and have significant gaps in coverage at lower altitudes, particularly in mountainous areas. Moreover, advanced radar networks are not available in many parts of the world because they are expensive to operate and maintain. While geostationary satellites provide outstanding horizontal and temporal sampling of multi-channel radiances, retrievals of thermodynamic properties of the lower atmosphere are too coarse to resolve horizontal variability important for short term predictions and are often hindered by the presence of clouds (e.g., Wulfmeyer et al. 2015).

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Reducing gaps in the observation of thermodynamic and kinematic properties of the lower atmosphere is critical for achieving more skillful mesoscale predictions of high-impact weather. For example, the U.S. National Oceanic and Atmospheric Administration's goal of developing a Warn-On-Forecast capability (Stensrud et al. 2009, 2013) hinges on improved observation of the lower atmosphere at space and time scales relevant for accurately predicting hazardous severe weather at the county scale. Temporal and spatial gaps in existing observing systems contribute to model forecast uncertainty (e.g., Dong et al. 2011; James and Benjamin 2017; James et al. 2020). In fact, the maximum skill of regional numerical weather prediction (NWP) models will not be realized until spatio-temporal sampling of the lower atmosphere is comparable to the model's effective resolution (Dabberdt et al. 2005).

Operational meteorologists have also pointed to the need for increased observation of the lower atmosphere to improve the accuracy of short-term (< 24 hour) forecast guidance products (e.g., Houston et al. 2020, 2021). Surveys of operational meteorologists in the U.S. have indicated a need for increased sampling of remote environmental locations during periods of rapidly changing conditions (e.g., evolution of temperature, moisture, wind profiles in pre-convective environment) to improve their short term forecast products (Houston et al. 2020, 2021). Moreover, the dearth of lower-atmospheric observations is particularly significant in less developed regions of the world, making it particularly challenging for both NWP models and NHMS meteorologists to produce accurate short-term forecasts of high impact weather events like severe thunderstorms (e.g., Woodhams et al. 2018) and dust storms (e.g., Wang 2015).

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In the late 1990s, small Uncrewed Aircraft Systems (UAS)[1] began to emerge as a new system for obtaining *in situ* measurements within the lower atmosphere (Holland et al. 2001; Curry et al. 2004). Note that the term “Uncrewed” is used to remove gender specificity following Bell et al. (2020), and is our preferred terminology for describing these aircraft systems. Here, the term “small UAS” refers to a class of autonomous aircraft weighing less than 25 kg (55 lbs) as defined by Federal Aviation Administration’s (FAA) Part 107 regulation (and similar European laws). In the last 10 years, the number of research programs focused on the development of UAS and UAS weather-sensing capabilities has flourished. At the same time, commercial applications for small UAS has grown dramatically (e.g., Gangwal et al. 2019; Rigby 2020) with this trend being expected to continue for several years (FAA 2020).

Today’s small weather-sensing UAS (hereafter referred to as WxUAS following Chilson et al. (2019) and Bell et al. (2020) are nearly 100% reusable (as opposed to radiosondes of which only 20% are recovered and a smaller fraction reused), can rapidly sample the lower atmosphere, are powered with batteries that can be recharged using locally generated solar energy, and are extremely adaptable; capable of flying targeted missions or performing routine systematic profiling (Elston et al. 2015). The term WxUAS is used here to distinguish between UAS that are dedicated to observing the atmosphere and those that may collect atmospheric data coincidentally while performing some other primary service (e.g., commercial delivery).

Recent development efforts have resulted in the production of fully autonomous systems that can automatically progresses through all stages of flight including take-off and landing, profiling, system checks and recharging (Leuenberger et al. 2020). Special permissions have been

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[1] Also known as drones, remotely piloted aircraft or unmanned aircraft systems.

obtained to allow WxUAS to fly up to 6 km AGL enabling sampling of rapidly varying weather features with high vertical resolution over a deep layer of the atmosphere (Figure 2). In this example, a profiling Meteodrone WxUAS (using Meteomatics Meteobase for automatic recharging) captured the evolution of temperature, humidity and winds during a recent fog evolution study. Note the deepening layer of relative humidity exceeding 90% just above the surface associated with a shallow layer of northeasterly winds. In addition to reliability and efficiency, the accuracy of wind, temperature, and humidity measurements obtained with WxUAS is now comparable to that of calibrated tower and radiosonde measurements (e.g., Leuenberger et al. 2020; Bell et al. 2020) with the consistency of observational errors also improving (Barbieri et al. 2019). These attributes, coupled with decreasing costs of UAS production, operation, and maintenance, are making WxUAS an economically viable option for use by NMHS to fill observational data voids (e.g., McFarquhar et al. 2020).

While the utility of WxUAS for collecting research quality datasets within the lower atmosphere is now well established (e.g., Houston et al. 2012; Elston et al. 2015; Bärfuss et al. 2018; de Boer et al. 2018; Vömel et al. 2018; Kral et al. 2020), their use in operational meteorology has been limited due, in part, to limitations on the accessibility of airspace for land-based flights (Houston et al. 2012), measurement accuracy, and the accessibility of data to forecasters (Koch et al. 2018). In recent years, UAS and WxUAS flights over land areas have become common-place (e.g., Chilson et al. 2019; Lee et al. 2019; Lee and Buban 2020; de Boer et al. 2020; Bailey et al. 2020; Frew et al. 2020) but linkages to operational meteorology have only just begun (Koch et al. 2018). Koch et al. (2018) found that forecasters didn’t use WxUAS observations to full effect because the data were not integrated into their operational display tools. In a separate, short-duration testbed, Cione et al. (2020) attempted to demonstrate the utility of WxUAS observations

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in short-term hurricane forecasting by providing WxUAS observations within the boundary layer of hurricanes (including their eyewalls) to NOAA's National Hurricane Center (NHC) in real time. These initial exercises by Cione et al. (2020) were critical for assessing the readiness of WxUAS and other system technologies (e.g., communications, flight systems, airframe design) required to permit the collection and transmission of unprecedented targeted measurements to hurricane forecasters, and pointed to the need for additional research and development efforts.

WxUAS observations can also influence operational meteorology and NHMS through their assimilation into operational numerical weather prediction models. As will be discussed briefly below, several studies have demonstrated the benefit of assimilating WxUAS observations into regional NWP research models; however, additional research is needed to fully assess their potential. Work is also needed to establish direct lines of communication between WxUAS and operational modeling centers such that the values of these new observations can be assessed in an operational environment.

The goal of this paper is to discuss the main factors influencing the adoption of WxUAS by NHMS. The role that recent, current, and planned testbed demonstrations will play in facilitating the potential adoption of WxUAS by NHMS is discussed. Finally, potential pathways from WxUAS testbed demonstrations to operational meteorology are proposed and recommendations for getting involved in the research-to-operations process are given.

FACTORS INFLUENCING THE PATH TO OPERATIONS FOR WxUAS. The adoption of WxUAS by NHMS will only occur if the value of improved forecasts and resulting support services significantly exceeds the cost of implementation. Because of massive investments in developing UAS technologies over the past 10 years by private industry, governments, and university research groups, the cost of WxUAS has decreased dramatically (Belton 2015; Nath 2020). The current cost of operating a WxUAS, particularly due to the requirement of one pilot per UAS and, in many cases, the need for human observers to meet sense-and-avoid (SAA) requirements, drives a relatively high cost to operate. However, progress toward widespread autonomous WxUAS flight without direct human management is being made via allowances for beyond visual line of sight (BVLOS) flight (Jacob et al. 2020) through both SAA technologies which requires intercommunication between UAS and detect-and-avoid (DAA) systems (Mitchell et al. 2020) which use sensors to detect obstacles (e.g., power lines, cell towers, other UAS, and piloted aircraft) and do not rely communications with other UAS to maintain air space separation.

While the cost associated with implementing WxUAS continues to decline, an increasing number of studies have demonstrated that WxUAS data assimilation (DA) can improve the skill of mesoscale weather predictions. An Observing System Experiment (OSE) study by Leuenberger et al. (2020) showed that the assimilation of WxUAS observations improved the short-term prediction of radiation fog events. Jensen et al. (2021a,b) used OSEs to demonstrate that WxUAS DA dramatically reduced biases in the analyses of low- and mid-level moisture and winds that were critical for more accurately predicting the timing and location of thunderstorms and subsequent outflows. An example of the impact of WxUAS DA on improving the representation of the pre-convective environment and subsequent storm prediction is shown in Figure 3. Here the assimilation of observations collected with several distributed profiling WxUAS (see Jensen et al. 2021b for details) reduced biases in both temperature and moisture profiles that 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) that demonstrated the value of WxUAS DA in predicting thunderstorm evolution. Both Jensen et al. (2021b) and Moore (2018)

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demonstrated the value of assimilating targeted profile of winds, temperature and humidity using WxUAS to improve prediction of storm evolution compared to that obtained when assimilating conventional observations alone.

While these results demonstrate the potential for UAS DA in NWP and hint at some of the requirements for data accuracy and sampling strategies, a great deal of work remains to assess the effectiveness of UAS DA across a range of challenging high impact weather prediction scenarios. In addition, strategies for implementation of WxUAS within an operational environment, with or without subsequent DA, need to be developed via close coordination with NHMS and operational forecast offices (Houston et al. 2020, 2021). Much of these efforts are in need of end-to-end testbed demonstrations that can help facilitate the establishment of linkages between WxUAS development efforts, operational meteorologists, and modeling centers.

DEMONSTRATION TESTBEDS. While there have been a few short-duration testbed demonstrations that looked at the use of WxUAS in operational environments (e.g., Koch et al. 2018; Cione et al. 2020), these testbeds have been limited in scope and duration. Longer duration testbeds of increasingly broader scope are needed to more completely assess the utility of WxUAS in operational environments. Such testbeds can also be used to develop data protocols, requirements, and standards (e.g., de Boer et al. 2020). Several testbeds described below are already underway or planned that will further facilitate research-to-operations of WxUAS. Key goals of these testbeds are to establish connections between the UAS operators and the weather enterprise and to facilitate interactions between the WxUAS developers, commercial UAS operators, operational meteorologists, and other stakeholders.

The NOAA Air Resources Laboratory (ARL) Atmospheric Turbulence and Diffusion Division (ATDD) in Oak Ridge, Tennessee has established a long-term WxUAS testbed to demonstrate the benefit of routine WxUAS observations to operational meteorology, to perform calibration of WxUAS observations, and to support boundary layer research. As part of this testbed, WxUAS are being used to obtained up to 8 profiles per day that are transmitted to the Morristown, TN Weather Forecast Office (WFO) in near real time to support their short-term forecast desk (Figure 4). As of this writing, over 350 flights have been performed for Morristown forecasters which is located 80 km away from the nearest radiosonde site. Forecasters have reported that the WxUAS observations have improved their understanding of local processes that contribute to boundary layer evolution and indicated that, once fully implemented into the forecast process, the high rate, local observations afforded by WxUAS would lead to greater skill and specificity of short term forecasts of winds, fog, and thunderstorms initiation needed to produce the Terminal Aerodrome Forecasts (TAFs).

In Finland, researchers at FMI (Finnish Meteorological Institute) have been operating a WxUAS testbed since mid-2020, collecting 1-2 profiles every hour during the day. These WxUAS observations are being validated against radiosonde observations. Work is also underway to establish a real-time feed of WxUAS data to Météo-France and eventually to the European Center for Medium-range Weather Forecasting (ECMWF) to facilitate data assimilation studies. More broadly, the World Meteorological Organization (WMO) is organizing a year-long global demonstration period (starting as early as the Fall of 2022) geared toward increasing the visibility of WxUAS for use in operational meteorology and will work toward establishing international standards for data protocols and data quality criteria that will facilitate usage of WxUAS observations by major modeling centers (WMO 2021).

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Several WxUAS demonstration testbeds are currently being planned throughout the world over the next few years. A 6-month testbed focused on assessing the performance and reliability of WxUAS in strong winds and icing conditions will commence in Switzerland in November 2021. The WxUAS observations will be compared with conventional radiosonde and remotely sensed observations. Moreover, the WxUAS observations will be transmitted to MeteoSwiss in near real time for parallel DA studies designed to evaluate the impact of WxUAS observations on NWP skill. The Oklahoma State University is leading a team of universities and private partners to develop a weather-aware UAS Traffic Management (UTM) system similar to the concept described in the sidebar. As discussed in the sidebar, WxUAS, possibly along with commercial UAS, will collect and transmit observations of the lower atmosphere that will inform other UAS operating nearby of winds and other potential UAS hazards (Jacob et al. 2021). The WxUAS observations will be made available for assimilation into experimental NWP models to evaluate the impact of these observations on the accuracy of predicted low-level winds and other UAS weather hazards. Similar studies have recently been initiated in the U.K. and involve the U.K. Met Office (Stonor 2021).

The utility of data collected with WxUAS will be fostered by the establishment of common data formats and reporting standards. Interactions within testbeds are needed to help define metadata requirements, which might include details of how the data were collected (type of aircraft, commercial UAS vs dedicated WxUAS) and provide additional information on the data quality and level of post-processing. It will be important to coordinate these activities with those ongoing within the ASTM (not an acronym) International F38 UAS committee which is focused on developing standards to support routine WxUAS operations[2]. Similarly in Europe, the UAS

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[2] https://www.astm.org/COMMIT/SUBCOMMIT/F3802.htm

Task team within **PRO**filing the atmospheric **B**oundary Layer at **E**uropean scale (PROBE) initiative is working to develop standards and minimum data quality requirements for application to operational meteorology through industry engagement and testbed demonstrations (Cimini et al. 2020).

Testbeds can also be used to develop cost-sharing approaches that can be evaluated in a real world environment (see the sidebar). 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 plan and execute safe and efficient commercial UAS operations. Likewise, the cost of maintaining and operating a small fleet of WxUAS by a NHMS can be weighed against the value of increased lead time in the prediction of severe or high-impact weather or improved air quality forecasts.

Within these testbeds, experiments can be designed to tackle hurdles with moving WxUAS into operational use by NHMS. Some of the most pressing hurdles to widespread adoption of WxUAS by NHMS are discussed below.

HURDLES TO ROUTINE OPERATIONS. Key challenges to the adoption of WxUAS by NHMS around the world include the cost of implementing new technologies, limitations on the range of operating conditions under which WxUAS can operate, system reliability and measurement accuracy, regulatory limitations (which vary from country to country) and societal acceptance.

Cost. With the continued expansion of commercial UAS operations, the cost of acquiring components to build WxUAS has declined markedly in the past decade. Nonetheless, the cost of purchasing a fully autonomous WxUAS including an automated recharging system is roughly

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$100K with operations/maintenance adding roughly $20K/year. These costs compare favorably to the cost of radiosonde launches (including materials and labor) which has been estimated at around $300/launch or roughly $200K/year/site (depending on the number of special launches requested), though automated radiosonde systems are beginning to reduce some of the operational costs (Madonna et al. 2020). WxUAS offer the advantage of providing near-continuous profiling of the lower atmosphere at a fraction of the cost of radiosondes without the extra burden of polluting the environment with circuit boards and batteries that are seldom recovered. Moreover, as the reliability of WxUAS increases and automation continues to become more sophisticated, the cost of operations should continue to decline whereby, ultimately, a single operator will be able to monitor an entire fleet of autonomously profiling WxUAS.

Range of operating conditions. Assuming that permission can be obtained to operate BVLOS within and above cloud layers (as is already being demonstrated at some testbeds), the conditions most impactful to unhindered autonomous profiling of the lower atmosphere include in-flight icing (from snow, supercooled cloud droplets, and freezing precipitation) and excessive winds. Icing can cause light-weight, low-powered UAS to quickly loose lift causing the platform to drop from the sky (e.g., Roseman and Argrow 2020). Strong winds that exceed UAS airspeed and heavy rain exceeding aircraft lift capacity can also ground operations. Algorithms that can automatically detect these conditions (either directly by the UAS or indirectly using external observations like those from weather radar), warn operators, and automatically commence abort sequences are needed. Recent efforts to mitigate icing have been pioneered by Meteomatics who demonstrated an active icing mitigation system that heats the blades to prevent icing (Figure 5). While this new anti-icing capability enables safe operations within some icing conditions, such capabilities need

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to be further developed and fielded in testbeds to determine the true range of safe operating conditions.

Reliability and accuracy. Related to that discussed above, work remains to demonstrate the reliability of fully autonomous WxUAS under a range of environments (Petritoli et al. 2018). Estimates for a required level of reliability must be developed based on perceived risk. The light-weight nature of WxUAS makes them very 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 the cost of operations and, as will be described further below, to support positive public perception. The accuracy of WxUAS measurements still varies significantly as a function of UAS type (fixed-wing versus multi-rotor), mounting, shielding and aspiration of the sensors, and wind retrieval techniques (Barbeiri et al. 2019). Standards for calibration and metadata requirements for WxUAS measurements must be established (e.g., Jacobs et al. 2018) and methods for on-the-fly evaluation of the quality of commercial UAS observations and possibly automated calibration methods are needed.

Regulatory challenges. For maximum effectiveness in thunderstorm prediction and other weather prediction scenarios, WxUAS will need to operate up to at least 1000 m AGL (Chilson et al. 2019) which is considered BVLOS. In the U.S. and Europe, UAS are generally allowed to fly up to 120 m AGL under Visual Line of Sight (VLOS) conditions by the FAA and the European Aviation Safety Agency (EASA) without requiring a waiver. Exceptions to VLOS and the 120 m AGL rules can be obtained in both the U.S. and Europe. In the U.S., this is done by obtaining a Certificate of Authorization (COA) from the FAA. In Europe, starting in 2021, a waiver that will permit BVLOS called a PDRA-01 (Pre-Defined Risk Assessment) may be obtained from the EASA. On a case-

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by-case basis, WxUAS have already been granted permission to fly up to 2 km AGL in the U.S. and up to 6 km AGL in Europe. However, in order to maximize the potential of WxUAS for operational meteorology, the process for obtaining these waivers needs to be streamlined and standardized. 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.

Sense-and-avoid technologies that minimize the risk of collision with other low-flying aircraft will further help alleviate regulatory restrictions. The development and implementation of sense-and-avoid and remote identification systems are already underway within the FAA UAS Traffic Management System Pilot Program (UPP)[3]. The outcomes of this work will lead to greater access to airspace above 120 m and further enable BVLOS operations in the U.S., paving the way for more routine WxUAS sensing of the lower atmosphere including the entire depth of the boundary layer. Once again, working with regulatory agencies (e.g., FAA) within a testbed framework will provide a safe environment for developing and testing protocols needed to integrate WxUAS operations with low-altitude crewed air traffic.

Societal acceptance. Another barrier that must be overcome in order to routinely operate WxUAS and to expand commercial uses for UAS is societal acceptance (Walther et al. 2019). UAS flights near homes and over people raise legitimate privacy and safety concerns. To address safety concerns, UAS operators must demonstrate that the risk of a UAS failure leading to injury or property damage is negligible. This can be done through proven mitigation engineering strategies and procedures such as equipping the UAS with a parachute and/or making them able to

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[3] https://www.faa.gov/uas/research_development/traffic_management/utm_pilot_program/

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disintegrate on impact. Privacy issues also need to be considered, particularly since forecasters have noted a desire to equip WxUAS with cameras to target and monitor rapidly evolving, high-impact weather conditions such as assessing whether convective cap is breaking or getting a view of supercell storm structure to evaluate severity (Houston et al. 2021). Significant outreach to educate the public will be required and can be achieved via testbeds. Additional steps such using consistent non-threatening colors that would make WxUAS readily identifiable by the general public would also help to alleviate public privacy concerns and mistrust.

Another notable aspect of UAS acceptance involves the development of regulations that promote national security. This aspect of UAS operations has been considered since the inception of UTM concepts (e.g., Kopardekar 2014). Remote identification technology will enable UTM system operators, as well as public safety or government agencies, to interrogate any UAS to determine its intent, operating parameters, and pilot information. Demonstrations of remote identification systems are planned for 2021 in the U.S. (Garret-Glasser 2020) and, where possible, should be coordinated with upcoming testbeds. Ultimately, this new remote identification system will be required by all UAS operating within the U.S. Resolution of security concerns will allow commercial UAS operations to expand while at the same time improving local, state, and national security, as well as the safety of the general public.

PATHWAYS TO OPERATIONAL IMPLEMENTATION. There are several potential pathways to implementation of WxUAS in support of operational meteorology. These pathways are being funded via research efforts at universities and government programs. For example, the U.S. NOAA has several ongoing programs designed to utilize UAS in support of their missions (uas.noaa.gov). Another approach could involve augmentation of existing surface observing

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networks with profiling WxUAS to create a three-dimensional mesonet (e.g., Chilson et al. 2019). This implementation approach takes advantage of existing infrastructure while offering a notable expansion of observational capabilities. Such augmentations could be implemented by NHMS, local governments, and/or the private sector. Depending on resources and funding mechanisms, there may be opportunities for cost sharing that can help build out WxUAS observing capabilities.

Another pathway for implementation may be through the introduction of targeted observations which take full advantage of the flexible nature of UAS. Under this approach WxUAS could be tasked to deploy to areas that drive uncertainty in the prediction of high impact weather event or to augment existing radiosonde launches with more frequent sampling of the lower-atmosphere in highly evolving weather scenarios. For example, multiple WxUAS could be deployed in the vicinity of a dry line to more accurately assess gradients, stability profiles and surface boundaries which can improve prediction of the location and intensity of severe thunderstorms. A recent survey of meteorologists revealed that targeted surveillance may be the preferred operational modality for forecasters in the U.S. (Houston et al. 2021).

A separate, yet potentially parallel pathway to operations for obtaining weather observations via UAS follows the Aircraft Meteorological Data Relay (AMDAR) model whereby commercial aircraft downlink weather observations for use by NWP modeling centers (Benjamin et al. 2010; Peterson 2016). Many commercial UAS that fly BVLOS already carry basic meteorological sensors that measure temperature and humidity in support of their operations (e.g., package or medical supply delivery). In fact, Robinson et al. (2020) posit that if even a small fraction of commercial UAS reported this weather information in the future this could have a profound influence on the safety and efficiency of their operations through improved situational awareness and improved weather guidance. As described in the sidebar, it will require additional infrastructure to get this weather information onto data servers where it can be made available to weather service providers, weather forecast offices, and modeling centers. Yet the benefits of these low costs are likely to pay for themselves many times over.

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. Commercial UAS may find that the weather data they collect can provide an opportunity for additional revenue. Agreements will need to be developed once the value of weather data collected by commercial UAS is better quantified. At the same time, data sharing may be an equitable approach whereby commercial UAS observations are provided to modeling centers and in turn weather prediction needed by UAS operators is improved, resulting in a win-win solution for all stakeholders involved (see Sidebar).

VISION FOR THE FUTURE. In addition to WxUAS observations improving weather prediction and supporting operational forecasters, UAS have demonstrated utility in a number of other NHMS services (see Manfreda et al. 2018 for a review of environmental applications). Specific examples of demonstrated capabilities include the use of UAS to perform detailed surveys of severe thunderstorm damage (e.g., Wagner et al. 2019), to assess the impact of tropical systems and synoptic storms on coastal erosion (Kaamin et al. 2016), and to monitor inland water body flooding (Imam et al. 2020; Dyer et al. 2020). UAS have also been used to collect measurements within volcanic plumes (Galle et al. 2020; Schellenberg et al. 2020) to assess the potential for hazardous air quality or volcanic ash impacts to passenger aircraft. These applications should

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continue to be explored and augmented through testbed demonstrations that facilitate partnerships between researchers and NHMS.

With the cost of UAS platforms, operations, and maintenance continuing to decline and as UAS move toward greener technologies (e.g., solar-powered battery recharging stations, more efficient engines, longer-lived batteries), the economics of using WxUAS to observe the lower atmosphere has become quite compelling. Efforts over the next five years should focus on establishing larger-scale testbeds that strengthen partnerships between WxUAS developers and potential stakeholders while at the same time facilitating the collection of observations over larger areas for a more complete assessment of potential benefits. In particular, the potential for serving as a means of filling observation gaps in less developed regions of the world should be explore in future demonstration testbeds. Commercial UAS operators can use testbeds to develop business models to determine the market value for weather observations through the demonstration of the impact of these observations on forecast skill (e.g., Zhang et al. 2016). The approach used here could be similar to that which unfolded with commercial transport aircraft observations via the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) program (Daniels et al. 2006).

While a number of smaller scale WxUAS testbeds have been undertaken, these endeavors need to be expanded in scope and duration in order to fully demonstrate the value of WxUAS observations in improving NHMS services. Key to furthering the use of WxUAS observations will be making the data available for modeling centers for use in side-by-side data assimilation experiments which is most easily done in a real-time environment. Having NHMS (both modeling centers and operational meteorologists) get involved with current and future testbeds will be critical for increasing the acceptance of this emerging source of weather observations. In addition, societal acceptance is also critical and should continue to be nurtured through outreach activities such as issuing press releases, talking to local news outlets, increasing presence on social media, holding public open houses during demonstration projects, and K-12 education opportunities (de Boer et al. 2020).

Given the rapid progress made over the last few years, there is little doubt that in the near future, WxUAS and commercial UAS will begin to fill the observational data gap in the lower atmosphere which will lead to significant advances in weather forecasting and the skill of regional NWP models.

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Sidebar SB1. WEATHER-AWARE UAS TRAFFIC MANAGEMENT SYSTEM

As commercial UAS operations continue to expand throughout the world, government regulatory agencies are working with aviation stakeholders and research partners to develop UAS traffic management systems (UTM) to organize and monitor this airspace. With small UAS being more susceptible to weather conditions than larger aircraft, a new suite of much higher resolution weather guidance products, such as that demonstrated by Pinto et al. (2021), will be needed to support UTM. The inclusion of tailored weather information in UAS flight path planning tools will aid in route optimization by helping operators find favorable winds that optimize power consumption along a user-defined flight path (yellow curve). Thus, it will be critical to improve the accuracy of low-level wind speed and direction analyses and forecasts at scales less than 1 km. In addition, more accurate prediction of weather conditions that are hazardous to commercial UAS operations (e.g., low ceilings or fog and areas of enhanced turbulence) will be vital for high mission success rates (Thibbotuwawa et al. 2020).

Weather prediction at sub-kilometer scales requires mesoscale-to-microscale coupling (e.g., Haupt et al. 2019). Operational mesoscale model predictions can be improved by filling the data gap in the lower atmosphere with observations obtained with WxUAS and commercial UAS. These new UAS-borne observations will be downlinked and transmitted to modeling centers to improve initial conditions used in their regional models (e.g., James and Benjamin 2017). Observations from dedicated profiling WxUAS may be used to complement existing observing networks like that of New York State Mesonet. Additional observations from commercial UAS would further increase data coverage and enhance forecast skill. In this way, commercial UAS can contribute to improving their own safety and efficiency while at the same time improving short-term weather prediction for the benefit of society.

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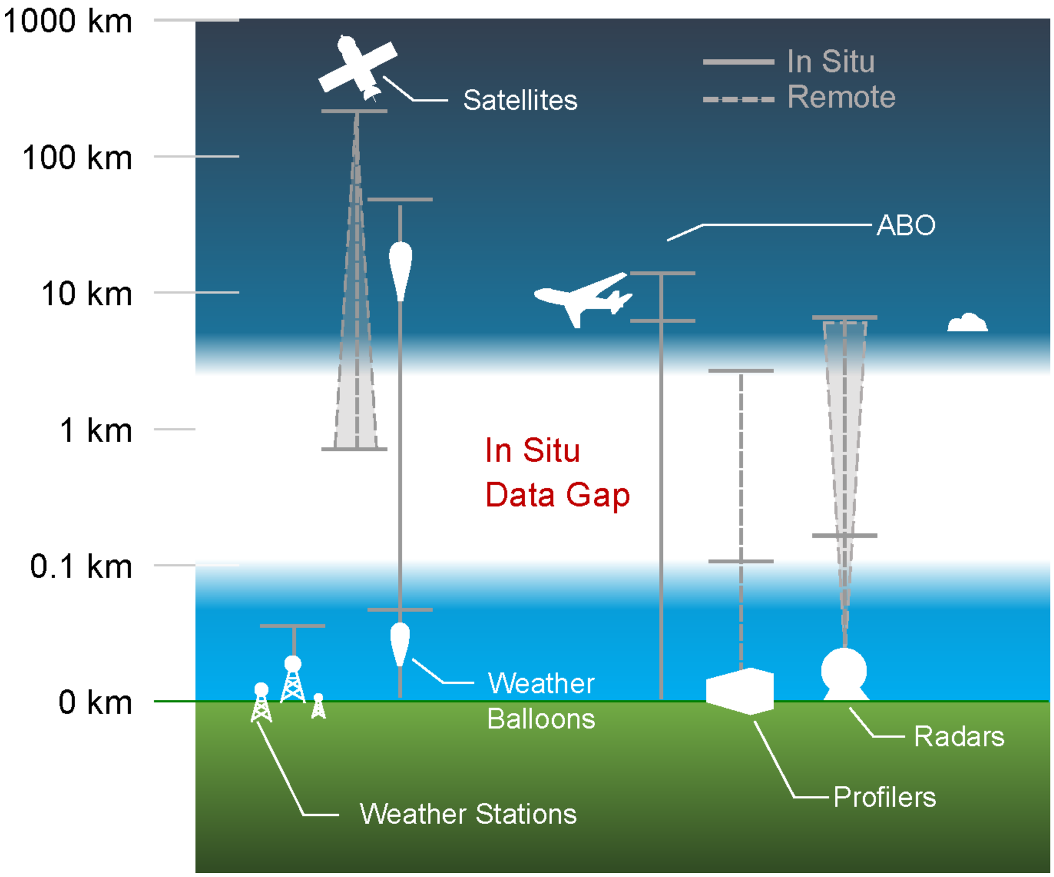


Figure 1. Schematic illustrating the *in situ* observation gap in the lower atmosphere. Horizontal lines indicate nominal regions of primary data collection. Diagonal lines indicate changing size of foot print with distance from remote sensor. ABO refers to commercial Aircraft Based Observations.

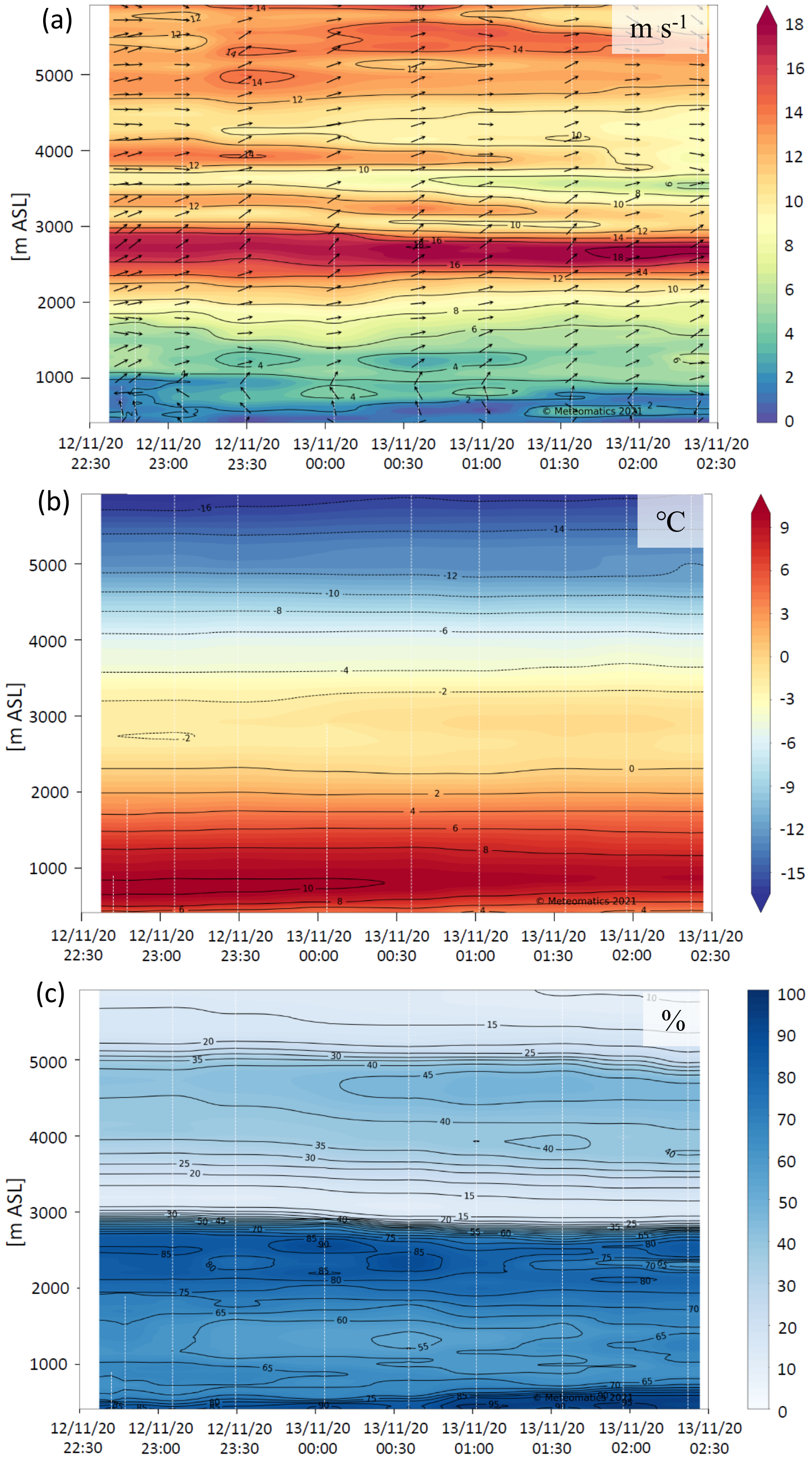


Figure 2. Time-height profiles of (a) wind speed (color fill) and direction (arrows pointing with the wind), (b) temperature and (c) relative humidity obtained with a Meteomatics Meteodrone collected prior to and during a fog event at Amlikon, Switzerland. Profiles were obtained every 30 min up to 6 km AMSL.

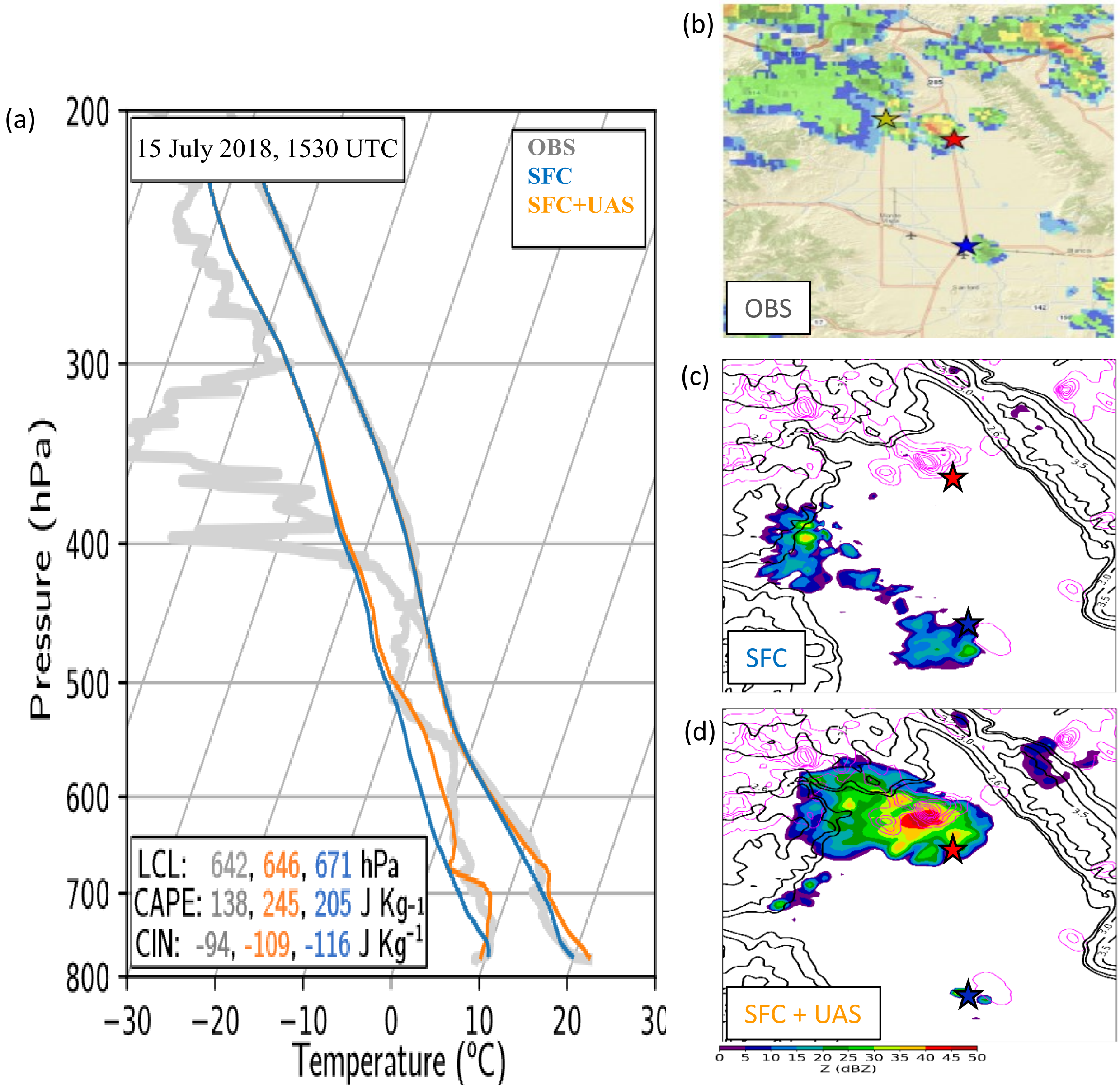
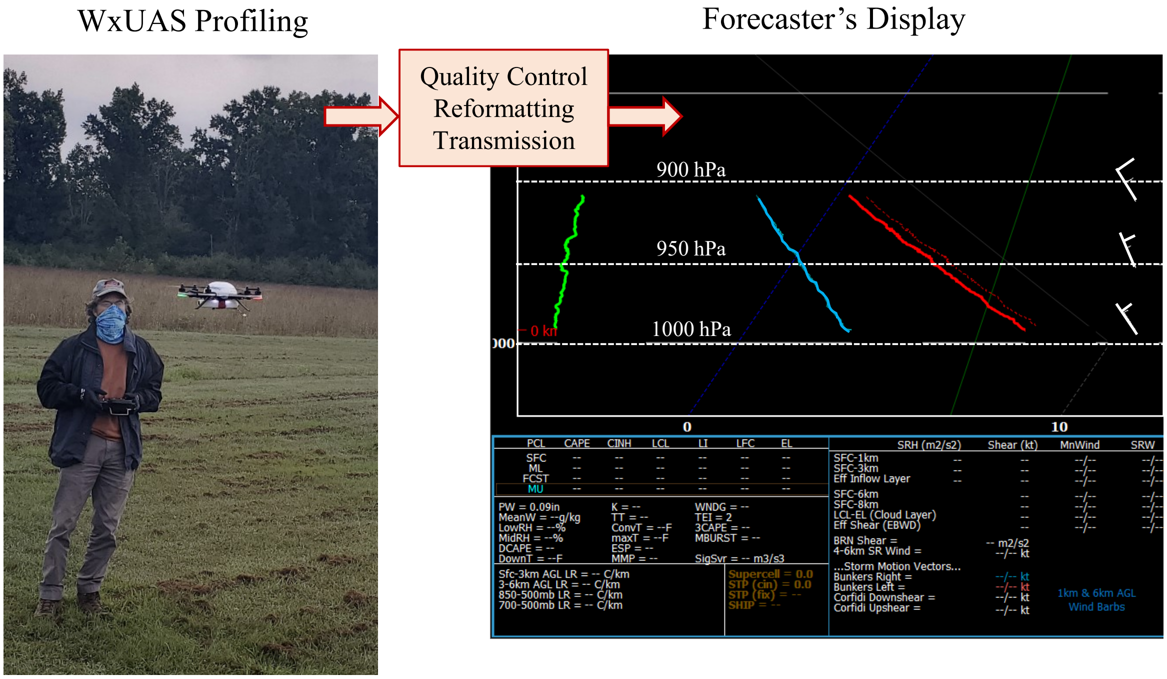


Figure 3. Analyses of temperature and dew point profiles obtained in the center of the San Luis Valley of Colorado using EnKF data assimilation with 15-minute cycling of surface observations (SFC) and surface plus WxUAS observations (SFC+UAS) along with independent observed values obtained with a radiosonde (OBS). Column on right shows (b) observed composite reflectivity and that obtained with a 30 min forecast with (c) SFC DA and (d) SFC+UAS DA valid at 2000 UTC. Magenta contours in (c) and (d) denote 3 hour accumulations estimated from the observed composite reflectivity. Red and blue stars denote locations of Moffat and Alamosa, respectively.



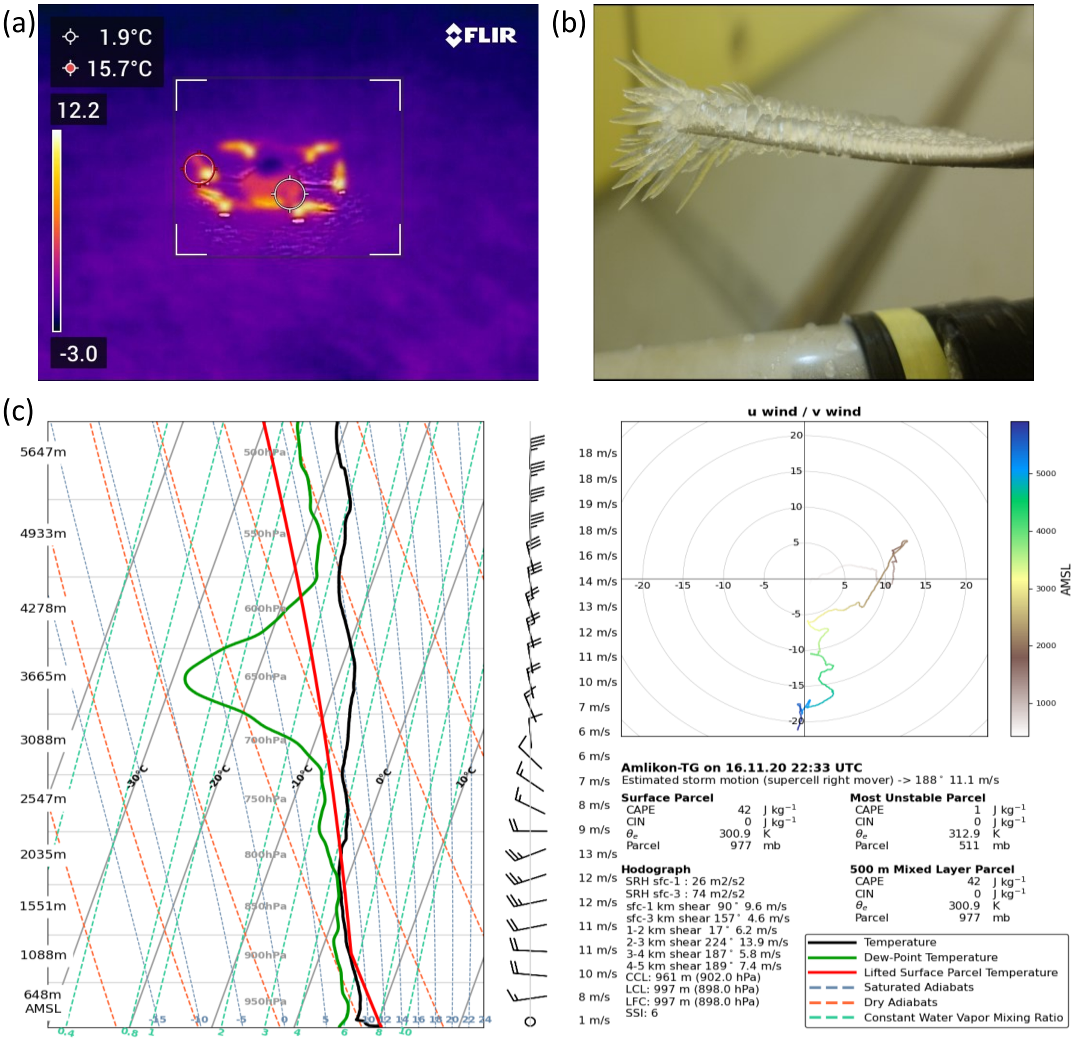
```
PCL   CAPE  CINH  LCL   LI    LFC   EL
SFC   --    --    --    --    --    --
ML    --    --    --    --    --    --
FCST  --    --    --    --    --    --
MU    --    --    --    --    --    --

PW = 0.09in          K = --          WNDG = --
MeanW = --g/kg       TT = --         TEI = 2
LowRH = --%          ConvT = --F     3CAPE = --
MidRH = --%          maxT = --F      MBURST = --
DCAPE = --           ESP = --
DownT = --F          MMP = --        SigSvr = -- m3/s3

Sfc-3km AGL LR = -- C/km            Supercell = 0.0
3-6km AGL LR = -- C/km              STP (cin) = 0.0
850-500mb LR = -- C/km              STP (fix) = --
700-500mb LR = -- C/km              SHIP = --

                      SRH (m2/s2)  Shear (kt)  MnWind  SRW
SFC-1km               --           --          --/--   --/--
SFC-3km               --           --          --/--   --/--
Eff Inflow Layer      --           --          --/--   --/--
SFC-6km                            --          --/--   --/--
SFC-8km                            --          --/--   --/--
LCL-EL (Cloud Layer)               --          --/--   --/--
Eff Shear (EBWD)                   --          --/--   --/--
BRN Shear =                        -- m2/s2
4-6km SR Wind =                    --/-- kt
...Storm Motion Vectors...
Bunkers Right =                    --/-- kt
Bunkers Left =                     --/-- kt    1km & 6km AGL
Corfidi Downshear =                --/-- kt      Wind Barbs
Corfidi Upshear =                  --/-- kt
```

Figure 4. On left, Meteomatics WxUAS being flown during demonstration testbed to assess their use in operational meteorology. Data are relayed to a ground station, post-processed with quality control software and reformatted before transmission to the WFO in Morristown, TN in real-time. On right, WxUAS data can be displayed at the WFO using SHARPpy display tool. Observations shown are dew point temperature (green), wet bulb temperature (blue), air temperature (red), and wind speed and direction (barbs on right) are used to support the development of short-term forecasts.



Amlikon-TG on 16.11.20 22:33 UTC
Estimated storm motion (supercell right mover) -> 188° 11.1 m/s

Surface Parcel

CAPE	42	J kg^{-1}
CIN	0	J kg^{-1}
θ_e	300.9	K
Parcel	977	mb

Most Unstable Parcel

CAPE	1	J kg^{-1}
CIN	0	J kg^{-1}
θ_e	312.9	K
Parcel	511	mb

Hodograph
SRH sfc-1 : 26 m2/s2
SRH sfc-3 : 74 m2/s2
sfc-1 km shear 90° 9.6 m/s
sfc-3 km shear 157° 4.6 m/s
1-2 km shear 17° 6.2 m/s
2-3 km shear 224° 13.9 m/s
3-4 km shear 187° 5.8 m/s
4-5 km shear 189° 7.4 m/s
CCL: 961 m (902.0 hPa)
LCL: 997 m (898.0 hPa)
LFC: 997 m (898.0 hPa)
SSI: 6

500 m Mixed Layer Parcel

CAPE	42	J kg^{-1}
CIN	0	J kg^{-1}
θ_e	300.9	K
Parcel	977	mb

Figure 5. (a) Thermal imagery of heated Meteodrone flying within icing conditions. (b) Picture showing horning icing on the rotary blade of a Meteodrone. (c) Observations of temperature, dew point and winds collected with Meteodrone WxUAS during flight into icing conditions including (left) Skew-T diagram and (right) hodograph and convective parameters. The freezing level is at 1600 m MSL.

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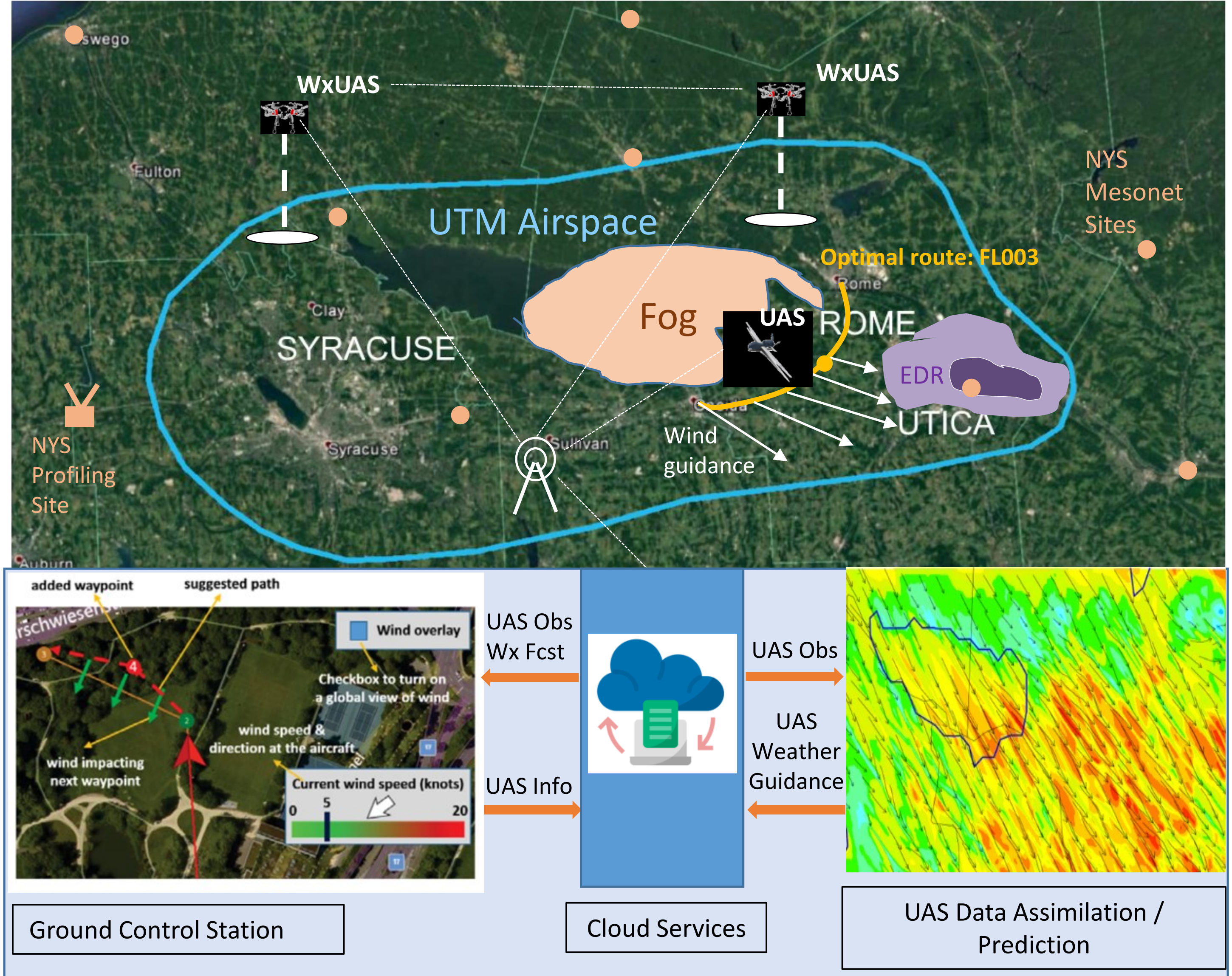
WEATHER-AWARE UAS TRAFFIC MANAGEMENT SYSTEM



Sidebar SB1. Example of a testbed where WxUAS and commercial UAS combine to collect weather observations along with an existing sensor network centered over Upstate New York. The UAS communicate observations with each other when within line of sight. Weather information can be transmitted to cell towers and processed / stored in the cloud for operators and other subscribers including modeling centers to access. Modeling centers process data to improve initial conditions needed to drive weather prediction models whose outputs are used as guidance for UAS flight planning. Other applications process model data to determine likelihood of conditions that are hazardous to commercial UAS operations such as low ceilings and reduced visibility caused by fog, icing layers and areas intense turbulence or wind shift boundaries. Wind information is used directly to optimize route planning and to estimate departure and arrival times, optimize commercial UAS fleet mix, set up metering/spacing between commercial UAS, etc.

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