What If Every Aeronautical Vehicle Operating in Our Airspace Were to Report Weather Conditions?

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1. Introduction

Since the inception of manned flight, reliable air operations have depended on our ability to accurately observe, measure, record, report and predict the weather. The rise, expansion, and maturation of civil and commercial air travel has also introduced society to the numerous types of impacts weather can have on aviation operations, resulting in significant passenger disruptions or, even worse, safety incidents and fatal accidents. Scientific communities (including aviation meteorology), working closely with government agencies, flight operators, and service suppliers, have significantly advanced the science of aviation meteorology and its application to air traffic missions. These efforts have helped cultivate a safe, reliable, and efficient National Airspace System (NAS) that operates daily amidst a myriad of weather conditions and hazards.

It is noted by [1] that "the aviation history serves as a key example of how societal needs drive advances in observing systems and, conversely, how the aviation industry and the flying public benefit from meteorological research using these observing systems." Symbiosis between meteorology and air traffic procedures is evident when considering airborne weather observations provided by aircraft while in flight. Currently, thousands of commercial aircraft routinely measure and report weather conditions across the globe from on-board sensors, collectively serving in the aggregate as an important atmospheric observing network. Reported meteorological conditions along aircraft flight paths include pressure, air temperature, wind speed and direction, turbulence, and water vapor. The demonstrated value of in situ aircraft-based observations (ABO) to more efficient and safe flight operations have been two-fold:

1. Direct benefits through ingest of weather information by aircraft flight management systems and by disseminating data to flight dispatchers, traffic managers, and/or situational awareness tools (by extension then informing other pilots and operators) for enhanced guidance;
2. Indirect benefits from numerical weather models made more accurate by assimilating ABOs and improving model estimates for initial conditions, all resulting in improved forecast guidance used by operators to anticipate and plan for likely aviation hazards.

An emergent air transportation transformation is underway that involves the rise of drone and electric vertical take-off and landing (eVTOL) vehicle technology, and the envisioned unmanned aircraft systems (UAS) and urban air mobility (UAM) operations these vehicles will support. Operating primarily in the lowest 400 feet (small UAS [sUAS] vehicles [2]) to 5000 feet (eVTOL vehicles [3]), UAS and UAM vehicles will largely operate in or near the atmosphere's planetary boundary layer (PBL), the portion of the earth's atmosphere that exhibits complex and challenging meteorological conditions, especially near thunderstorms, mountainous terrain, or urban landscapes. These aerial operations will require improved weather information in the lower atmosphere to achieve levels of safety, efficiency and reliability equivalent to those associated for many years with commercial aviation [4].

There is a growing opportunity to address the essentials now. The very air vehicles that will require the weather information to operate, sUAS and UAM platforms, can be part of the PBL data collection solution. Additionally, the time is right to address avionics systems as these new air vehicles are outfitted with all its sensors and the technology required to accomplish the task. Promoting proactive discussion and policy debate, and aggressively supporting and leveraging research and technology, will help preclude retrofitting challenges, in turn reducing cost and spurring faster returns on investment.

Beyond addressing new entrant operational needs, improved real-time information and augmented data collection, and expanded profiling of the lower atmosphere will benefit and address continued shortfalls for the current day operations. Airlines would realize benefits in descent profiles with improved real-time wind, turbulence, and icing conditions for a more robust mitigation of these impactful conditions. The strategic planning environment could be sharpened as well, leading to less unrecoverable delay in flight schedules. The industry itself would see improvement in time-based operations and advancements in NextGen's Trajectory Based Operations [5].

Finally, the needs of the aviation community for robust weather information in the PBL and lower atmosphere are shared by numerical weather prediction models, which require assimilated observations within this critical tropospheric stratum for more accurate meteorological predictions. The lack of assimilated observations and data from the PBL persists as a significant need by numerical weather models (e.g., [6]). Combine the benefits that are possible for aviation operations with the improvements in weather model predictions and improved weather impact forecasts, and a broader societal benefit is envisioned. The aviation community and weather community can collaboratively lead research and address the challenges as leading organizations to spearhead the realization of other benefits to society in general, including ground transportation and other societal needs for real-time weather information.

Given the above, the authors promote the following mandate for "Ubiquitous ABO" (U-ABO), asserting that:

All aeronautical vehicles operating in the NAS must measure, transmit, and share in situ weather conditions, to benefit aviation missions and society as a whole.

The MITRE/NCAR authors consider the coming decade to be the right time to provide significant weather impact mitigations and to reduce the weather sensitivity of the aviation and aerospace industries and society at large. Using recent breakthroughs in vehicle, sensor, communications and computing technologies, we believe the aviation, aerospace and meteorological communities are ready to collaboratively leverage big-data analytics, cloud storage, networking, artificial intelligence and material innovations so as to collect, provide, and apply in situ weather observations to realize significant air travel safety, efficiency and reliability improvements for all current operations. These breakthroughs and advancements will address the new operational concepts to be deployed in the NAS over the next decade and at the same time produce significant weather forecast improvements applicable to society as a whole. The opportunities exist now to significantly improve our awareness and understanding of atmospheric conditions throughout the troposphere and lower stratosphere (Figure 1), leading to multi-faceted innovations that improve overall societal safety and well-being.

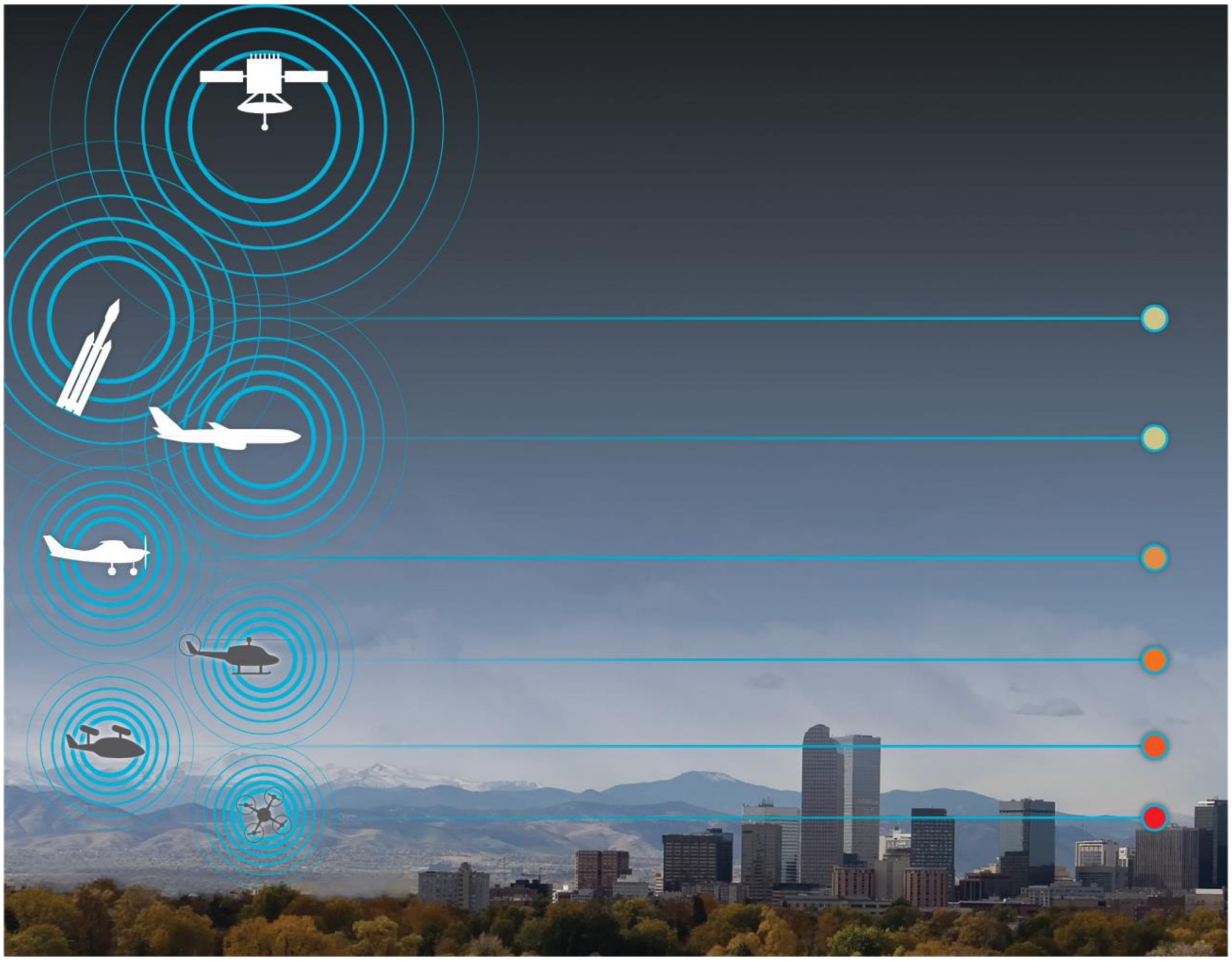

Figure 1. Vision for future, ubiquitous observations of in situ weather conditions from all airborne aeronautical vehicles operating in the National Airspace System.

This paper defines the landscape and path forward to meet the objective requiring observations and access to in situ weather measured by all aeronautical vehicles operating in our airspace. Specifically, it provides background information and motivation to help justify the U-ABO position. At the same time, recognizing that many challenges and obstacles must be overcome to meet this objective, this paper also attempts to summarize the source and significance of potential impediments. Finally, a proposed path forward for convening communities of experts, enablers, and potential early adopters is presented and discussed as a means for addressing known challenges, uncovering and managing others, defining consensus needs and developing prioritized solutions to achieve realistic, fair, and forward-thinking implementation roadmaps.

2. Motivating Background

The need for real-time weather information by traditional and new entrant aeronautical vehicles, along with their ability to measure and report in situ meteorological conditions, initially motivated this concept. The positive impact of ABOs on numerical weather prediction models, the advent of crowd-sourcing and big-data automation and the miniaturization and improvement in airborne weather sensors themselves further motivated it. Each area is discussed below.

2.1 Use of Real-time ABOs in Aviation Today

Flight safety and maximum efficiency depend in large part on the ability of today's pilots to optimally define and manage their aircraft flight trajectory (route) in the face of evolving weather conditions or constraints. Pilots place high value on acquiring near-real-time in situ weather information. Advancements in recent years in aircraft on-board Internet access, increased access and permitted use of computer tablets (e.g., iPads in cockpits as electronic flight bag (EFB) tablets), and weather apps available to pilots have provided significant opportunities for real-time use of ABO for improved aviation operations. Delta Air Lines, for example, is one of several commercial air transport companies that utilize ABOs from sensors on many aircraft in their fleet to power a cockpit application used by pilots to identify and target flight routes where airborne weather hazards may be mitigated [7] (Figure 2).

Figure 2. Delta Air Lines pilot utilizing Flight Weather Viewer App to investigate airborne turbulence observations and associated turbulence conditions (from [7]*).*

These successes by individual airlines in providing real-time guidance of airborne weather hazards to pilots and aircraft dispatchers has in turn motivated the International Air Transport Association (IATA) to promote industry-wide sharing of ABO-reported turbulence for expanded and collective situational awareness of turbulence hazards. With this effort, IATA is helping to define and exercise the concept and rules of access and engagement for an ABO data exchange platform seeking to contribute to safer aviation operations [8].

The flight management systems (FMS) of commercial aircraft make direct, constructive use of sensed, in situ winds aloft to navigate more efficient individual and aggregate four-dimensional trajectories. Specifically, aircraft sensed winds have a role in improving the performance of the FMS Required Time of Arrival (RTA) function, in turn contributing to more timely and accurate compliance to Time-Based Management (TBM) strategies that enhance NAS efficiency [9]. These in situ wind observations and their use by aircraft FMS will also be leveraged for more efficient Flight Interval Management (FIM), or relative aircraft spacing, for still more predictable and efficient trajectory-based operations.

Envisioned future autonomous UAS and UAM operations will require similar trajectory-based applications of airborne wind observations. Specifically, safe separation from other UAS or UAM aircraft operating in close airspace areas will require advanced sense and avoid technologies that leverage real-time in situ wind conditions for accurate trajectory predictions and interval spacing assignments as part of governing traffic management operations.

2.2 ABO Contributions to Improved Weather Forecasts

Data assimilation for numerical weather prediction (NWP) is summarized by [10] as a minimization problem focused on obtaining a best estimate of three-dimensional atmospheric conditions, on a grid and for a given time, in order to initialize the NWP. As such, acquisition of pertinent weather observations is fundamental to data assimilation, which in turn is the foundation from which accurate weather forecasts are derived. Commercial ABOs have been found to be critical data that have notably contributed to improved regional and global forecast skill (e.g., [11], [12]). These forecast improvements have continued as the number of global ABO reports increased from 7,000 per day in the early 1990s to over 800,000 per day globally by 2017 [10].

One of the most compelling illustrations of the significant impact of ABO data assimilation on the performance of numerical weather predictions was illustrated by [13], who noted consistent year-over-year (2011-2016) improvements in six-hour upper level wind forecast skill from the NOAA Rapid Update Cycle (RUC) forecast, even while its model code was frozen. The improvements were attributed almost exclusively to increased ABO data assimilated into the model, and allowed it to keep pace with its successor, the NOAA Rapid Refresh (RAP) model, which continues to be fully maintained and whose model code continues to be enhanced to this day (Figure 3).

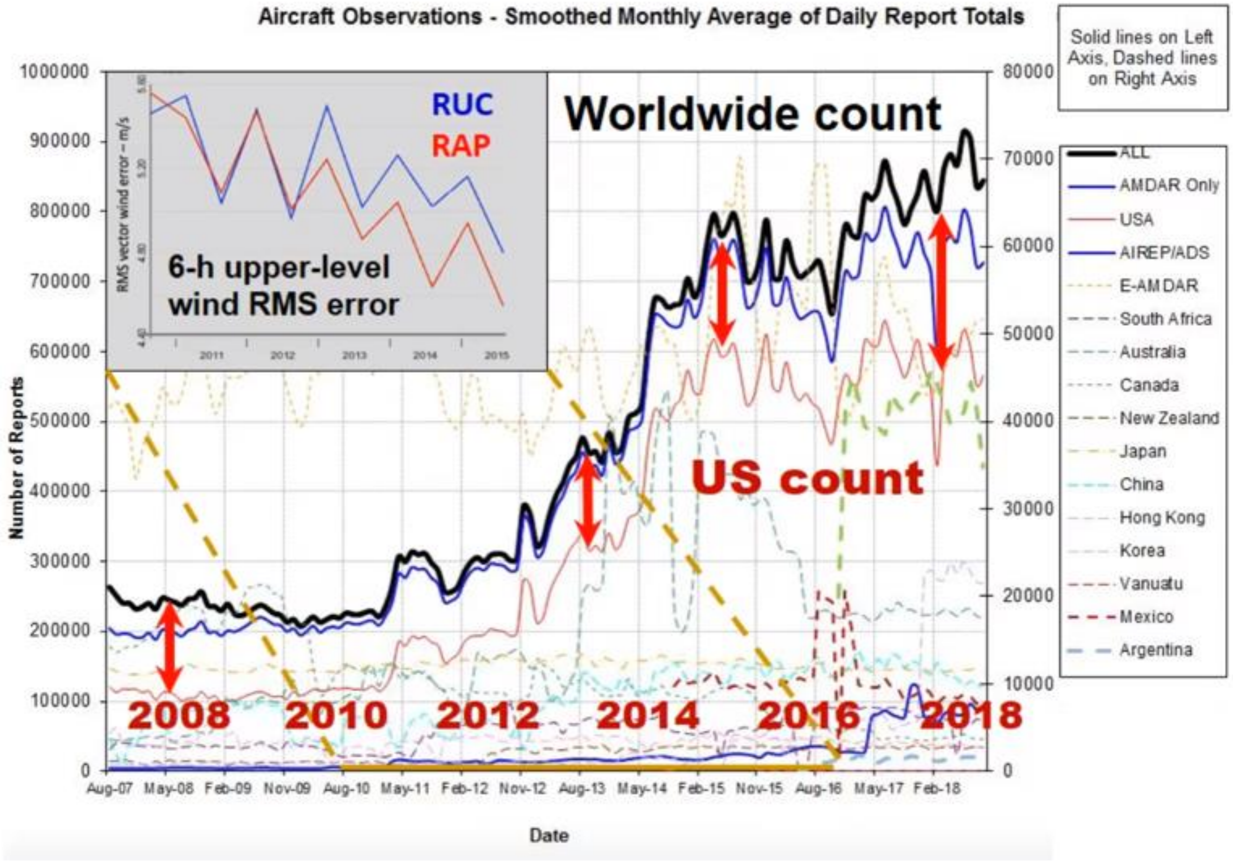

Figure 3. Improved performance (decreased RMS error) in RUC 6-hour forecasts for upper-level winds due primarily to continued assimilation of increased ABOs during period of interest (from [13]*).*

Despite these advancements, in situ observations (and associated data assimilation) of atmospheric conditions in the PBL, deemed critically important for all weather forecast endeavors, are still relatively infrequent and irregularly spaced. As ABO-reporting commercial aircraft climb and descend in terminal airspace, they do provide some observations of atmospheric conditions in the PBL, but these observations are typically redundantly located within highly structured routing near major commercial airports. Many more frequent observations of the PBL and lower atmosphere, expanded across much larger spatial areas, are likely to significantly contribute to still greater understanding of current conditions and processes taking place in this part of the atmosphere and thus improvements in forecast skill. This is the opportunity offered by UAS and UAM vehicles and future operations.

2.3 Equipage Opportunities and Analogous Retrofitting Challenges

When considering requirements for all aeronautical vehicles to measure and report key weather variables, one must consider the activity and momentum of pertinent research communities and the associated maturity of technology that will ensure small, lightweight, and energy-efficient sensors suitable for very small aviation vehicles (e.g., sUAS). Many universities, government labs and private companies are devoting research to develop viable ABO sensors satisfying these requirements while still making accurate atmospheric measurements. Jacob et al. note that most ABO sensor technology for sUAS originates with radiosondes and their associated, operationalized sensor miniaturization [14].

From here, many sensor options for measuring the basic atmospheric parameters of pressure, temperature, and humidity from onboard small aviation vehicles are commercially available (Figure 4) or may be readily adapted for this use. For instance, research groups testing atmospheric sensors aboard sUASs are flying pressure-temperature-humidity (PTH) sensors, sometimes extracted from existing radiosondes [15]. Early testing is uncovering calibration challenges, and that sensing with such miniaturized technology for other phenomena such as wind conditions, turbulence, and cloud properties (and associated visibility) is particularly difficult. Solutions for these challenges are being researched at a rapid pace, presenting new innovations and opportunities that may be leveraged by a future U-ABO vision.

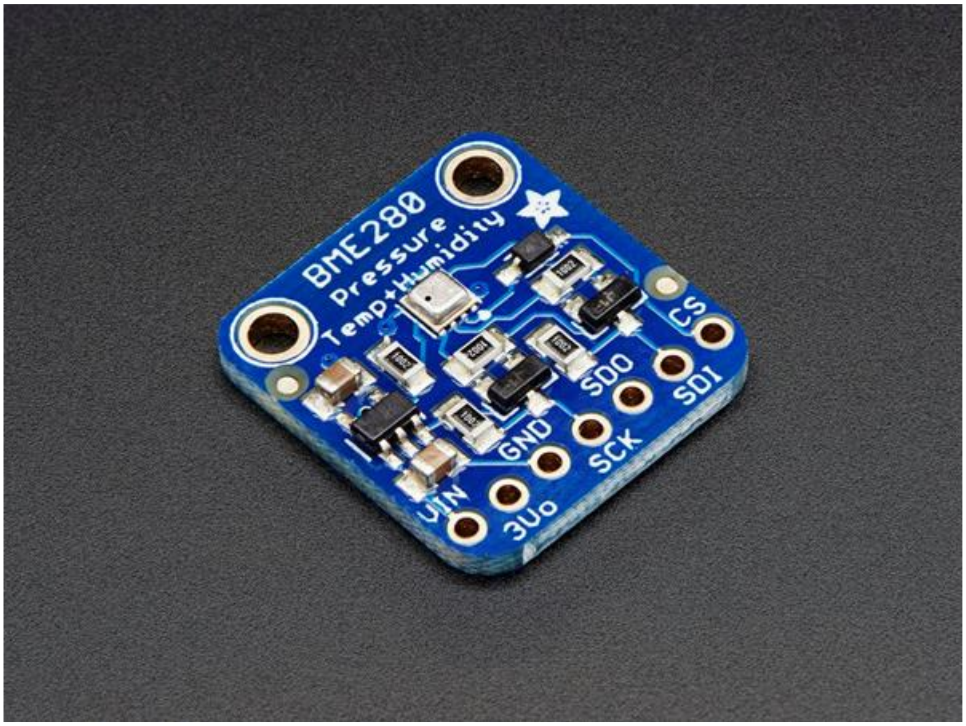

Figure 4. Example of a miniaturized pressure, temperature and humidity sensor. The actual size of this unit is slightly smaller than a U.S. quarter, and it weighs one fifth as much. These sensors are commercially available at very affordable prices (< $20) [16].

Though meteorological sensor miniaturization and energy-efficient technologies are still under development and maturing, the timing is good. UAS and UAM vehicles are just now growing into more significant existence, and mission concepts for advanced (and common) use are still emerging. Policy debate and focused technological solutions developed now in support of a U-ABO mandate will enable proactive “forward-fitting” of meteorological sensors and weather data transmission protocols for most new aeronautical vehicles still to come. Even for the more than one million UAS vehicles already registered with the Federal Aviation Administration (FAA) in the U.S., and the estimated three to six million sUAS vehicles that may be flown in the U.S. by hobbyists or commercially by 2021 [17], these vehicles have much faster ‘refresh-rates’ (replacing old vehicles with new vehicles) – perhaps on the order of a couple years – compared to conventional aeronautical vehicles, which often remain in use for decades. Therefore, while a U-ABO mandate is being established, and more of these vehicles hit the field, the most prevalent vehicles will also be those being replaced most frequently, offering ample opportunities for forward-fitting to catch-up over time.

A cautionary tale for retrofitting aircraft to meet equipage needs for advanced operational concepts can be found with the FAA's Performance Based Navigation (PBN) efforts and associated equipage needs of Part 121 commercial aircraft. In summary, PBN is a major thrust of the FAA's Next Generation Air Transportation System (NextGen). It requires aircraft to use Area Navigation (RNAV) systems that meet Required Navigation Performance (RNP) standards. RNP, which describes the ability of an aircraft to navigate within listed performance standards, is RNAV with additional onboard performance monitoring and alerting capabilities that ensure even more precise routing. Most commercial aircraft today are already equipped with RNAV systems. For older, legacy commercial aircraft, however, additional equipment is often needed to achieve RNP status, and this requires operators to retrofit the aircraft to minimize less optimal, 'mixed-equipage' RNP / PBN operations. Because of the associated aircraft downtime and costs, operators are extremely reluctant to go down the retrofit path absent a clear benefits case.

The first FAA Advisory Circular approving guidance for RNP operations (AC 90-105) was published in January 2009 [18]. RNP retrofitting has proven to be a challenge that has persisted over the next decade to limit the potential effectiveness of PBN operations. In fact, several independent assessments by the U.S. Department Transportation (DOT) and the Government Accounting Office (GAO), as well as independent NextGen assessments by research organizations during 2009-2018 routinely cited lagging RNP (and overall NextGen) equipage retrofitting as key impediments to meeting operational objectives [19], [20], [21], [22].

Conversely, most commercial aircraft manufacturers now install ("forward-fit"), by default, Aircraft Meteorological Data Relay (AMDAR) weather sensors, which have been in existence and have matured for more than two decades [23]. With the sensors available on the aircraft, access to data is then offered by the aircraft manufacturers as an option, typically agreed to by customers who have come to recognize the value proposition and operational advantages offered by in situ ABO data [24]. The key lesson here, to ensure broader adoption and technologically and financially feasible implementation of a U-ABO mandate for all aeronautical vehicles, is that the multi-faceted value proposition must be defensible, well understood and widely and routinely shared to ensure manufacturers and operators remain committed to implementation and advancement.

3. Emergent Vehicles, Operations, and Weather

UAS and UAM vehicles comprise the class described as emergent aeronautical vehicles. They are sometimes referred to as "new entrants" within NAS operations[1]. The proliferation of this class of aeronautical vehicles will generate our nation's greatest opportunity for increased amounts of in situ atmospheric observations over the next decade. As compared to traditional aircraft, expectations are that UAS and UAM vehicles will add a significant number of units in the coming years. The latest FAA estimates are that hobbyist sUASs currently exceeds 1.25 million [25], while The RAND Corporation estimates that three to six million sUAS vehicles may be flown in the U.S. by hobbyists or commercially by 2021. [17] Comparable growth rates are expected beyond 2023. Given these projections, there is now great potential, through U-ABO, to fill in long-standing critical weather observation gaps[2]. Moreover, these gaps do not belong solely to the meteorological community, since these same observations will be needed to directly support the varied aviation missions of pervasive UAS and UAM vehicles seeking to share airspace safely and efficiently.

3.1 UAS Operations

A UAS is defined by the International Civil Aviation Organization (ICAO) as an aircraft system operating with no onboard pilot [26]. A UAS is primarily categorized by its type (e.g., fixed wing vs. rotary wing), size, weight, and horizontal and vertical operating domain. UAS aircraft sizes and weights range from insect-sized vehicles weighing less than one gram to full-sized aircraft weighing tens of thousands of kilograms and powered by jet engines[3]. The smallest UAS aircraft may only be able to fly for less than one kilometer over a sub-one-hour period up to 400' altitude, while the largest vehicles can fly for thousands of kilometers over multiple days up to the top of or above controlled airspace (FL600).

UAS operations are conducted by numerous participants to satisfy a wide variety of needs and objectives. These include hobbyists flying sUASs for pleasure, businesses conducting aerial photography, aerial medical supply (e.g., Zipline), package delivery (e.g., UPS and Google Wing), infrastructure inspection (e.g., refineries, utility lines, and bridges) and television reporting, and governmental agencies in support of police surveillance, emergency response, and warfighting. As battery technology, improved vehicle composites and design, and supporting aircraft sense and avoid capabilities advance beyond research, new mission types are being considered and implemented. The potential uses of UAS vehicles going forward appear quite numerous, as industries look to increase operational efficiencies while reducing costs.

In the U.S., many sUAS operations are carried out under Federal Aviation Regulations (FAR) Part 107. These regulations require the unmanned aircraft to weigh 55 pounds or less, the operations to be

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[1] The commercial space industry and its associated class of vehicles is also increasing its operations in the NAS, with expectations for significant growth in the future. These vehicles also offer unique opportunities to increase weather observations in atmospheric strata beneficial to research and development that will benefit our society. Therefore, commercial space vehicles are also targeted by the U-ABO mandate (see U-ABO vision in Figure 1), but they are not emphasized as part of this initial U-ABO position paper.

[2] One package service delivery analysis indicates that package deliveries by UAS will eventually reach 86 million operations a day [48]. By comparison, current commercial and general aviation flight operations equal approximately 100,000 flights per day.

[3] The smallest UAS vehicles are likely beyond the scope of the proposed U-ABO mandate, given that the size and weight of these vehicles are comparable to the size and weight of weather sensors intended for UAS vehicles.

conducted under Visual Line Of Sight (VLOS), the prevailing visibility to be three nautical miles or greater and the aircraft to remain no more than 400 feet above the ground or ground-based structures and 500 feet below / 2,000 feet horizontally away from clouds. UAS operations that do not qualify for FAR Part 107 must either apply for and receive waivers from FAR Part 107 requirements, or comply with FAR Part 135, the only FAR that can be used by UAS operators conducting Beyond Visual Line of Sight (BVLOS) operations for compensation (e.g., package delivery).

3.2 UAM Operations

The vision of avoiding gridlock on the ground by speedily traveling across metropolitan areas through the air, dubbed “Urban Air Mobility” or UAM, has galvanized the aviation industry. Innovations are leading to a new generation of vehicles that use electric propulsion and can take off and land vertically. These eVTOL vehicles, coupled with ride-sharing business models and technology adopted by ground transportation, are expected to revolutionize transportation in the urban setting. In the early years, this UAM air taxi market is projected to reach 55,000 annual operations, with an annual market value of 2.5 billion USD [27].

Not surprisingly, UAM’s anticipated area of operations, based on various initial concepts of operation (ConOps), will be over the urban landscape. This means operations of eVTOLs will include takeoff and landing from rooftops, parking garages, or locations surrounded by a mix of building configurations and heights, a combination that can lead to highly variable winds and significant levels of turbulence. UAM operations may be quite demanding under windy conditions, as the dynamic winds flow around buildings to produce strong, transient turbulent eddies. The eVTOL’s transition from vertical to horizontal flight at the departure point, and horizontal to vertical flight near the destination, will likely be most sensitive to these wind and turbulence impacts.

Since they will be carrying passengers and operating in densely populated areas, UAM safety regulations are expected to be comparable to or stricter than those with which today’s commercial operators must comply. Observations and forecasts of urban weather will need to improve markedly as the UAM concept continues to evolve.

Atmospheric observations in urban environments to support UAM (and UAS) operations are very limited today. Thus, there is a need to enhance the urban observation infrastructure, which should include instrumenting eVTOLs operating in this arena for their direct operational benefit and to share situational awareness of the weather conditions across and within the urban landscape. To ensure reliable and predictable UAM operations, all operating eVTOL vehicles will likely need to observe and share in situ weather conditions [28].

Over many years, the FAA and the commercial flight industry have developed processes and procedures that have enabled flight operations with uncompromised safety in almost all-weather conditions, and the general public has come to expect this while flying. For public acceptance, the UAM and UAS communities must strive for the same level of safety. For these industries, the challenges may be more severe, given that weather hazards encountered more routinely near the surface and among buildings significantly increase the likelihood of collisions and crashes.

The emergent vehicle manufactures and the industries that will operate them see great market value for achieving their visions. They will want and need to consider their vehicles in part as needed weather sensing platforms, whose data will shape risk modeling and advanced automation and be used to ensure optimal and safe missions.

3.3 UAS and UAM Weather Considerations

UAS and UAM operations are constrained by the same hazardous weather phenomena that impact legacy aviation operations, including strong winds, wind shear, turbulence and icing, hail and lightning. Differences in vehicle characteristics (e.g., size, performance, and flight-critical systems) will lead to varying levels of sensitivity to these weather conditions. Smaller and lighter aircraft are typically more vulnerable to high-wind conditions than are larger aircraft. The degree to which sUAS and UAM are constrained appears much greater, since most of the vehicles themselves are substantially smaller and less powerful than legacy aircraft. In addition, because of the size differences, sUAS operations are also highly susceptible to conditions that would not be considered hazardous by legacy aircraft. Wind shear or turbulence that would barely be felt by a small commercial aircraft can upend a sUAS. In addition, multirotor eVTOL designs are only starting to be flight tested and their sensitivity to atmospheric conditions remains to be fully examined.

sUAS aircraft are primarily powered by batteries that attempt to provide an optimal size, weight, and energy supply solution. Similarly, eVTOLs will operate on battery power to minimize environmental pollution. As a result, battery life and operating range will always be a consideration. The performance of these batteries can be affected by the ambient temperatures, especially in extreme cold or hot conditions. Moreover, the batteries drain more quickly than usual when turbulence requires frequent autopilot-commanded control inputs to keep the sUAS or eVTOL in level, stable flight required for remote sensing applications or passenger ride comfort. Precipitation and lightning are additional hazardous conditions, as most sUAS may not be weatherproof. In sum, weather constraints for sUAS operations are more numerous and in ways that would not be considered even remotely impactful to most legacy aircraft or larger UAS aircraft.

There may be other mission-specific weather sensitivities to be considered. For example, sUASs or eVTOLs navigating between city buildings to deliver packages or passengers will experience much different atmospheric conditions, and need to react differently to them, than sUASs operating over rural areas to inspect pipelines or agricultural crops. Therefore, understanding how to address modeling of the weather and weather avoidance at various micro-scale settings will become critical for UAS and UAM operations under the variety and range of missions they will conduct. This will require the weather enterprise and the aviation industry to collaboratively engage in an ongoing dialogue about the operator information needs and requirements to minimize avoidable weather-related risks through the timely provision of location-specific, actionable weather guidance [4]. Moreover, the quest for safe flight operations in an era of increasing automation and the use of atmospheric sensors to power guidance algorithms requires a full comprehension of how weather affects sensor readings and an understanding of how potentially misleading atmospheric information may be processed.

4. Potential Aeronautical and Societal Value and Benefits

The great value of U-ABO lies with its potential exponential return on investment, and the benefits that may be achieved when all aeronautical vehicles are contributing weather information deemed critical to broader aviation and societal needs. As discussed earlier, the value of ABO data to improving weather forecasts is significant. Imagine how much more accurate weather forecasts will be when they are able to assimilate U-ABO information from potentially 100-200 times more vehicles, many of which will be observing weather conditions in the critical, near-land PBL? The significant growth in future U-ABO data will also propel AI-based forecast technology for still more opportunities to significantly improve weather forecasts. All of this is important – a significant driver for U-ABO – because weather sensitivities and the need for improved forecast guidance are prevalent in all industrial and economic sectors, thus affecting all facets of society. The broader, potential aeronautical and societal value and benefits of U-ABO are explored more closely in this section.

4.1. Enhancing Legacy Aviation Weather Guidance and Forecast

Improving the accuracy of forecasts of hazardous weather phenomena such as turbulence, icing, wind shear, convection/lightning and wintry precipitation is a standing objective of the aviation weather community supporting legacy flight operations. How might U-ABO data support and satisfy key legacy aviation weather needs, particularly when also considering emerging UAS and UAM operations?

Aircraft-based observations do more than improve the accuracy of NWP models and specialized aviation forecast products. By measuring and providing temperature and humidity information at key points in space, forecasters can more accurately make critical, site-specific predictions about the locations of in-flight icing and the likelihood and type of winter weather that, due to vertical and horizontal resolution limitations, would not be possible to explicitly derive from today's high resolution forecast models. Objective, in situ measurements of turbulence enable the Graphical Turbulence Guidance (GTG) family of products to more accurately depict the turbulent state of the atmosphere. Equally important, they are key pieces of information for all pilots, enabling each one to make tactical decisions appropriate to the size and type of their aircraft and the type of operation being conducted.

The information provided by properly equipped UAM / UAS vehicles to ground receiving systems would be assimilated by weather forecast systems and used to improve their predictions. This includes both traditional NWP models and newer microscale, Large Eddy Simulation (LES) models, whose output would be tailored to satisfy and support UAM / UAS operations, particularly in challenging urban environments. By enabling the provision of focused analyses and forecasts of wind and turbulence to UAM / UAS operators and improving the accuracy and resolution of traditional forecasts of icing and precipitation, the needs of UAM / UAS operations are both supported and satisfied by the members of the community themselves.

4.2. Forecast Improvements and Benefits to Society

The potential value of U-ABO will not be confined to aviation missions and the overall NAS operation. As discussed, assimilation of significantly more in situ weather observations from aeronautical vehicles operating in expanded airspace regions, including the near-surface PBL, for both rural and urban areas, will lead to substantial improvements to numerical weather forecasts. These forecasts will then be used for better weather impact planning and constraint management for conventional and emergent aviation operations. However, the full user base for these improved forecasts includes much of society and its associated, wide-ranging needs.

Initial evaluations of the pervasive, societal needs of weather information and forecasts, examined in 2002, note that approximately one-third of U.S. private industry activities, representing approximately $3 trillion in revenue, have at least some degree of weather and climate risk [29]. Lazo et al. estimate that annual weather variability in the U.S. may directly translate into 3.4% variability in the Gross Domestic Product (GDP) [30].

Weather sensitivity across our society is far-reaching and affects all 11 nongovernmental sectors of our economy.[4] [30] Each of these sectors has their own, numerous subsectors that collectively contribute to our society's livelihoods and overall comfort and well-being. Across all economic sectors and subsectors, societal needs that account for and manage weather sensitivities are best met when risks are understood and proactively managed. This requires the effective use of improved weather forecasts. Given that increased data assimilation of in situ ABOs has been demonstrated to be one of the most significant contributions for improving numerical weather models (recall Section 2.2), assimilated U-ABO data retrieved with higher frequency and coverage in critical layers of the atmosphere are expected to further improve weather forecasts that will aid planning and decisions critical to almost every aspect of society.

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[4] These nongovernmental sectors of the U.S. economy include: (1) agriculture, (2) communications, (3) construction, (4) manufacturing, (5) mining, (6) retail trade, (7) services, (8) transportation (9) utilities , (10) wholesale trade, and (11) finance, insurance, and real estate.

5. Potential Challenges and Solution Considerations

The concept for observing and sharing ubiquitous in situ aeronautical weather information is not without its challenges and obstacles. These fall into the following general categories (Figure 5):

- Airborne Weather Sensing
- Data Communication
- Data Storage and Access
- Data Quality, Privacy, and Security
- Costs and Return on Investment

Each of these challenge areas are further discussed below.

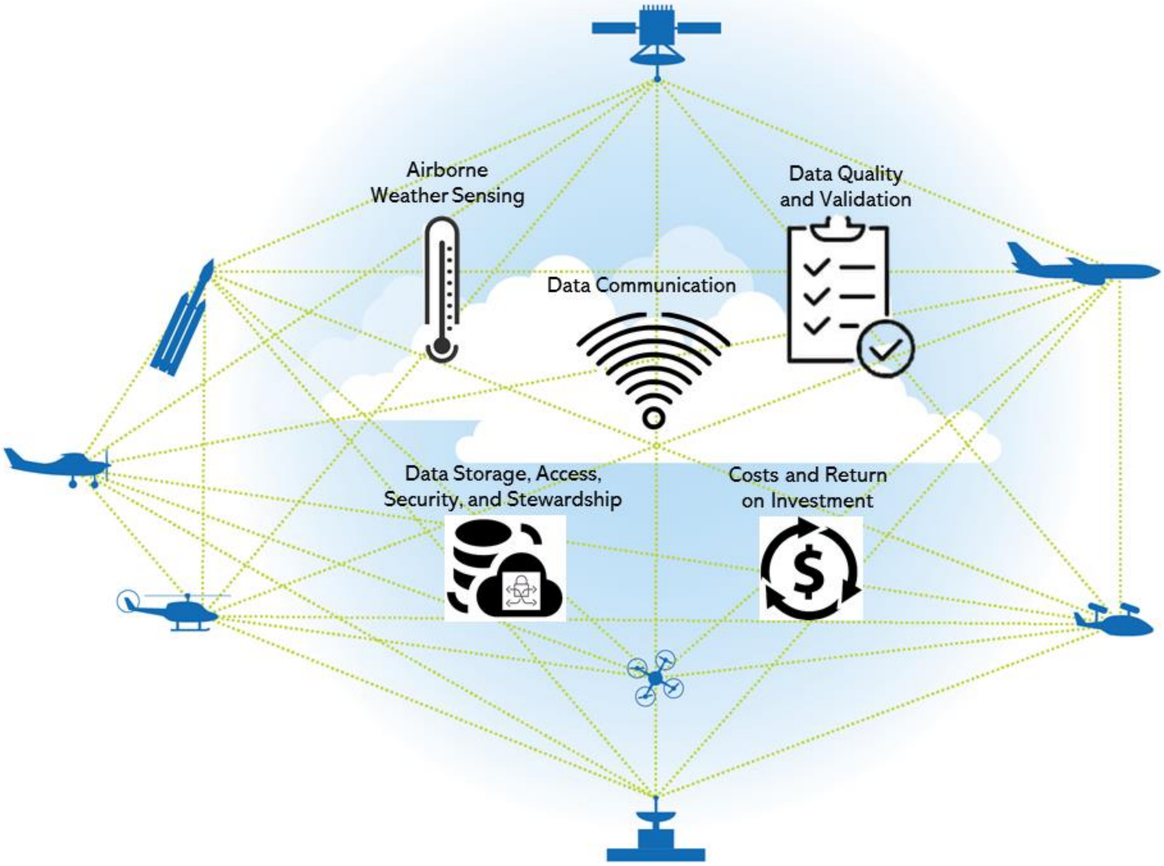

Figure 5. Key challenge areas associated with U-ABO.

5.1 Potential Technical Challenges: Sensors, Communication, and Storage

In order to properly capture all technical hurdles associated with this concept, it is useful to first look from a systems engineering perspective at the prospective, overall U-ABO process for observing, disseminating (air and ground), managing and storing, and consuming in situ weather conditions from all airborne vehicles. By doing so, key, required, end-to-end elements, along with any associated technical impediments, can be summarized, appropriately aggregated, and evaluated as potential challenges.

There are two primary categories of needed onboard components that will prove challenging for U-ABO:

- Airborne Weather Sensing
- Data Assimilation and Communications

Similarly, two primary categories of needed ground components will prove challenging for U-ABO:

- Ground Receivers and Relays
- Data Repositories

All four categories are further discussed in the following sections.

5.1.1 Airborne Weather Sensing

Technical challenges associated with aircraft weather sensors, particularly those intended for sUAS vehicles, include size, power consumption, accuracy (uncertainty), calibration and mounting location, and response time and sampling frequency. Each is briefly discussed below.

Weather Sensor Size and Power Consumption

Despite weather sensor miniaturization advancements (recall Section 2.3 of this paper), the size and weight of weather sensors will pose challenges to sUAS vehicles. Today, some sUAS vehicles are too small to install even miniaturized weather sensors currently available or being developed. This subclass of sUAS vehicles may never be large enough to support even the smallest, envisioned weather sensors. Therefore, consensus will eventually be needed to define the minimal size / weight of sUAS for which U-ABO capabilities will be required. Power consumption of onboard weather sensors is also a critical component that must be managed for all electric-powered sUAS vehicles, whose range of missions and applications may be largely dependent on very finite battery power reserves.

Weather Sensor Calibration and Mounting Location

Weather sensors should be calibrated against known conditions prior to being installed on the aeronautical vehicle, so that their measurement uncertainty is minimized and understood. There is a need to develop calibration standards that can be followed by the pertinent suppliers and operators of all aeronautical vehicles supporting U-ABO.

Over time, the accuracy of some weather sensors can degrade, necessitating their recalibration or repair. Unfortunately, the weather sensors themselves do not, at this time, recognize when recalibration is required. Therefore, aeronautical vehicle operators, manufacturers and/or weather sensor suppliers must define and execute procedures for routine calibration monitoring and management. Standards will be needed to define recalibration protocols for onboard weather sensors.

Weather sensor performance, particularly for specific weather phenomena, will also be sensitive to where the sensor is positioned on an aeronautical vehicle. For example, Greene et al. demonstrate how observed, in situ temperature measured by a weather sensor aboard rotary-wind UAS vehicles can be significantly influenced by sensor placement on the vehicle [31]. Much more research is needed to identify the optimal locations for weather sensors on the various types and classes of aeronautical vehicles, using potentially different types of weather sensors to observe different weather phenomena.

Weather Sensor Accuracy (Uncertainty)

Considerable research has been conducted on uncertainties associated with properly calibrated, relatively new weather sensors used on commercial aircraft participating in the AMDAR program. Through these efforts, potential inconsistencies among weather sensors and retrieved measurements for different aircraft types have been mitigated. Information on aircraft weather sensor uncertainties compiled by the World Meteorological Organization (WMO) is available in [32].

Comparable efforts and associated information may not currently exist for other types of conventional aeronautical vehicles (e.g., general aviation aircraft, helicopters), and must eventually also be comprehensively conducted for UAS and UAM vehicles and the potential range of utilized, onboard weather sensors. Although some initial efforts have explored the potential variability in airborne weather measurements observed by sUAS aircraft (e.g., [33]), significant efforts will need to be undertaken to produce similar accuracy or standards information for these under-represented aeronautical vehicle types.

Weather Sensor Response Time and Sampling Frequency

The response time and sampling frequency of a weather sensor ultimately defines the resolution of onboard observations (horizontal and vertical). They are also partially determined by the amount of data that is transmitted by the aeronautical vehicle to other, nearby aircraft and to the ground. Although sensor response time standards have been proposed (e.g., see [15] , pages 76-77), there remains a strong need for the development and publication of robust, consensus sensor range, accuracy, response time and sampling frequency standards. These standards will be dependent upon the capabilities of the weather sensors and the observation needs of vehicle types, operating conditions and missions, as well as the potential improvements to numerical weather predictions that may result from additional assimilated ABO data by weather type and location.

5.1.2 Assimilation/Communications Capability

In situ weather information only benefits the sensing vehicle until it is communicated from that aircraft and assimilated (automatically or via external service intervention) for subsequent consumption by other aeronautical vehicles. Legacy commercial and (some) business aircraft, as well as larger, unmanned aircraft (most often operated by the military) are equipped with systems that can accomplish the needed assimilation and communications tasks. It is the group of aeronautical vehicles “in the middle” that may prove most challenging.

For most legacy commercial aircraft, assimilation/communications capabilities are well understood, relatively mature and commonly installed. Weather sensors are connected to internal aircraft systems so that the sensed atmospheric information can be leveraged by consuming onboard components such as the Flight Management System (FMS). They are also connected to communications capabilities such as the Aircraft Communications, Addressing and Reporting System (ACARS) and/or the Automatic Dependent Surveillance – Broadcast (ADS-B) system, so that the sensed weather information can be distributed from the aircraft to ground-based receiving stations and/or adjacent aeronautical vehicles. As was the case with weather sensors, manufacturers automatically install the assimilation and communications capabilities needed to provide aircraft-based observations in most new aircraft by default, while the installation of similar capabilities on existing aircraft will continue to take place at a much slower pace, due to the retrofitting costs mentioned in Section 2 and below.

Assimilation/communications solutions for UAM / UAS vehicles are comparable to those found on legacy aircraft, differing primarily in size and communications methods. All UASs have built-in communications capabilities by default. However, how best to use these capabilities to transmit (and receive) in situ weather information to/from nearby vehicles as well as to ground receiving stations will require significant evaluation and testing.

It is important to note that less sophisticated business aircraft, general aviation aircraft, and helicopters have not been routinely outfitted with similar assimilation and communications systems, and it may be a challenge to convince manufacturers of these platforms of the need to do so. However, there are several portable assimilation and communications options that all legacy and emerging vehicles can leverage in support of U-ABO, along with multiple third-party systems and satellite technology that could help resolve potential equipage gaps. Industry organizations such as the Aircraft Owners and Pilots Association (AOPA) and the General Aviation Manufacturers Association (GAMA) may also need to be engaged to fully resolve this gap.

5.1.3 Ground Receivers and Relays

For legacy aircraft participating in the AMDAR program in the U.S., a robust system of ground receiving stations exists, and that system is already set up to automatically relay weather information received via ACARS to the appropriate NOAA / National Weather Service (NWS) data repository. A similarly effective number of ground stations exists for in situ weather information transmitted from any aeronautical vehicle equipped with ADS-B, which is scheduled to go operational in the U.S. in 2020. However, a challenge associated with the implementation of the ADS-B system is that the process used to relay weather information transmitted via the ADS-B system (i.e., ADS-Wx information) from the ground receiving station to the appropriate NWS data repository has not yet been implemented.

Systems that will be used to capture and relay weather observation information communicated from UAS vehicles via cellular networks have also not yet been widely implemented. Methods of taking crowd-sourced surface weather information and transmitting that via cell phones are in existence (e.g., see [34]) and should be appropriately considered and leveraged, though how best to accomplish this will require investigation and research. Some preliminary investigations into the use of the cellular network and cloud-based services to perform these functions for UAS platforms have taken place (e.g., [35]) but efforts like this require much more time and attention.

5.1.4 Data Repositories

NOAA has been successfully receiving AMDAR information from thousands of aircraft, storing it centrally and making it available via its Meteorological Assimilation Data Ingest System (MADIS) [36] for many years. Preliminary conversations with key NOAA personnel [e.g., Dr. Stan Benjamin, personal communication] suggest that this system is sufficiently scalable to receive, store, and disseminate the additional information that would be generated if every aircraft operating in the NAS was sensing and transmitting in situ weather observations.

Even if the current MADIS system is theoretically capable of being upscaled to support the anticipated increase in aircraft weather observations, changes in storage and communications capabilities will undoubtedly be required to accomplish this. Moreover, the data quality control capabilities employed currently by MADIS may likely need to be revisited and expanded to appropriately ensure that the much larger volumes of ABO data, from a larger range of aircraft vehicles types operating in more diverse airspace regions, are of suitable quality for intended uses. Additional U-ABO data challenges are further discussed in Section 5.2.

Finally, the concept of use for these collected and stored U-ABO observations may evolve significantly from the legacy use of MADIS-provided ABO, given much more frequent queries of significantly many more airborne observations for applications that will be more numerous and diverse (and often powered directly by automation). This may require that the MADIS-type data repository be supported by more advanced cloud services capable of handling the increase in number and types of queries.

5.2 Data Challenges and Considerations

There are several important questions pertaining the observed in situ weather data itself, including those related to data ownership, stewardship, access and validation. These are discussed below. In addition, important data privacy and security questions will persist; these are discussed separately in a subsequent section.

5.2.1 Data Ownership and Access

In the NAS today, only a relatively small number of operators have invested in advanced in situ weather observation systems that provide objective reports of relative humidity, turbulence and icing. These operators consider that the weather information they collect belongs to them, even while understanding and appreciating its potential impact to flight safety; they only share it with other operators who have also invested in similar advanced in situ weather observation systems and share the same hazardous weather information with them. This question of data ownership and access becomes significantly more complex when they are many more operators, including substantially more commercial companies utilizing UAS and UAM vehicles to support both direct and indirect business objectives. If U-ABO is implemented as a directive for all aeronautical vehicles, then, by definition, all vehicle owners and operators would be observing weather and sharing it with all others who are doing similarly. However, scenarios where “collective access” may be considered unfair or inequitable, as well as potential opportunities to game this agreement, can be envisioned. Thus, data ownership and access agreements will require careful consideration, and more detailed evaluations of best practices for similar situations in other domains (e.g., energy, natural resource access).

Finally, for whatever data access agreements are to be used for U-ABO, the minimum level of in situ weather data provision must also be determined, as some vehicles and operators may be investing in additional sensors / capabilities to observe still more atmospheric characteristics (e.g., chemistry and air quality). As more and more aeronautical vehicles invest in maturing technology to observe additional atmospheric phenomena, and as the data-driven case may then be made to justify broader equipage for observing these additional features, then the minimum level of data provision should be allowed to evolve to support future benefits to aviation missions and to society as a whole.

5.2.2 Data Stewardship

As the number of aeronautical vehicles across multiple aviation sectors that support U-ABO increases dramatically over time, formal data stewardship will be required to ensure proper retrieval and storage, appropriate data quality (validation), and ease of access for approved data users. Today, there are multiple organizations who feel they own this responsibility, such as the International Air Transport Association (IATA) for objective turbulence information from commercial aircraft, the NOAA NWS for all AMDAR data in the U.S. and FLYHT Aerospace Solutions Ltd. for all TAMDAR data worldwide. These efforts will serve as initial roadmaps and provide some best practices for data stewardship.

However, as cloud services advance in support of big data management (including a data source such as U-ABO), and the different needs for U-ABO data evolve given the broader range of vehicle types, airspace location, and applications, oversight of the U-ABO data, either through a single effort or, more likely, a connected network of ‘stewards,’ will need to be closely evaluated to ensure all needs are met.

5.2.3 Data Quality Control and Validation

Given issues associated with sensor uncertainty (accuracy, calibration and mounting location), data quality control and validation will be critically important functions required for all U-ABO data. Challenges here are multi-faceted and include considerations for:

- Defining data as “accurate” and “well-calibrated” for discrete weather variables (e.g., temperature, wind speed and direction) measured by different sensors on different vehicles operating in different operating environments (airspace)
- Assuring data quality and validated performance with appropriate timeliness and frequency
- Using “crowd sourcing” techniques to leverage vicinity observations and a denser ABO network to enhance data quality assurance and validation capabilities
- Defining the proper organizational approach for data quality control and validation (e.g., one centralized effort / organization or executed as part of the responsibilities of a network of data stewards?)

5.3 Privacy and Security Challenges and Considerations

Communal use of U-ABO data collected from many individual users may come with conditions for use that will need to be defined and implemented. For example, shared U-ABO data will likely need to be encrypted and/or de-identified of the source of information, to better protect privacy concerns. These types of data privacy steps will help companies and organizations maintain some anonymity when operating aeronautical vehicles for purposes specific to their business or operation. How best to define, implement, and govern U-ABO data privacy policies and technologies to prevent misuse of information must be evaluated as part of this proposed mandate in order to prevent the misuse of information, which must also be more closely considered.

Methods to be deployed for communicating and relaying U-ABO information from one aeronautical platform to another, or from an aircraft to the ground, will be at risk for cyber interference. Researchers have already demonstrated the exploitation of modern automobile automation systems; given that the implication of such intrusion to airborne automation systems is even greater, more consideration is needed to determine how best to protect aeronautical vehicles, the environment in which they operate, and vast archives of collected U-ABO data from bad actors.

5.4 Costs and Return on Investment

As discussed earlier, a U-ABO mandate will contribute significantly to improved weather forecasts that will provide benefit to both the aviation community and society as a whole. Analyses have indicated that weather forecast improvement benefit/cost ratios range from 4:1 to >10:1 (e.g., [37] [38] and [39]). Given that U.S. does not directly charge for domestic use of its airspace, requirements for observing and transmitting airborne, in situ weather information could be considered a shared contribution (for being able to operate in the NAS) that collectively supports all aviation missions and broader societal needs.

The above notwithstanding, the necessary aeronautical weather sensors and systems, the requisite communications capabilities and any required new ground systems or upgrades to existing systems will still come at a cost. Although operators may agree that the projected values and ROIs are real, they will struggle to understand how they will individually benefit from their financial participation. Funding this proposed U-ABO position, as is the case with most weather-related infrastructure improvements, will be a significant challenge, and the resistance to the concept will be extreme if its financial aspects are not handled adroitly.

One overall financial strategy would be to minimize initial and ongoing operator costs to the extent practical, while taking advantage of existing systems and technologies, and the convergence of developing technologies wherever possible. Even with these measures, acceptance of additional financial needs will be challenging. Therefore, for all efforts to develop, define, standardize, and execute a U-ABO mandate, the quantifiable benefits and return on investment, understood from the perspectives of operators and stakeholders, must be routinely included as part of the implementation narrative.

6. Charting a Path Forward

We believe the mandate proposed in this paper for required in situ weather observations and reporting from all aeronautical vehicles in the NAS is a targeted objective that the communities of interest should strive to achieve. To start, we have summarized the motivation, opportunities, potential benefits, and mindful challenges that start to shape the overall value proposition of this proposed mandate, as well as prioritized hurdles for which concerted focus and momentum must be mounted to manage and overcome.

Successful achievement of envisioned U-ABO will require multi-faceted advancements that can be shared among diverse stakeholders. They must clearly and objectively understand and recognize the need and value of the constituent components that will ensure the overarching goals are attained. In practice, this is extremely difficult to achieve.

Given the challenges and complexities associated with the 'moving parts' that will contribute to achieving this mandate, it is important that initial execution and outreach processes are not over-engineered. At the same time, some structure is required to ensure that early attention is parceled appropriately for both execution and outreach efforts. U-ABO needs must be understood (and eventually addressed) and demonstrable evidence of opportunities and value must be used to help build momentum and to ensure buy-in. This paper starts the conversation and provides the auspices to begin outreach to key, yet-to-be-identified stakeholders.

MITRE and NCAR, in line with their charters as operating Federally Funded Research and Development Centers (FFRDCs), are willing to help organize and host initial U-ABO workshops. These will be used to drive towards key objectives defined by initial stakeholders and informed, interested parties. Ideally, stakeholders participating in these workshops would represent pertinent government agencies (e.g., NOAA, NASA, FAA, DOT, DHS, NIST[5]), private industry (e.g., sensor and vehicle manufacturers, vehicle operators, UAS Service Suppliers and mission support, cloud services providers), and university researchers. Workshops could be organized as a series of multi-day sessions targeting key topic areas requiring closer scrutiny and clearer vision for achieving U-ABO. Experts pertinent to the above topics would be targeted as participants for these specified workshops, but the workshop would be open to the broader, interested community, in the hopes that "cross-pollinating" discussions and debates would increase collective understanding, buy-in, and near/far-term opportunities for achieving U-ABO.

U-ABO workshops could be organized along dual-tracks that balance the needs for articulating a comprehensive U-ABO value proposition while dedicating effort and resources towards greater understanding, and eventual resolution, of U-ABO challenges and obstacles. Ideally, an initial U-ABO workshop series will empower stakeholders from various areas of expertise to take ownership in this position and advocate, as experts, for the position's value and merits. They will also then be able to extend these early thoughts, concepts, and the initial framework and shape it from their informed perspectives, better honing value propositions, refining opportunities for achievable innovations to meet critical needs for this mandate, and better prioritizing key challenges that will require significant attention and collaboration to overcome.

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[5] DHS: Department of Homeland Security; NIST: U.S. National Institute of Standards and Technology

Stakeholder empowerment and associated clarity of opportunities and needs borne out of U-ABO workshops may lead to more advanced, collaborative concept and technology development engagements to further test and validate U-ABO. Opportunities to include U-ABO activities include the following:

- FAA UAS Integration Pilot Program (IPP) evaluations [40]
- NASA Aeronautics Research Mission Directorate (ARMD) “Grand Challenge” collaborative partnership demonstrations, such as the NASA UAM Grand Challenge [41]
- “Flight Week” field evaluations sponsored by the International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA) (e.g., [42], [33])
- Pertinent commercial industry testing and evaluation, such as is planned by Google Wing, UPS, Uber Elevate, Amazon Prime Air, and Airbus Voom (e.g., [43], [44], [45], [46], [47])
- Standards Body (e.g., accommodating new observations, aligned with legacy, etc.); U.S. and International

Successful culmination of the U-ABO workshop series may be an incremental implementation strategy and roadmap, ideally championed by a public-private consortium dedicated to supporting and funding needed research, development, testing, validation, and execution of defined U-ABO activities.

7. Summary

The MITRE and NCAR authors promote the following mandate for “Ubiquitous ABO” (U-ABO):

All aeronautical vehicles operating in the NAS must measure, transmit, and share in situ weather conditions, to benefit aviation missions and society as a whole.

This mandate is a product of the following:

- The successful deployment and demonstrated utility of conventional ABO’s collected and shared by commercial aircraft over the past several decades
- The significant value assimilated ABO data provides to numerical weather prediction models, notably contributing to improved weather forecasts
- The opportunity presented by the emergent air transportation transformation involving advanced vehicle technologies supporting envisioned UAS and UAM operations, which take place largely within the PBL, where atmospheric measurements important to weather modeling have been limited to date
- The expected significant increase in the volume of airborne vehicles as UAS and UAM operations mature, and their (a) commensurate need for situ weather information to ensure safe, efficient flight and (b) the opportunity to ‘forward-fit’ and equip these vehicles with appropriate weather sensors while the industry is still developing.

This paper has initially defined the U-ABO landscape that motivates the presented position while also recognizing and presenting the associated range of challenges and potential obstacles that must be overcome. Given these, and likely other, U-ABO challenges, it is recommended that initial execution and outreach efforts by interested stakeholders not be overly engineered. Instead, a series of initial U-ABO workshops (which MITRE and NCAR are willing to help organize and host) should be convened by government and private industry stakeholders with interest and expertise specific to key U-ABO topic areas. These workshops could be organized along dual-tracks that balance the needs for clearly defining and prioritizing U-ABO value propositions, and resources could be dedicated towards technological advancements and procedural and implementation best practices that can be leveraged to resolve challenges and eliminate obstacles.

The MITRE/NCAR team considers the coming decade to be the right time to provide significant weather impact mitigations and to reduce the weather sensitivity of the aviation and aerospace industries and society at large. Using recent breakthroughs in vehicle, sensor, communications and computing technologies, we believe the aviation, aerospace and meteorological communities are ready to collaboratively leverage big-data analytics, cloud storage, networking, artificial intelligence and material innovations to collect, provide, and apply U-ABO data for significant air travel safety, efficiency and reliability improvements for all current operations; address the new operational concepts to be deployed in the NAS over the next decade; and at the same time produce significant weather forecast improvements that benefit overall societal safety and well-being.

References

[1] J. Stith et al, *100 Years of Progress in Atmospheric Observing Systems (Chapter 2), Mongraph: A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial,* American Meteorological Society (AMS), 2019.

[2] Federal Aviation Administration, "Fact Sheet - Small Unmanned Aircraft Regulations (Part 107)," 23 July 2018. [Online]. Available: https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22615. [Accessed November 2019].

[3] M. Patterson, K. Antcliff and L. Kohlman, "A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements," in *American Helicopter Society (AHS) International 74th Annual Forum and Technology Display*, Phoenix, AZ, 2018.

[4] M. Steiner, "Urban Air Mobility - Opportunities for the Weather Commuity," Bulletin of the American Meteorological Society, 100(11), 2019.

[5] Federal Aviation Administration, "Vision for Trajectory Based Operations, Version 2.0," 2017.

[6] National Academies of Sciences, Engineering, and Medicine, "The Future of Atmospheric Boundary Layer Observing, Understanding, and Modeling: Proceedings of a Workshop," in *National Academies Press*, 2018.

[7] K. Modolo, "Three Ways Delta's Groundbreaking Turbulence App is Changing the Way We Fly," December 2018. [Online]. Available: https://news.delta.com/3-ways-delta-s-groundbreaking-turbulence-app-changing-way-we-fly. [Accessed 2019].

[8] International Air Transport Association (IATA), "IATA Launches Platform Enabling Airlines to Share Turbulence Data," December 2019. [Online]. Available: https://www.iata.org/pressroom/pr/Pages/2018-12-12-02.aspx?utm_source=turbulence-webpage&utm_medium=resource&utm_content=article-link. [Accessed 2019].

[9] G. Enea, R. Sgorcea, J. Timberlake, S. Osborne and W. Symionow, "Operational Integration of Required Time of Arrival (RTA) with Time Based Management (TBM): Concept of Operations and Human-in-the-Loop Simulation Results," in *Aviation Forum: Aviation Technology, Integration, and Operations Conference*, Atlanta, 2018.

[10] S. Benjamin, J. Brown, G. Brunet, P. Lynch, K. Saito and T. Schlatter, "100 Years of Progress in Forecasting and NWP Applications," *AMS Monograph: A Century of Progress in Atmospheric and Related Sciences: Celebrating the American Meteorological Society Centennial,* 2019.

[11] M. Buehner, J. Morneau and C. Charette, "Four-dimensional Ensemble-variation Data Assimilation for Global Deterministic Weather Prediction.," *Nonlinear Processes Geophys.,* vol. 20, pp. 669-682, 2013.

[12] E. James and S. Benjamin, "Observation System Experiments with the Hourly-updating Rapid Refresh model using GSI Hybrid Ensemble-variational Data Assimilation," *Monthly Weather Review,* vol. 145, pp. 2897-2918, 2017.

[13] E. James, B. Jamison and S. Benjamin, "The Spatial and Temporal Distribution of Commercial Aircraft Weather Observations for Assimilation into Numerical Weather Prediction Models, 19th Conference on Aviation, Range, and Aerospace Meteorology," 2019. [Online]. Available: https://ams.confex.com/ams/2019Annual/videogateway.cgi/id/50660?recordingid=50660. [Accessed 2019].

[14] J. Jacob, D. Axisa and S. Oncley, "Unmanned Aerial Systems for Atmospheric Research: Instrumentation Issues for Atmospheric Measurements," in *NCAR / EOL Community Workshop on Unmanned Aerial Systems for Atmospheric Research*, 2017.

[15] B. Argrow et al., "The NCAR / EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research, Final Report," 2017.

[16] https://www.adafruit.com/product/2652, "BME280 I2C or SPI Temperature Humidity Pressure Sensor," 2019.

[17] K. Kuhn, "Small Unmanned Aerial System Certification and Traffic Management Systems," RAND Corporation, 2017.

[18] Federal Aviation Administration, "Advisory Circular 90-105: Approved Guidance for RNP Operations and Barometric Vertical Navigation in the U.S. national Airspace System," 23 January 2009. [Online]. Available: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC%2090-105.pdf. [Accessed December 2019].

[19] U.S. Department of Transportation, "Challenges in Implementing Performance-Based Navigation in the U.S. Air Transportation System: Statement of Ann Calvaresi Barr, Principal Assistance Inspector General for Auditing and Evaluation, U.S. DOT," 29 July 2009. [Online]. Available: https://www.oig.dot.gov/sites/default/files/WEB_FILE__RNAV_and_RNP_Testimony.pdf. [Accessed November 2019].

[20] U.S. Government Accountability Office, "Next Generation Air Transportation System: FAA Faces Implementation Challenges," 12 September 2012. [Online]. Available: https://www.gao.gov/assets/650/648122.pdf. [Accessed November 2019].

[21] The MITRE Corporation, "NextGen Independent Assessment and Recommendations," McLean, VA, 2014.

[22] U.S. Department of Transportation Inspector General, "Top Management Challenges for Fiscal Year 2019: Federal Aviation Administration Action Plans," 2018. [Online]. Available: https://www.faa.gov/about/plans_reports/media/FY18_Action_Plans.pdf. [Accessed 2019 November].

[23] World Meteorological Organization (WMO), "About the AMDAR Observing System," WMO, May 2017. [Online]. Available: https://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/About.html. [Accessed 2019].

[24] T. Rahmes, R. Stone and N. Polderman, "Increasing Adoption of Weather and Turbulence Observations," in *3rd Turbulence Impact Mitigation Workshop*, McLean, VA, 2018.

[25] FAA, "FAA, "FAA Aerospace Forecasts: Unmanned Aircraft Systems," Federal Aviation Administration, Washington DC, 2019.," DOT-FAA, Washington, D.C., 2019.

[26] International CIvil Aviation Organization, "Unmanned Aircraft Systems (UAS), Cir 328, AN/190," International CIvil Aviation Organization, Montreal, Quebec, Canada, 2011.

[27] Booz Allen Hamilton, "Executive briefing. Urban air mobility (UAM) market study.," 2018.

[28] "Flight plan 2030, An Air Traffic Management Concept for Urban Air Mobility," 2019.

[29] J. Dutton, "Opportunities and Priorities in a New Era for Weather and Climate Services," *Bull. Amer. Meteor. Soc.,* vol. 83, pp. 1303-1311, 2002.

[30] J. Lazo, M. Lawson, P. Larson and D. Waldman, "U.S. Economic Sensitivity to Weather Variability," *Bull. Amer. Meteor. Soc.,* 2011.

[31] B. Greene, A. Segales, S. Waugh, S. Duthoit and P. Chilson, "Considerations for Temperature Sensor Placement on Rotary-Wind Unmanned Aircraft Systems," *Atmospheric Measurement Techniques,* vol. 11, pp. 5519-5530, 2018.

[32] World Meteorological Organization, "Aircraft Meteorological Data Relay (AMDAR) Reference Manual," Geneva, Switzerland, 2003.

[33] L. Barbieri et al., "Intercomparison of Small Unmanned Aircraft System (sUAS) Measurements for Atmospheric Science during the LAPSE-RATE Campaign," *Sensors (Basel),* vol. 19, no. 9, 2019.

[34] CitizenScience.gov, "mPING - Crowdsourcing Weather Reports," National Weather Service, [Online]. Available: https://www.citizenscience.gov/mping-weather-reports/#. [Accessed 17 12 2019].

[35] J. Burns, "Drone Enterprise Solutions," Friends and Partners in Aviation Weather, Las Vegas, NV, 2017.

[36] National Oceanic and Atmospheric Administration, "MADIS Meteorological Assimilation Data Ingest System," 25 July 2018. [Online]. Available: https://madis.ncep.noaa.gov/. [Accessed 17 12 2019].

[37] M. Gray, "Public Weather Service Value for Money Review," 2015.

[38] P. Nurmi, A. Perrels and V. Nurmi, "Expected impacts and value of improvements in weather forecasting," *Meteorological Applications,* vol. 20, pp. 217-223, 2013.

[39] J. K. Lazo and L. G. Chestnut, "Economic Value of Current and Improved Weather Forecasts in the U.S. Household Sector," Stratus Consulting, Boulder, CO, 2002.

[40] Federal Aviation Administration, "UAS Integration Pilot Program," December 2019. [Online]. Available: https://www.faa.gov/uas/programs_partnerships/integration_pilot_program/. [Accessed December 2019].

[41] National Aeronautics and Space Administration, "NASA's UAM Grand Challenge," December 2019. [Online]. Available: https://www.nasa.gov/uamgc. [Accessed 2019 December].

[42] International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA), "ISARRA," December 2019. [Online]. Available: http://www.isarra.org/. [Accessed December 2019].

[43] Transport Topics, "Walgreens, Google Affiliate Wing to Launch Drone Delivery Test," 20 September 2019. [Online]. Available: https://www.ttnews.com/articles/walgreens-google-affiliate-wing-launch-drone-delivery-test. [Accessed December 2019].

[44] CNBC, "UPS Wins First Broad FAA Approval for Drone Delivery," 1 October 2019. [Online]. Available: https://www.cnbc.com/2019/10/01/ups-wins-faa-approval-for-drone-delivery-airline.html. [Accessed December 2019].

[45] Paper City, "Uber's new Flying Taxis to Take Off in North Texas," 20 September 2019. [Online]. Available: https://www.papercitymag.com/culture/uber-flying-taxi-frisco-texas-testing-groud-close-look/. [Accessed December 2019].

[46] Business Insider, "Amazon's Drone Delivery Service is One Step Closer to Taking Flight," 5 June 2019. [Online]. Available: https://www.businessinsider.com/amazon-prime-air-drones-approved-by-faa-2019-6. [Accessed December 2019].

[47] Airbus, "Voom: An On-Demand Helicopter Booking Platform," July 2019. [Online]. Available: airbus.com/innovation/urban-air-mobility/voom.html. [Accessed December 2019].

[48] D. Jenkins, B. Vasigh, C. Oster and T. Larsen, "Forecast of the Commercial UAS Package Delivery Market," 2017.

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