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Preliminary Weather Information Gap Analysis for UAS Operations

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16. Abstract

Unmanned Aircraft System (UAS) operations in the National Airspace System (NAS) are rapidly increasing. For example, 2017 has seen dramatically increased low altitude UAS usage for disaster relief and by first responders. The ability to carry out these operations, however, can be strongly impacted by adverse weather conditions. This report documents a preliminary quick-look identification and assessment of gaps in current weather decision support for UAS operations. An initial set of surveys and interviews with UAS operators identified 12 major gaps. These gaps were then prioritized based on the importance of the weather phenomena to UAS operations and the current availability of adequate weather information to UAS operators.

Low altitude UAS operations are of particular concern. The lack of observations of ceiling, visibility, and winds near most low altitude UAS operational locations causes the validation of numerical weather forecasts of weather conditions for those locations to be the highest priority.

Hazardous weather alerting for convective activity and strong surface winds are a major concern for UAS operations that could be addressed in part by access to existing FAA real time conventional aircraft weather products.

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ABSTRACT

Unmanned Aircraft System (UAS) operations in the National Airspace System (NAS) are rapidly increasing. For example, 2017 has seen dramatically increased low altitude UAS usage for disaster relief and by first responders. The ability to carry out these operations, however, can be strongly impacted by adverse weather conditions. This report documents a preliminary quick-look identification and assessment of gaps in current weather decision support for UAS operations. An initial set of surveys and interviews with UAS operators identified 12 major gaps. These gaps were then prioritized based on the importance of the weather phenomena to UAS operations and the current availability of adequate weather information to UAS operators.

Low altitude UAS operations are of particular concern. The lack of observations of ceiling, visibility, and winds near most low altitude UAS operational locations causes the validation of numerical weather forecasts of weather conditions for those locations to be the highest priority.

Hazardous weather alerting for convective activity and strong surface winds are a major concern for UAS operations that could be addressed in part by access to existing FAA real time conventional aircraft weather products.

EXECUTIVE SUMMARY

Unmanned aircraft system (UAS) operations in the National Airspace System (NAS) are rapidly increasing, and the trend is expected to continue as regulations are refined to allow broader access to the airspace.[1] However, the system must maintain a high level of safety throughout its growth in order for the potential of UAS to be realized.

Historically, weather has presented a significant hazard to all types of aviation, and weather products for manned aviation have evolved over time to reflect changing user needs. The unique characteristics of UAS (e.g., extensive operations in populated areas at altitudes below 500 feet, speed capability, control systems) will require that existing aviation weather products be further refined to address differences between unmanned and manned operations.

The objective of this study is to identify information gaps in the ability of current weather products[2] to meet the needs of UAS operations. It is important to understand that not addressing the information gaps could delay or preclude the many unique benefits of UAS operations. For example, weather-induced safety incidents not only risk damage to people, property, and other aircraft, but they also degrade the public perception of UAS. Moreover, the life-saving benefits of certain first responder UAS missions are dependent on the ability of the mission to be completed in a variety of weather conditions. Lastly, successful UAS integration is contingent on the ability of future airspace management strategies to remain both feasible and efficient in different weather situations.

Figure 1 shows the weather information gap identification process. The process is based on survey and interview feedback from the UAS operational community in addition to an analysis of currently available aviation weather products. In all, this report is based on 90 survey responses and 16 interviews from a range of operators, including emerging UAS missions such as first responders (e.g., firefighters and disaster relief). UAS integration and traffic management strategies and responsibilities are gathered from the Federal Aviation Administration (FAA) UAS Concept of Operations, and the National Aeronautics and Space Administration (NASA) UAS Traffic Management Concept of Operations. UAS weather needs are classified based on the typical altitude, range, and duration of similar missions and use cases, and are listed

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[1] The 2016 FAA Aerospace Forecast suggests that more than 7 million small unmanned aircraft are expected to be purchased by 2020 with 2.5 million sales forecasted for 2016 alone. By 2020, the FAA projects that there will be 4.3 million aircraft flying for recreational purposes and 2.7 million flying for commercial reasons.

[2] Examples of currently available weather information for UAS operators are the NWS Aviation Weather Center (AWC) website and commercial providers such as ForeFlight (https://www.foreflight.com/).

in Table 1. The division of the mission classes is intended to distinguish UAS weather needs for different operational profiles.

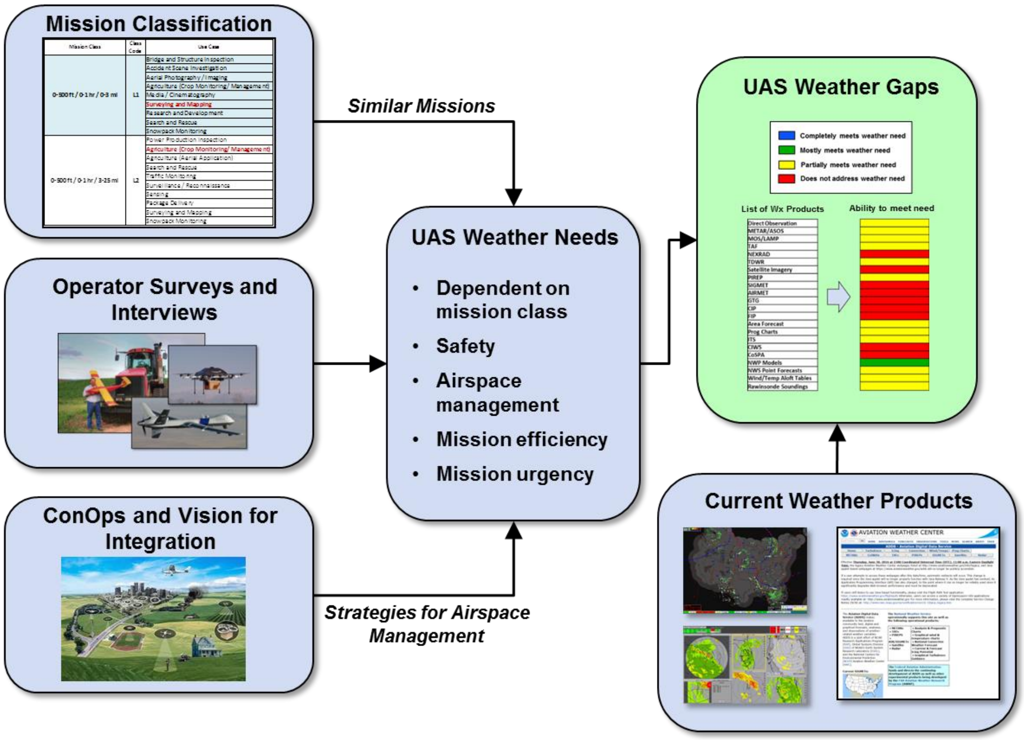

Figure 1 Weather information gap identification process.

Table 1. UAS Mission Classification

Mission Class	Altitude	Mission Range	Mission Duration
1	0–500 feet	0–3 NM	0–1 hour
2	0–500 feet	3–25 NM	0–1 hour
3	0–500 feet	3–25 NM	1–12 hours
4	0–500 feet	25+ NM	1–12 hours
5	500 feet – FL250	25+ NM	1–12 hours
6	FL250+	25+ NM	1–12 hours
7	FL250+	25+ NM	12+ hours

Table 2 lists the weather elements considered in the analysis. The weather elements are selected to represent a comprehensive set of conditions that may impact UAS operations.

Table 2

Weather Elements

Weather Elements	
Surface Wind	Convective Weather
Wind Aloft	Clouds/Ceiling
Temperature	Visibility
Barometric Pressure	Turbulence
Precipitation	Icing

Weather information gaps for each of the weather elements and mission classes are rated based on the significance of each weather element across the mission classes and the effectiveness of current weather products to meet the specific needs of each mission class. Table 3 provides the scoring methodology for weather significance and product effectiveness. The weather information gap rating is the sum of the weather need significance and weather product effectiveness scores.

Table 3

Weather Information Gap Scoring

Score	Weather Need Significance	Weather Products
3	Always influences safety / airspace management	Infrequently meets weather need
2	Frequently influences safety / airspace management	Partially meets weather need
1	Occasionally influences safety / airspace management	Mostly meets weather need
0	Infrequently influences safety / airspace management	Completely meets weather need

It is important to note that the majority of survey feedback comes from small UAS (weight < 55 lbs) Visual Line of Sight (VLOS) operators. The only Beyond Visual Line of Sight (BVLOS) survey feedback is based on large UAS military operations. This is mainly driven by the current operational environment, meaning the survey feedback is reflective of weather needs for the current type of UAS operations. Weather needs for to-be-realized UAS operations (e.g., more frequent BVLOS operations and use by first responders and homeland security) are identified through 1) interviews with the FAA Pathfinder program, 2) by inferring operational needs in the FAA UAS Concept of Operations and the NASA UAS Traffic Management (UTM) Concept of Operations, and 3) by interviewing first responder stakeholders. Weather information gaps are identified by first qualitatively comparing the current set of available weather information to the weather needs. The qualitative analysis is then followed by quantitative analysis of the weather information content where possible.

Operator Survey Results

As explained above, the significance of each weather element is determined mainly through survey feedback. Figure 2 shows the response of small and large UAS operators to the question of "*Provide the significance of each weather condition to the feasibility of your operation.*" It is important to note that this is the significance of the weather for the current operational environment, not an indication of the size of a weather information gap.

Convective weather is the most significant weather condition for both small and large UAS. For small UAS, precipitation is significant due to the water-sensitive nature of typical small UAS platforms. Small UAS are also more sensitive to surface wind speed, visibility, and ceiling. Large UAS operators find ceiling and visibility less significant, but icing more significant – most likely due to the BVLOS nature of large UAS operations and lack of deicing equipment. Large UAS are also sensitive to surface wind direction because they typically operate out of runways and have conservative crosswind limits.

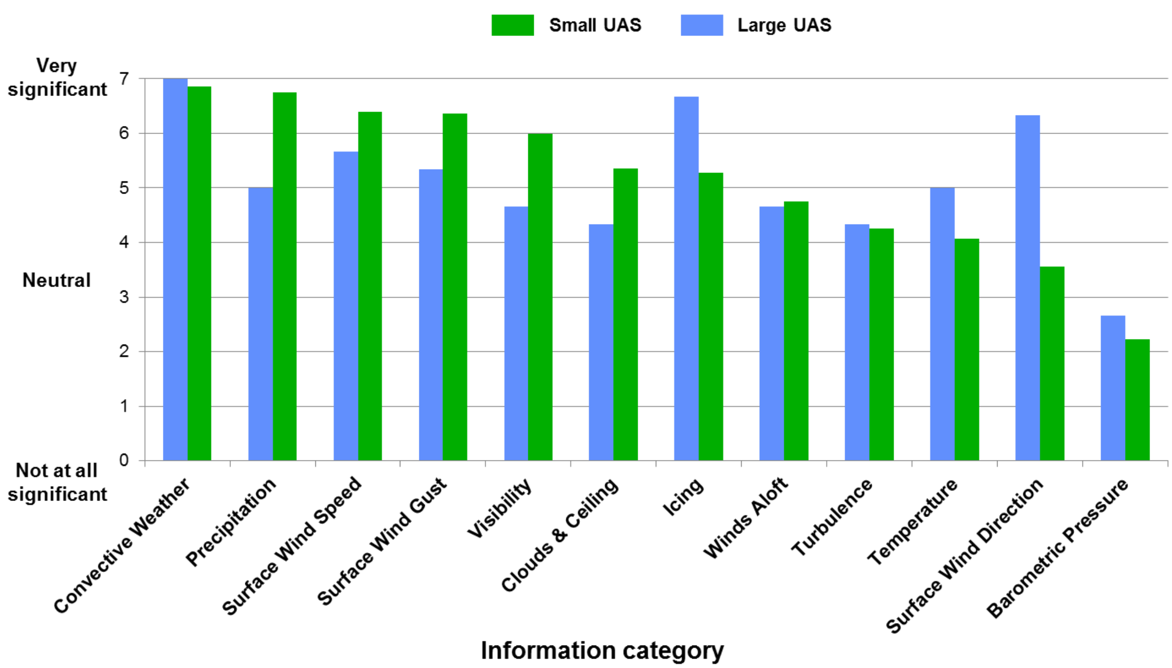

Figure 2. Weather condition significance as determined by survey feedback. Results are broken out by small UAS and large UAS respondent scores.

VLOS Weather Needs

The FAA has established small UAS operating rules (CFR Part 107) to guide VLOS operations. From a weather standpoint, Part 107 rules require the operator be aware of local weather conditions, only operate if the slant range visibility to the UAS is greater than 3 statute miles, and maintain cloud clearances of 500 feet below and 2000 feet horizontal distance from the clouds.

An interesting side-effect of VLOS operations is that the operator is physically located at the mission site, where they can visually and tactically observe the local weather conditions. This allows the UAS operators to 'ball-park' local weather conditions in making operational decisions. In general, survey respondents who conduct VLOS operations noted that they do not have an effective method to determine wind speed and direction above tree-level, or if they are operating in an urban environment or a location with complicated terrain. This was also true in making local visual estimates of ceiling height and visibility to conform to Part 107 regulations.

Wind gusts and turbulence can decrease flight endurance due to the additional flight control power necessary to maintain steady flight. Moreover, strong or gusty winds can overcome the ability of a small UAS to maintain position if the wind speed is greater than the forward speed capability of the UAS. Furthermore, UAS that conduct VLOS operations are not typically sealed to water, meaning that any precipitation can cause electrical failure. Lastly, UAS are susceptible to altitude errors if they utilize a pressure altimeter calibrated to ground level at launch to determine height above the landing site in lieu of a radar altimeter.

BVLOS Weather Needs

Small UAS are differentiated from large UAS by their size, but also by the typical altitude that they operate. Small UAS are envisioned to predominately occupy the low-altitude domain from the surface to 500 feet. Currently envisioned missions include pipeline monitoring, search and rescue, and transportation infrastructure inspection. The specific weather needs for small UAS BVLOS operations are as follows (in no particular order).

1. Turbulence/wind gusts can decrease battery performance, as well as interfere with the integrity of a satellite control & communications link.
2. Windshear and more generally, strong outflows from thunderstorms can be very dangerous at low altitude, especially for fixed wing platforms, or if the winds exceed the available airspeed capability of the UAS.
3. Barometric pressure changes can influence pressure altimeter calibration, and can be very dangerous at low altitude if a radar altimeter is not installed on the UAS.
4. Icing can build on a small airframe or propeller much faster than on a conventional aircraft.
5. Low temperatures have been shown to decrease battery life, and in turn, mission endurance.

On the other hand, a large UAS has the potential to operate at very high altitudes (FL600) and for very long mission durations (30+ hours). Turbulence is a great concern to large UAS operators due to its effect on the control and communications link. The unsteadiness caused by turbulence can destabilize the Satellite Communications (SATCOM) and interfere with communications. Many of the large UAS platforms are not equipped with deicing capabilities and are therefore susceptible to icing on departure and arrival. Moreover, large UAS are sensitive to wind direction because they typically operate out of runways and have very conservative crosswind limits. Lastly, because the large UAS typically operate at high-altitude, they have the ability to fly over convective weather as long as they know the height of the cloud tops.

The accuracy of winds aloft is critical to flight planning and the feasibility of time-based integration strategies. Small UAS that have a slow cruising speed can be overwhelmed by winds greater than 20 knots. BVLOS operations require very strict contingency planning to ensure that a feasible lost-link path is available if the UAS loses communication or control. Weather forecast uncertainty significantly impacts lost-link contingency planning due to the need to avoid the safety problems that arise with lost-link, coupled with the need to avoid overly conservative assessments of weather impact. More effective contingency planning would be possible if there were validated weather uncertainty information that could be used for risk-based planning.

Weather Needs for Airspace Management

Airspace management is a critical component of UAS integration. Both NASA and the FAA have developed visions for integration, where the NASA effort is focused on small UAS whereas the FAA considers the entire spectrum of UAS. Strategies for airspace management come in many forms and different levels of complexity:

1. The most basic form of airspace management is the static geofence, which effectively creates virtual barrier to preclude flight into certain areas. From a weather standpoint, a static geofence can be defined around an area of severe weather, but it is important to understand that different UAS types have different weather sensitivities which correspond to difference geofence boundaries. Moreover, static geofences do not capture the dynamic nature of weather, and in turn, can be a very conservative approach to airspace management.
2. Dynamic geofences move with weather or can surround a UAS along the planned route of flight to ensure separation from other aircraft. However, the usefulness of a dynamic geofence is only as good as the weather forecasts supporting it (both spatially and temporally).
3. Time-based operations are expected to be an important strategy for UAS integration. In this strategy, UAS plan and fly a 4-dimensional route to define time-on-waypoint so that flight plans are separated from other aircraft. Accurate winds aloft information are critical to achieve time-based operations. Other weather elements can also impact the feasibility of time-based operations, where the permeability of weather (e.g., the level of icing or convective weather tolerance) is largely dependent on the type of UAS being considered.
4. As the number of UAS in the airspace increases, demand and capacity balancing may be necessary to effectively allocate UAS flights to the airspace. “Airspace capacity” models for weather constrained airspace may eventually be needed to estimate and forecast the impact of weather on a heterogeneous mixture of UAS platforms.

Weather Information Gaps

It is important to understand that not addressing the information gaps could delay or preclude the many unique benefits of UAS operations. For example, weather-induced safety incidents not only risk damage to people, property, and other aircraft, but they also degrade the public perception of UAS. Moreover, the life-saving benefits of certain first responder UAS missions are dependent on the ability of the mission to be completed in a variety of weather conditions. Lastly, successful UAS integration is contingent on the ability of future airspace management strategies to remain both feasible and efficient in different weather situations.

Table 4 ranks the weather elements based on the total weather gap score across all of the mission classes. The list is divided into four groups to highlight similar weather gap scores. In other words, weather elements with similar scores are grouped together (e.g., 1a, 1b, …) to establish levels of weather gap importance. The ranking within the groups is less important than the ranking of the groups. Each weather element entry in Table 4 provides the aggregate weather significance and weather product effectiveness scores, a description of the gaps assuming access to currently available weather products, and notes on the opportunity to leverage FAA weather products to address the gaps.

There are several trends in the information gaps which surfaced repeatedly. A key item is the availability of weather observations and forecasts tailored for on-airport operations are not necessarily sufficient for off-airport operations. Surveyed users indicated that airport-specific weather information (e.g., Meteorological Terminal Aviation Routine Weather Report (METAR), Terminal Aerodrome Forecast (TAFs), etc.) did not readily translate to conditions at remote launch locations, which may be 10–30 miles from the nearest airport, and influenced by local terrain, vegetation, and water sources. Moreover, the results showed significantly less weather information available to support low-altitude flight than for typical manned-flight profiles. This is especially true in urban areas, or in areas with complicated terrain.

This brings to light the utility of numerical models, which continue to be developed at increasingly high resolution. Numerical model skill would help to resolve the off-airport issues, but more widespread and rigorous validation of numerical models would likely be necessary. This is particularly true for weather elements that are largely impacted locally, like cloud ceiling, visibility, and low altitude wind/gusts which are heavily influence by local obscurations.

Table 4

Ranking of Weather Condition by Information Gap Score and Product Availability

Rank	Weather Condition	Gap Score (Significance/ Product/Total)	Information Gap Description Assuming Access to Currently Available Weather Products	Opportunity to Leverage FAA-current and near term Weather Products
1a	Convective Weather	21/13 34	Tactical products lack short-term storm forecasts and are susceptible to latencies. Strategic products lack precision at long forecast horizons and need better uncertainty information to support decision making.	FAA products (CIWS, CoSPA, NWP) would reduce the weather gap.
1b	Winds Aloft	21/11 32	Current wind aloft forecasts lack precision and winds aloft observations are lacking in the low-altitude and super high-altitude regions.	FAA ITWS and ASR-9 WSP products provide significant improvements in wind aloft and wind shift information for major metropolitan areas.
2a	Visibility	14/11 25	Sparse off-airport observation field. Models are often inadequate, especially where there is a large variation in terrain and soil moisture	N/A
2b	Clouds and Ceiling	14/11 25	Sparse off-airport observation field. Models need evaluation in off-airport areas, especially where there is a large variation in terrain. Also, cloud layers are not resolved well, especially away from airports.	N/A
2c	Surface Winds	14/10 24	Sparse off-airport observation field. Rapid changes in surface winds (e.g., due to microburst outflows, gust fronts and sharp synoptic fronts) are not alerted. Urban wind effects are uncertain.	FAA ITWS and ASR-9 WSP products provide significant improvements in wind shift information for major metropolitan areas.

3a	Turbulence	10/12 22	Lack of validated stratospheric and low-altitude turbulence information. Models not calibrated for small UAS. Forecasts lack uncertainty element.	N/A
3b	Icing	11/11 22	Ice will build up faster on a small airframe. Models not calibrated for small UAS. Models do not account for 'cold soak'. Forecasts lack uncertainty element.	N/A
3c	Precipitation	11/7 18	Only significant for small UAS.	FAA products (CIWS, CoSPA, NWP) would reduce the weather gap.
4a	Temperature	7/5 12	No significant gaps identified.	N/A
4b	Barometric Pressure	6/4 10	No significant gaps identified.	N/A

VLOS operations were found to have higher need for weather forecasts, uncertainty information, and contingency planning than VLOS operations. For example, tactical convective weather products lack short term forecasts and can give an erroneous depiction of current storm location due to latency. Strategic convective weather products lack precision, especially at long forecast horizons, and do not provide sufficient uncertainty information to support contingency planning. Moreover, winds aloft products do not provide information to support low-altitude or super high-altitude operations. Similarly, turbulence forecasts and models are not designed to support low-altitude or super high-altitude operations, which has an impact on UAS that rely on a satellite communications link. Lastly, icing is a relatively rare event, but can have a catastrophic impact on flight safety, especially for small UAS. Icing prediction models lack uncertainty information necessary for contingency planning and may not be calibrated to properly reflect the icing risk to small UAS.

Airspace management strategies are also affected by the weather information gaps. For example, low-altitude time-based operations require validated winds aloft models and forecasts below 500 feet. Additionally, the feasibility of time-based operations (e.g., time-based metering for UAS) depends on an understanding of UAS weather impact models that are highly dependent on UAS type. Weather-based geofences will require similar UAS weather impact models for a spectrum of UAS platforms and weather conditions.

Table 5 distills the information in Table 4 into twelve specific weather information gaps that are prioritized based on current operational need. The ranking of the gaps listed in Table 5 is generated from the ranking of the weather conditions in Table 4, but also the maturity of the operation that the gap affects. For example, consider two gaps that are scored equally in Table 4. If one of the gaps influences VLOS operations and the other affects BVLOS operations, the VLOS gap will be prioritized higher than the BVLOS gap because VLOS operations are currently more mature and common than BVLOS operations.

The most significant gap is validation of numerical weather model performance in UAS domains. This is driven by the significance of low level winds aloft (Table 4, Rank 1b) for all types of UAS operations, and the importance of local ceiling and visibility (Table 4, Ranks 2a and 2b) to VLOS operations. The second gap is hazardous weather alerting of convective weather and winds (Table 4, Ranks 1a, 1b, and 2c), primarily for VLOS operations (i.e. the UAS operator cannot continuously monitor weather information due to the need to maintain visual contact with the UAS). The third gap is related to the sparse network of airport observations for ceiling, visibility, and wind (Table 4, Ranks 2a, 2b, and 2c) to determine if local Part 107 (VLOS) weather requirements are met. The information gaps ranked four through seven are lower priority than the first three mainly due to their emphasis on BVLOS and urban operations, which are far less operationally mature than VLOS operations. Gaps eight through twelve address turbulence and icing (Table 4, Ranks 3a and 3b), and weather impact models for far-term UAS traffic management concepts. No specific weather gaps are listed for precipitation, temperature, and barometric pressure due to their low significance scores (Table 4, Ranks 3c, 4a, and 4b).

Table 5

Prioritized Ranking of Specific Weather Information Gaps

	Weather Information Gap	Impacted UAS Operation
1	Numerical weather model performance is uncertain, especially where there is a large variation in terrain.	All UAS missions, especially in the low-altitude domain
2	No mechanism to alert operators to rapid changes in winds (e.g., due to microburst outflows, gust fronts and sharp synoptic fronts)	Primarily small UAS operations
3	Off-airport weather observations (visibility, ceiling, wind) are sparse	All UAS missions that operate off-airport, especially VLOS operations (Part 107)
4	Tactical convective weather products lack short-term storm forecasts and are susceptible to latencies	Primarily BVLOS missions for UAS without onboard weather radar
5	Current wind aloft forecasts lack precision and winds aloft observations are lacking in the low-altitude and super high-altitude regions	Primarily BVLOS mission planning, especially for time-based operations
6	Strategic convective weather products lack precision at long forecast horizons and need better uncertainty information to support decision making	Primarily BVLOS missions with durations greater than 2 hours
7	Urban wind products are not sufficient and are not available to the public	All UAS missions in an urban environment
8	Lack of validated stratospheric and low-altitude turbulence information	Very high-altitude missions / low-altitude missions in the boundary layer
9	Icing and turbulence forecasts lack an uncertainty element to support contingency planning	Primarily BVLOS missions
10	Icing models do not account for ‘cold soak’ effect	High-altitude BVLOS missions
11	Turbulence and icing models not designed for small UAS	Primarily BVLOS missions with small UAS
12	Weather impact models do not exist for UAS	Airspace management, including geofences, airspace capacity balancing, time-based ops

There were several issues identified as a result of the research process that should be addressed in follow-on work to address the gap analysis needs that became apparent late in the analysis effort reported here:

1. First, there should be more interaction with operational users who have “pushed the envelope” in operating with low altitude surface winds, surface wind gusts and turbulence. Examples of this type of operation are introduced in Appendices B and C.

2. Also, more thought should be put into differences in the flight control ability of different UAS platforms. Although this information is typically proprietary, it is necessary to understand the operational impact of low altitude/near surface turbulence and, the ability of the UAS to complete the envisioned UTM procedures such as time based operations.

3. Assess National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS) products currently not being utilized for aviation purposes (e.g., products not available on the Aviation Weather Center (AWC) WWW site) to see if they might have applications for UAS weather decision support.

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1. INTRODUCTION

Unmanned aircraft system (UAS) operations in the National Airspace System (NAS) are rapidly increasing, and the trend is expected to continue. Commercial UAS operations are anticipated to grow over the next few years as regulations are refined to allow quicker and easier access to the airspace. However, UAS are not as resilient to weather as manned aircraft, having less power and lower performance, no inflight deicing, and no on-board pilot to visually avoid adverse weather. Moreover, UAS mission objectives are much different than manned aviation and often require certain weather minimums for onboard sensing and imaging. Lastly, as UAS are integrated into the NAS there will be increasing need for active airspace management through time-based procedures and demand/capacity balancing. Weather products for manned aviation have a long history and evolved over time to reflect changing user needs. The unique characteristics of UAS may require weather products to be further refined to address differences between unmanned and manned operations.

The purpose of this paper is to highlight weather information gaps influencing both UAS operational safety and airspace management strategies critical to enable UAS integration in the NAS. The term *weather information gap* is intended to describe any deficiency in currently available weather products to meet the operational needs of the UAS community. It is important to note here that a *currently available weather product* refers to a source of weather information that is easily consumed by the UAS operator. There are many examples of current weather data that are not readily available to the average user, and therefore are not included in the set of currently available weather products.

UAS operational weather needs are derived largely from surveys to both government and civil operators, in addition to interviews with stakeholders in the Federal Aviation Administration (FAA) Pathfinder program. Weather needs for UAS integration and airspace management are inferred from operational strategies published in the FAA UAS Integration Concept of Operations and the National Aeronautics and Space Administration (NASA) UAS Traffic Management (UTM) Concept of Operations. Both documents outline preliminary strategies to integrate UAS into the NAS and provide use cases that illustrate the significance of weather to operations.

The organization of the paper is as follows. Section 2 provides an overview of the methodology used to identify and rank the weather information gaps mentioned above. Section 3 describes the set of currently available weather products. Section 4 summarizes the weather needs survey results, operator interviews, and UAS integration literature. Section 5 describes weather information gaps for each of the weather elements considered in the study. Section 6 summarizes the weather information gaps and provides a prioritized list set of gaps to be address in future work.

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2. WEATHER GAP IDENTIFICATION AND RATING METHODOLOGY

This section describes the methodology employed to identify and rank weather information gaps. At a high level, the process is a comparison of the weather needs of UAS operators and corresponding sources of weather information. For example, if the currently available weather information does not fully address a weather need, a gap is identified and ranked against other weather gaps. The weather needs are derived from a combination of UAS operator survey feedback and interviews, as well as FAA and NASA UAS integration documentation. A *User Weather Needs Survey* was distributed to a set of government and civil stakeholders to acquire feedback on their typical mission profile (altitude, range, duration) and the level of significance they apply to different weather conditions. In all, this report is based on 90 survey responses, and 16 interviews from operators representing a variety of UAS types and missions. UAS integration and traffic management strategies are gathered from the FAA UAS Concept of Operations the NASA UAS Traffic Management (UTM) Concept of Operations. UAS weather needs are classified based on the typical altitude, range, and duration of similar missions and use cases. Seven mission classes are identified in this report and are listed in Table 2-1. The division of the mission classes is intended to distinguish UAS weather needs for different operational profiles.

Table 2-1

UAS Mission Classification

Mission Class	Altitude	Mission Range	Mission Duration
1	0–500 feet	0–3 NM	0–1 hour
2	0–500 feet	3–25 NM	0–1 hour
3	0–500 feet	3–25 NM	1–12 hours
4	0–500 feet	25+ NM	1–12 hours
5	500 feet – FL250	25+ NM	1–12 hours
6	FL250+	25+ NM	1–12 hours
7	FL250+	25+ NM	12+ hours

Figure 2-1 shows the weather information gap identification process. Each mission class corresponds to unique weather needs that are required for operational safety, airspace management feasibility, and mission efficiency.

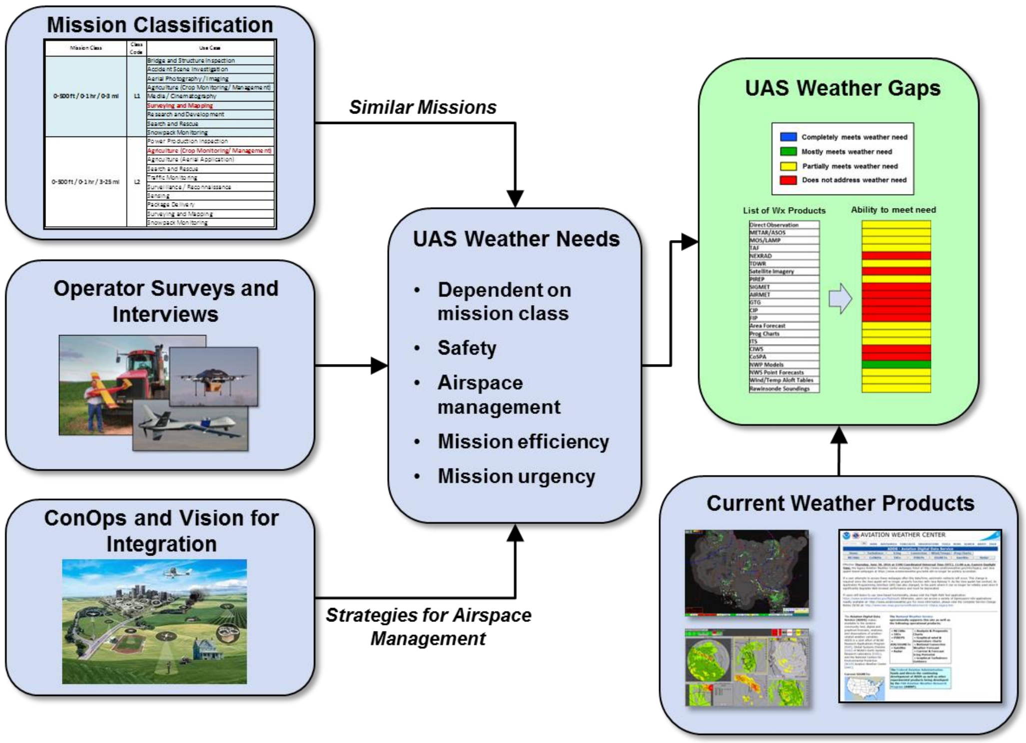


Figure 2-1 Weather information gap identification process

The weather needs (described in more detail in Section 4) are categorized by the individual weather elements listed in Table 2-2. They are then compared to the currently available weather products (described in more detail in Section 3) to determine whether or not a weather gap exists.

Table 2-2

Weather Elements

Weather Elements	
Surface Wind	Convective Weather
Wind Aloft	Clouds/Ceiling
Temperature	Visibility
Barometric Pressure	Turbulence
Precipitation	Icing

The weather information gaps are rated by combining the significance of the weather element to a given mission class and the degree to which available weather products can meet the need. Weather need significance is determined by a qualitative assessment of germane survey feedback, interview responses, and anticipated airspace management needs. Weather product effectiveness is determined by comparing available weather product information to the specific needs identified for each weather element and mission class. Table 2-3 provides the scoring methodology for weather significance and product effectiveness. The weather information gap rating is the sum of the weather need significance and weather product effectiveness scores.

Table 2-3

Weather Information Gap Scoring

Score	Weather Need Significance	Weather Products
3	Always influences safety / airspace management	Infrequently meets weather need
2	Frequently influences safety / airspace management	Partially meets weather need
1	Occasionally influences safety / airspace management	Mostly meets weather need
0	Infrequently influences safety / airspace management	Completely meets weather need

$$Total\ Score = Significance\ Score + Product\ Effectiveness\ Score$$

For example, weather needs for the 'Winds Aloft' weather element in Mission Class 1 (0–500 feet altitude) can be addressed by a number of weather products with varying levels of effectiveness. Surface wind point observations (e.g., anemometers on poles) provide a sparse network of observed winds, but infrequently meet the weather need because wind profiles can change drastically with altitude and horizontal displacement. Numerical wind models provide a higher resolution grid of wind information, including winds away from the surface, but they do not completely meet the need because 1) the grid resolution may be too large, 2) the model output is not easily observable to a UAS operator, 3) the accuracy of the model needs additional validation in the domain of interest. In this case, the weather need significance score is 2 and the weather product effectiveness score is 2 based on the ability of numerical wind models to meet the need. Therefore, the weather information gap score is 4.

It should be noted that there can be geographic differences in weather product performance and availability, and the significance of weather needs can vary between difference operational environments (e.g., urban versus rural operations). These differences are accounted for in the qualitative assignment of weather need significance and weather product effectiveness based on the likelihood of different mission classes operating in different geographic areas. Any significant differences are discussed for each weather element in Section 5.

3. CURRENT WEATHER PRODUCTS

Identification of potential weather information gaps was made in the context of existing weather products that are widely-used in support of current manned aircraft operations. For this purpose, a number of the most commonly used weather information and products are listed here. In essence, this represents the “core” of current weather information that may be available to support UAS operations. A capsule summary is provided for each information/product source, including a notation of limitations as they relate to the identification of potential weather information gaps. Table 3-1 maps these products to the key UAS weather impact elements which they address, in terms of weather observation (o) and forecast (f). Appendix D provides an example of a mobile weather application used to display weather information.

Surface Observations/METAR: These are standard surface weather observations taken from Automated Surface Observing Stations (ASOS) and Aviation Weather Observing Stations (AWOS), typically located at airports. Reported weather elements include temperature, dew point, wind speed and direction (10 m AGL), precipitation, cloud cover (layers), cloud height (layers), visibility, and barometric pressure. Information is disseminated hourly in internationally standardized Meteorological Terminal Aviation Routine Weather Report (METAR) format at one-hour intervals, or upon significant changes in conditions. More frequent observations (every 5 minutes or every 1 minute) are also available via direct station access, and are archived. *Limitations: Surface observations are primarily available for on-airport locations, and do not necessarily represent conditions for more remote UAS launch/landing locations.*

Radiosonde/Rawinsonde soundings: Weather balloons are released twice daily (00Z and 12Z) from to provide atmospheric profiles of pressure, temperature, relative humidity and wind/speed and direction from ground level up to above 50,000 feet Above Ground Level (AGL). The Airport Surveillance Radar (NWS) launches balloons from 92 stations, 82 of which are in the coterminous U.S. and Alaska. *Limitations: Soundings are available only twice daily. The network of soundings is relatively sparse, so wind conditions may not be representative of remote locations.*

Satellite Imagery: The primary source of satellite weather information used for operational purposes comes from the visible, infrared, and water vapor channels of the Geostationary Operational Environmental Satellites (GOES) satellite systems. In standard configuration, two GOES satellites (East and West) provide coverage for North America. These satellites provide high resolution indication of cloud areal coverage and moisture, as well as cloud top height. *Limitations: Individual cloud layer heights (tops and bases) are not provided. Higher clouds obscure lower cloud layers.*

Pilot Reports (PIREPS): Pilots provide near real time reports of aviation-impacting weather elements, including sky cover, temperature, wind speed and velocity, turbulence, and icing. Time and spatial location are provided within each report. *Limitations: Reports are typically triggered by unusual weather encounters with sometimes vague requirements for reporting; as such, the temporal (frequency) and spatial resolution is generally irregular.*

WSR-88D Radar (NEXRAD): The primary source of operational weather radar information in the United States is made available from a network of 160 high resolution S-Band Doppler weather radars operated by the NWS, FAA, and Department of Defense (DoD). Spatial resolution ranges from 0.25–1km by 0.5–1.0 degree beam width, out to a range of 230–460 km depending upon resolution. Volume scan times range from 4.5–10 minutes. In addition to providing information on precipitation intensity, Next Generation Weather Radar (NEXRAD) algorithms provide capability to detect radar signatures of mesocyclones and tornadoes, and the capability to differentiate precipitation type (rain, snow, hail, etc.) NEXRAD provides microburst and gust front detection as well as 20 minute predictions of future gust front locations. *Limitations: Low level (boundary layer) coverage is limited at longer ranges. Coverage is also restricted, particularly at low elevations, in mountainous regions.*

Terminal Doppler Weather Radar (TDWR): TDWR is a 5-cm Doppler weather radar system designed to detect wind shear, currently situated to cover airspace surrounding 45 U.S. airports. Spatial resolution ranges from 0.15–0.3 km by 0.55 degree beam width, out to a range of 135–460 km depending upon resolution. Horizontal scans are performed every minute; composite scans can be performed over a period of 6 minutes. TDWR algorithms provide capability to detect radar signatures of microbursts, gust fronts, and storm extrapolated position as well as 0–20 minute forecasts of future gust front locations and of the winds behind the gust front. *Limitations: Since TDWR is intended to provide specific high resolution weather information at key airports, the operational range of individual radar and the overall coverage of the network is limited compared to that of NEXRAD.*

ASR-9 Weather Systems Processor (WSP): The Airport Surveillance Radar (ASR-9) is a 10 cm fan beam radar with an effective update rate of 30 seconds. The WSP algorithms provide capability to detect radar signatures of microbursts, gust fronts, and storm extrapolated position as well as 0–20 minute forecasts of future gust front locations and of the winds behind the gust front. *Limitations: Because WSP is an add-on process to a system that was not designed specifically for weather detection, the resolution of weather information is inferior to that of conventional weather radars.*

Figure 3-1 provides the locations of TDWR, ASR-9, and LLWAS systems across the United States.

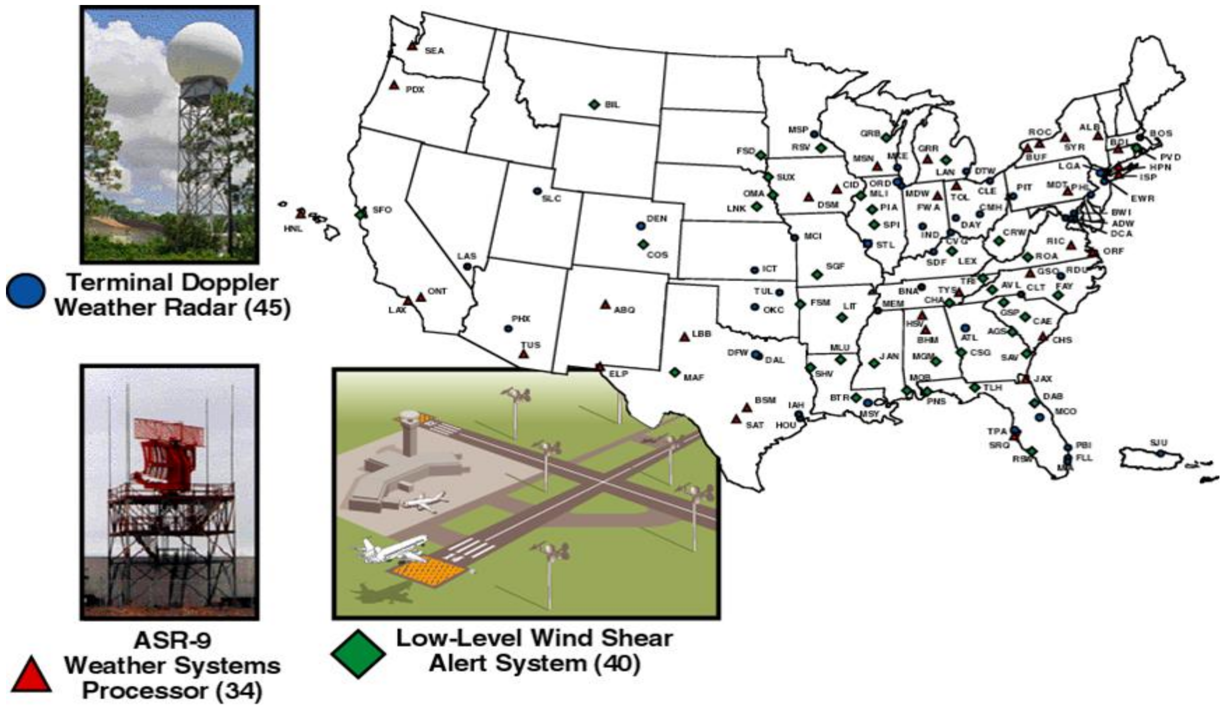


Figure 3-1 Network of TDWR, ASR-9, and LLWAS systems.

Integrated Terminal Weather System (ITWS): ITWS provides FAA air traffic managers and controllers with a graphical display of airport terminal-impacting weather via synthesis of data from FAA and NWS sensors, radars, numerical models, and aircraft-derived weather data. Derived products focus on convective precipitation, including detection of microbursts, wind shear, gust fronts, wind shifts, storm cell information, and storm motion. Forecast/product time horizon is 1 hour for the precipitation products and 20 minutes for the gust front/wind shift product. Also included is a Terminal Winds gridded analysis product with a 2 km horizontal spatial resolution inside a larger 10 km resolution grid. The ITWS Terminal Winds grid covers 34 major metropolitan areas (see Appendix A). *Limitations: Designed as an internal system intended to meet weather information needs of the FAA, ITWS products are not readily available to external users.*

Corridor Integrated Weather System (CIWS)/ Consolidated Storm Prediction for Aviation (CoSPA): CIWS extends the ITWS concept to provide 3D en route weather depiction and 0–2 hour forecasts of precipitation Vertically Integrated Liquid (VIL) and storm echo tops for the continental U.S. and southern Canada. CIWS also provides 0–2 hour forecasts of winter precipitation. The CIWS weather depictions are updated every 2.5 minutes and forecasts are updated every 5 minutes. CoSPA extends CIWS capabilities to include convective and winter precipitation forecasts out to 8 hours by use of both weather radar derived forecasts and forecasts from the High Resolution Rapid Refresh (HRRR). *Limitations: These systems are designed to integrate weather information primarily associated with precipitation. As such,* *they are lacking information with regard to other weather elements, such as wind, clouds/ceilings, and visibility.*

Model Output Statistics (MOS)/ Localized Aviation MOS Program (LAMP): MOS and LAMP provide forecast of key aviation elements derived statistically from output of numerical models. North American Model (NAM) MOS provides forecasts at 3-hour increments out to 72 hours. Global Forecast System (GFS) MOS provides both short term (out to 72 hours, 3 hour increments) and extended (out to 192 hours, 12 hour increments) forecasts. Gridded versions of MOS derived from numerical models are also available, but the inter-station reliability requires further validation. The LAMP extends the statistical forecast using additional recent surface and radar observations. LAMP runs out to 24 hours and provides forecasts at 1-hour increments. *Limitations: Station-specific forecasts are restricted to airport locations. However, this gap is being addressed through recent advancement of Gridded MOS products.*

Terminal Aerodrome Forecast (TAF): TAFs are weather forecasts of aviation-related conditions in METAR-like for specific airport terminal airspace. They are a key determinant for strategic air traffic planning. They are issued every 6 hours and amended as necessary, with a forecast horizon of 24–30 hours. *Limitations: They are generally restricted to airport locations. Also, there tends to be latency in forecast updates when conditions are changing rapidly.*

Significant Meteorological Information (SIGMET) Advisories: These weather advisories are issued by the Aviation Weather Center. Non-convective SIGMETS are issued as needed and are valid up to 4 hours, and provide advisories on the presence or expectation of severe or greater turbulence or icing, or Instrument Meteorological Conditions (IMC) due to dust, sand, or volcanic ash. Convective SIGMETS are issued hourly and are valid up to 2 hours, and provide advisories on thunderstorms and severe surface weather including high winds, hail, and tornadoes. *Limitations: Due to the difficult nature of forecasting convection, turbulence, and icing, these forecasts tend to be generalized geographically.*

Airmen's Meteorological Information (AIRMET): AIRMETs provide a concise description or forecast of weather along an air route that may affect aircraft safety. AIRMETS cover less severe weather than SIGMETS, and include advisories of turbulence, icing, surface winds, or widespread restricted visibility. They are issued at 6-hour intervals, and amended as necessary due to changing weather conditions or issuance/cancellation of a SIGMET. *Limitations: Broad geographical coverage makes it difficult to avoid latency issues when forecast conditions are changing rapidly.*

Aviation Area Forecast: "Area Forecasts" are a message product of the NWS describing weather conditions over a large regional area. They are issued for 15 regions 3 times daily valid for 18 hours, and are modified as necessary. They provide a summary and forecast of conditions including precipitation, thunderstorms, surface winds, cloud coverage, and visibility. They also include a summary of the location and movement of fronts, pressure systems, and circulation patterns. *Limitations: By their nature, these forecasts tend to lack geographic specificity.*

Prognostic Charts: This category includes graphical weather prediction products generated manually by Aviation Weather Center and National Centers for Environmental Prediction (NCEP). *Limitations: These graphical products inherit the limitations of their underlying text forecasts.*

Graphical Turbulence Guidance (GTG): The GTG product provides contours of turbulence potential based on numerical model forecasts out to 18 hours lead time. *Limitations: The product does not include the low altitude domain below 1000 ft or the domain above FL450. It is also unclear if the model output properly represents the turbulence hazard for UAS significantly smaller than conventional aircraft.*

Current Icing Product (CIP) and Forecast Icing Product (FIP): CIP combines sensor and numerical model output to provide an hourly, 3-dimentional diagnosis of the icing environment. FIP provides an icing forecast out to 12 hours based on numerical models. CIP/FIP outputs include calibrated icing probability, icing severity, and potential for supercooled droplets. They are output on a grid with pixels every 20k min the horizontal and 1000 feet in the vertical. *Limitations: It is unclear if the model output properly represents the icing hazard for UAS significantly smaller than conventional aircraft.*

Ceiling/Visibility Analysis (CVA): This product available via Aviation Weather Center (AWC) provides an analysis of ceiling and visibility conditions using a blend of surface METAR observations and satellite imagery. There is an accompanying experimental product that provides graphical ceiling and visibility forecast out to 15 hours. *Limitations: Ceiling and visibility estimation and forecasting is challenging away from airport locations where there tend to be limited observations for validating performance.*

Aviation Weather Center (AWC) Winds/Temp Aloft Forecast: AWC provides tabular and graphical format predictions of winds and temperatures for forecast horizons of 6, 12, and 24 hours for the following flight levels: 3K, 6K, 9K, 12K, 18K, 24K, 30K, 34K, and 39K feet. *Limitations: These products are limited by the skill of the underlying models from which they are derived.*

Numerical Models: This category broadly includes all numerical operational models, most notably Rapid Refresh (RAP), Global Forecast System/Aviation (GFS/AVN), HRRR, North American Mesoscale/Weather Research & Forecasting (NAM/WRF), and the European Center for Medium-range Weather Forecasting (ECMWF). *Limitations: Model performance is generally validated by quantification of forecasting pressure and precipitation fields over broad areas. As such, forecast confidence in forecasting specific weather elements at specific geographic locations has not been established.*

NWS point forecasts: These are point-specific locations derived from gridded NWS forecast maps. They are available in text form, and graphical meteogram format. *Limitations: Though these forecasts provide forecast much improved precision from previous generations of weather forecasts, the accuracy at these finer scales has not generally been quantified.*

NextGen Weather Improvements: This product category is still in the development stage, but included here in anticipation of future capabilities; the new architecture is expected to provide a platform for advancements in weather forecasting and information dissemination that may address or facilitate solutions to many of the UAS weather-related gaps identified in this report. As designed, the fully-automated NextGen Weather Processor (NWP) identifies terminal and enroute safety hazards, and provides translated weather information needed to predict route blockage and airspace capacity constraints up to eight hours in advance.

NWP combines information from weather radars, environmental satellites, lightning, meteorological observations (from surface stations and aircraft), and National Oceanic and Atmospheric Administration (NOAA) numerical forecast model output to generate improved products for all FAA users and NAS stakeholders, while maintaining today's ITWS/TDWR terminal safety products. NWP includes the functionality discussed above for ITWS, CIWS and CoSPA.

The Next Generation Air Transportation System (NextGen) weather improvements include an Aviation Weather Display (AWD), providing consistent weather information "at a glance" for enroute and terminal users and the CSS-Wx is the single provider of weather data, products, and imagery within the NAS, using standards-based weather dissemination via System Wide Information Management (SWIM). CSS-Wx makes available both NOAA and FAA NWP weather products for integration into air traffic decision support tools, improving the quality of traffic management decisions and reducing controller workload during severe weather. Products are provided via a set of common Web Services for weather, using internationally recognized data access and data format standards. CSS-Wx also offers a mechanism for private industry UAS weather providers to access NOAA and FAA NWP weather products.

Table 3-1

Mapping of Weather Product to Weather Element (o=observation; f=forecast)

	Surface Wind	Surface Wind Gust	Aloft Wind	Aloft Wind Gust	Turb	Temp	Pressure	Precip	Winter precip	Convective Wx	Cloud/ Ceiling	Visibility	Icing
Sfc Obs/METAR	o	o				o	o	o	o	o	o	o	
Radiosonde	o		o			o	o				o		
Satellite											o		
Pilot Reports	o	o	o		o	o		o	o	o	o	o	o
Aircraft reports (MDCRS)			o			o	o						
NEXRAD	o	o	o	o/f[1]				o/f	o/f	o/f			
TDWR	o	o[1]	o	o/f[1]				o/f	o/f	o/f			
ITWS	o	o[1]	o	o/f[1]				o/f	o/f	o/f			
CIWS/CoSPA								o/f	o/f	o/f	o		
MOS/LAMP	f					f		f		f	f	f	
TAF	f	f						f	f	f	f	f	

SIGMET	o/f				o/f					o/f	o/f	o/f	o/f
AIRMET	o/f				o/f			o/f		o/f	o/f	o/f	o/f
Area Forecast	o/f				o/f			o/f		o/f	o/f	o/f	o/f
Prog Charts	f		f			f		f		f			
GTG					o/f								
CIP/FIP													o/f
CVA/Forecast											o/f	o/f	
Wind/Temp Tables			o/f			o/f							
Numerical Models	o/f		o/f		o/f	o/f	o	o/f		o/f	o/f	o/f	
NWS Point Fcsts	o/f					o/f	o	o/f	o/f	o/f	o/f	o/f	
NWP (planned)	o	o	o	o/f[1]	o			o/f	o/f	o/f	o		o

Notes:

1. "Organized changes" in winds (e.g., storm outflows such as microbursts and gust fronts). Gust front forecast 0–20 minutes.

4. WEATHER NEEDS FOR UAS OPERATIONS

This section describes specific weather needs for different types of UAS operations. The weather needs are broken down into operational categories to summarize and consolidate the information. The first category is Visual Line of Sight (VLOS) operations, which are predominately composed of small UAS missions. Another category, Beyond Visual Line of Sight (BVLOS) operations can be conducted by both small and large UAS, although presently the primary BVLOS operator is the military using medium and large UAS. The Airspace Management category represents needs for defining weather-related airspace constraints to enable UAS integration in the NAS. Lastly, the Mission Efficiency category describes operational needs related to the ability of UAS to successfully accomplish their mission requirements, such as capturing clear images of the ground from the air. A more detailed description of the weather needs is found in the *Preliminary Weather Impacts and UAS Weather Needs* report.

4.1 VISUAL LINE OF SIGHT OPERATIONS

VLOS operations are a class of operation defined by the ability of the UAS operator to maintain visual identification of the vehicle. Some operators conduct VLOS operations up to 3 miles from the launch site; however the range of VLOS is largely dependent on the size of the UAS. Currently, VLOS operations are predominately flown by small UAS and the FAA has established small UAS operating rules (CFR Part 107) to guide VLOS operations. From a weather standpoint, the Part 107 rules require that the operator be aware of local weather conditions, not operate if the slant range visibility to the UAS is less than 3 statute miles, and maintain cloud clearances of 500 feet below and 2000 feet horizontal distance from the clouds. An interesting side-effect of VLOS operations is that the operator is physically located at the mission site, where they can visually and tactically observe the local weather conditions. This allows the UAS operators to 'ball-park' local weather conditions and make operational decisions. In general, survey respondents who conduct VLOS operations noted a need for wind speed and direction above tree-level, if they are operating in an urban environment, or at a location with complicated terrain. Wind gusts and turbulence can decrease flight endurance due to the additional flight control power necessary to maintain steady flight. Moreover, strong or gusty winds can overcome the ability of a small UAS to maintain position if the wind speed is greater than the forward speed capability of the UAS. In general, the UAS that conduct VLOS operations are not sealed to water, meaning that any precipitation can cause electrical failure. UAS are also susceptible to barometric pressure changes if they are equipped with a pressure altimeter calibrated to ground level at launch. A summary of the VLOS weather needs are as follows.

1. Local weather conditions, including wind, wind gusts, low-level winds aloft, precipitation, ceiling, and visibility.
2. Wind speed and direction near buildings and/or terrain.
3. Weather updates (e.g., hazardous weather alert) or forecasts to help identify changing weather conditions (wind, precipitation, ceiling, and visibility) that are not easily observable by the operator.

4.2 BEYOND VISUAL LINE OF SIGHT OPERATIONS

4.2.1 General

The purpose of this section is to describe weather needs for BVLOS operations. Weather needs that are specific to small and large UAS operations are broken out separately. However, both small and large UAS are assumed to operate under Instrument Flight Rules (IFR) during BVLOS operations. Winds aloft affect all sizes of UAS and the accuracy of winds aloft is critical to flight planning and the feasibility of time-based integration strategies. In general, survey feedback indicates that UAS operators try to maintain 20 nautical miles distance from convective weather, and significant preflight planning is necessary to ensure the feasibility of lost-link contingency plans.

4.2.2 Small UAS Considerations

Small UAS are differentiated from large UAS by their size, but also by the typical altitude that they operate. Small UAS are envisioned to predominately occupy the low-altitude domain below 500 feet above ground level. Typical BVLOS missions include pipeline monitoring, search and rescue, and transportation infrastructure inspection. The specific weather needs for small UAS BVLOS operations are as follows.

1. Turbulence/wind gusts can decrease battery performance, as well as interfere with the integrity of a satellite control & communications link.
2. Windshear is very dangerous at low altitude, especially for fixed wing platforms.
3. Barometric pressure changes can influence pressure altimeter accuracy, and can be very dangerous at low altitude if a radar altimeter is not installed on the UAS.
4. Icing can build on a small airframe or propeller much faster than on a conventional aircraft.
5. Low temperatures have been shown to decrease battery life, and in turn, mission endurance.
6. Tactical weather information is needed to support inflight decision making during unexpected weather events.
7. Weather forecast uncertainty information is needed to support contingency planning.

4.2.3 Large UAS Considerations

Large UAS have the potential to operate at very high altitudes (FL600) and for very long mission durations (30+ hours). The specific weather needs for large UAS BVLOS operations are as follows.

1. Turbulence is a great concern to large UAS operators due to its effect on the control and communications link. The unsteadiness caused by turbulence can destabilize the Satellite Communications (SATCOM) and break the communication link.
2. Many of the large UAS platforms are not equipped with deicing capabilities and are therefore susceptible to icing on departure and arrival.
3. Because large UAS typically operate off of runways, they are sensitive to wind direction due to the very conservative crosswind limits of the UAS platforms.

4. Large UAS typically operate at high-altitude and have the ability to fly over convective weather, but they need to know the height of the cloud tops.
5. Tactical weather information is needed to support inflight decision making.
6. Weather forecast uncertainty information is needed to support contingency planning.

4.3 AIRSPACE MANAGEMENT

Airspace Management is a critical component of UAS integration. Both NASA and the FAA have developed visions for integration; the NASA effort is focused on small UAS, whereas the FAA considers the entire spectrum of UAS. Airspace management comes in many forms and different levels of complexity. The most basic form of airspace management is the static geofence, which effectively creates a virtual barrier to preclude flight into certain areas. From a weather standpoint, a static geofence can be defined around an area of severe weather, but it is important to understand that different UAS types have different weather sensitivities that correspond to different geofence boundaries. Moreover, static geofences do not capture the dynamic nature of weather, and in turn, can be a very conservative approach to airspace management. The next step in complexity is a dynamic geofence, which can move with weather or surround a UAS along the planned route of flight to ensure aircraft separation. A benefit to a dynamic geofence is that it can move in response to changing conditions. However, the usefulness of a dynamic geofence is only as good as the weather forecasts supporting it. Another UAS integration strategy focuses on time-based operations, which essentially means that UAS plan a four-dimensional route to define time-on-waypoint to enable integration with the flight plans of other aircraft. Accurate winds aloft information is critical to achieve time-based operations. Other weather can also impact time-based operations, but the permeability of weather (e.g., icing) is largely dependent on the type of UAS being considered. As the number of UAS in the airspace increases, demand and capacity balancing will be necessary to effectively allocate UAS flights to the airspace. Airspace capacity models for weather constrained airspace will be needed to estimate and forecast the impact of weather on a heterogeneous mixture of UAS platforms.

1. Weather impact information (winds, convective weather, icing, turbulence, precipitation, ceiling and visibility) to define geofence boundaries.
2. Winds aloft information to support time-based operations.
3. Weather-impacted airspace capacity estimates to inform traffic management strategies.

4.4 MISSION EFFICIENCY

The mission objectives of UAS missions are fundamentally different than the objectives of manned aviation. Manned aviation is primarily intended to transport passengers or cargo from an origin to a destination. UAS are envisioned to have a variety of mission objectives, but many missions are intended to perform aerial imagery of the ground. Moreover, BVLOS operations require very strict contingency planning to ensure that a feasible lost-link path is available if the UAS loses communication or control. Contingency plans ensure that there is a feasible route for the UAS to return to base autonomously. The specific mission efficiency needs are as follows.

1. Visibility and cloud layer information to enable flight planning based on aerial imaging mission needs.
2. Weather forecast uncertainty decreases the efficiency of lost-link contingency planning due to overly conservative assessments of weather impact. More effective contingency planning can be enabled though validated weather uncertainty information that informs risk-based planning.

5. UAS WEATHER INFORMATION GAPS

This section provides a discussion of the weather information gaps that exist for UAS operations. Each subsection is devoted to a specific weather element to highlight the weather impact and operational considerations, operational efficiency issues, and airspace management concerns. The utility of existing weather products for each weather element is discussed and then potential shortfalls (i.e. weather information gaps) are presented.

5.1 SURFACE WIND INFORMATION GAP

5.1.1 Impact and Operational Considerations

This weather element refers to surface winds and surface wind gusts. Surface winds and surface gusts are important for takeoff and landing of an UAS. If a human is present at UAS takeoff or landing, it is assumed that the human would make a local surface wind assessment to insure that surface winds are within the tolerable envelope. However, if the UAS is landing or taking off at a location without a human present (e.g., a package delivery), then it may be necessary to infer the landing/takeoff site winds from forecasts and/or measurements at other locations. If the UAS is landing or taking off from a small area surrounded by objects, unexpected strong gusts (e.g., exceeding horizontal speed capability of the UAS) could cause the UAS to hit a nearby object. If the nearby object is a human, building or other man-made object, such unplanned encounters on landing or takeoff would be a safety risk.

5.1.1.1 Surface Wind UAS Safety Considerations

In the discussion above, it is noted that the safety concerns associated with low altitude storm outflows (i.e., microbursts and gust fronts). An outflow boundary, also known as a gust front, is a storm-scale or mesoscale boundary separating thunderstorm-cooled air (outflow) from the surrounding air; similar in effect to a cold front, with passage marked by a wind shift and usually a drop in temperature and a related pressure jump.

Outflow boundaries can persist for 24 hours or more after the thunderstorms that generated them dissipate, and can travel over a hundred miles from their area of origin. A microburst is a compact roughly circular outflow boundary typically associated with relatively small storms. Microburst outflows generally have much shorter time durations than the gust fronts that come from long lasting storms (e.g., squall lines, super cells, etc.). Strong synoptic fronts may have a gust front associated with the gust front passage.

A very important factor for UAS operations is that the outflow leading edge can be far removed from the generating storm. Hence, avoiding UAS operations when there are storms clouds overhead may not insure avoidance of low altitude storm outflows.

The frequency of microburst and gust front events was studied extensively in a Lincoln Laboratory report ATC-341 [1]. Figure 5-1 provides the frequency of microburst (MB) and gust front (GF) outflows based on analysis of years of TDWR/ITWS archives.

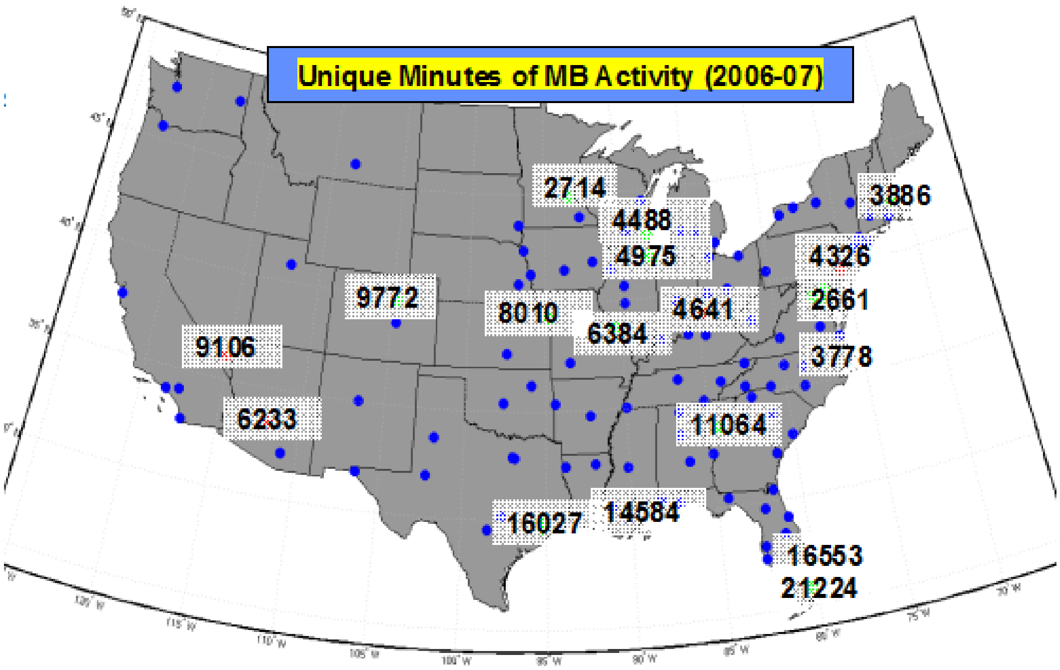


Figure 5-1Measured number of minutes per year where at least one microburst was within a 30km radius of the respective TDWR/ITWS archive site [1]. Blue circles are airports studied in [1].

5.1.1.2 Surface Wind UAS Operational Efficiency Considerations

Surface winds do not appear to be a significant consideration for operational efficiency other than an impact on operations at joint use (i.e., UAS and conventional aircraft) airfields.

5.1.1.3 Surface Wind Impact on Airspace Management

Surface winds do not appear to be a significant consideration for airspace management other than an impact on operations at joint use (i.e., UAS and conventional aircraft) airfields.

5.1.2 Utility of Existing Products and Information

The primary source of observed surface winds and wind gusts for conventional aircraft operations is the ASOS which typically is located at airports at an altitude of 10 meters. For short range UAS operations, local observations at the time of UAS approach and landing are probably the principal source of surface winds information.

The FAA wind shear detection systems (TDWR, Low Level Windshear Alert System (LLWAS), ASR-9 WSP) and the NEXRAD detect microburst and gust fronts as well as forecasting gust fronts out to 20 minutes in the future. The LLWAS anemometers (which are at heights to minimize shadowing of winds by trees, buildings, etc., provide microburst and gust front detections along the approach and departure paths near the runways and on the runway. The pencil beam radar based systems typically detect wind shear phenomena out to a range of 60 km from the radar [2] with high reliability (<90%).

Surface winds are principally forecast by numerical weather models (e.g., HRRR) and by NWS offices in the form of TAFs. An assessment of HRRR forecasts and TAF show that surface wind errors are virtually independent of forecast lead time and that errors in excess of 10 knots are not uncommon (e.g., about 20% of the wind speed errors are greater than 10 knots) [3]. Errors of that magnitude are a concern for many UAS operations.

One of the mitigating factors for low altitude UAS operations is that the magnitudes of the surface winds that have trees and/or buildings in close proximity (e.g., within 100–200 feet) is that the surface wind magnitude will be reduced by sheltering effects [4].

Numerous techniques are used by national met services and researchers to predict wind gusts based on output from large scale forecasts. For forecasting purposes, severe gusts are most often divided into those originating in convective, and in non-convective environments. The former are generally associated with convective downdrafts and the vertical mixing associated with deep convection, and attempts to parameterize them focus on representing these mechanisms. Accurate prediction in time and space of severe gusts from convective environments does not exist currently and will be very difficult to accomplish.

Contrasting with these physically/heuristically-based parameterizations are empirical/statistical models generally derived from the variation of the behavior of observations with different static and meteorological factors. A number of predictors are usually tested in regression formulae to model the overall gust behavior without specific reference to gust-producing mechanisms, though some account of these may be implicit in the choice of predictors. For example, a recent NWS evaluation of wind gust forecasting concludes that mean and 90 percentile gusts can be forecast fairly well from the forecast steady state wind [5].

5.1.3 Potential Shortfalls

Both the significance of surface wind gaps and the weather product capability for surface winds depend on the mission class and the location of operation.

For example, for the low altitude missions that might be conducted in urban/suburban areas [e.g., package delivery, first responders such as fire departments (appendix B), and disaster relief (appendix C), building inspections and photography], an unplanned UAS incursion into a “geofence banned area” and/or crash in a highly populated location is a major safety concern.

On the other hand, for major metropolitan areas east of the west coast, the FAA have a fairly robust low altitude wind detection capability (see Appendix A). At several major west coast airports, there is a low altitude wind shear detection phenomena detection capability which would be of some aid. All of the US NEXRADs now have wind shear phenomena capability within about 60 km of the radar site (albeit the NEXRAD's on the west coast are of little help in wind shear phenomena detection for populated areas due to the locations where they have been sited).

By contrast, in rural areas and some small metropolitan areas (e.g., Portland, ME) very few capabilities exist for detection of strong surface winds. On the other hand, the safety consequences in low density locations are likely to be far lower (e.g., much lower density of aircraft at low altitudes; lower population per square mile. Table 5-1 provides a summary of the surface wind gap scores across the mission classes.

Table 5-1
Surface Winds Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	2	1	3
0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	2	1	3
0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	2	3	5
0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	2	2	4
500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	2	1	3

5.2 WINDS ALOFT INFORMATION GAP

5.2.1 Impact and Operational Considerations

Winds aloft are a very important factor for low altitude UAS operations. The safety considerations discussed above for surface winds when there are strong wind changes (e.g., storm outflows) are even more serious for the winds aloft portion of a flight because the winds typically are stronger aloft than at the surface (due to surface friction effects reducing the magnitude of the winds at the surface). Additionally, errors in time of flight (including safely arriving in the area of the desired destination) arising from inaccuracies in the assumed winds aloft can impact UTM and may result in the UAS be forced to land prematurely.

Two key factors are the maximum air speed of the UAS and, the impact on winds on time of flight. Table 5-2 shows maximum airspeeds for a number of UAS corresponding to the various mission classes identified earlier. Figure 5-2 shows the impact of a worse case headwind on time of flight. Figure 5-3 shows the effective ground speed impact of winds aloft as a function of the bearing angle of the winds aloft from the desired direction of flight.

Table 5-2
Maximum Airspeed and Endurance Profiles

Mission Class	Example UAS	Max Speed	Endurance
1	DJI Phantom	31 knots	20 min
2	Precision Hawk	43 knots	45 min
3	Amazon Prime Air	50 knots	1 hour
4	Scan Eagle	80 knots	24 hours
5	Reaper	260 knots	14 hours
6	B747	533 knots	20 hours
7	Global Hawk	340 knots	32 hours

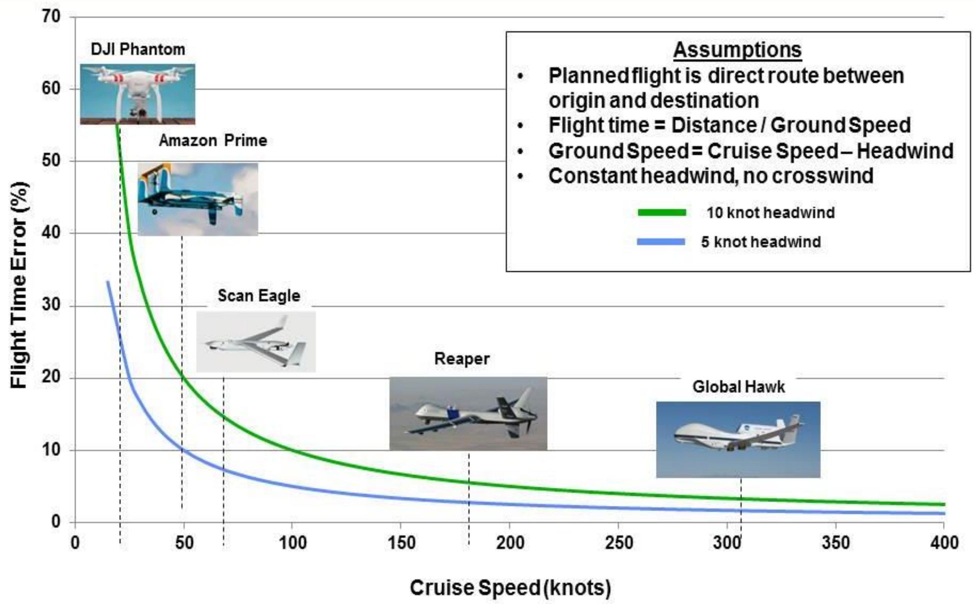


Figure 5-2 Effect of a headwind on flight time for various UAS.

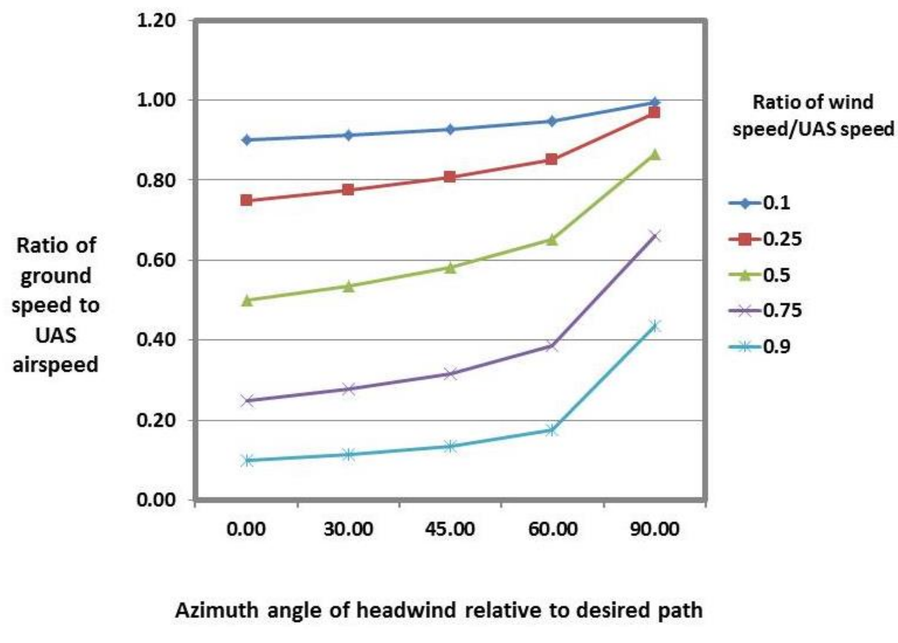


Figure 5-3 Impact of a headwind on ground speed as a function of the headwind bearing angle relative to the UAS desired straight line of flight. An azimuth of 0 degrees corresponds to a pure headwind (the case considered in Figure 5-2). Note that a cross wind (e.g., azimuth angle > 0 degrees) impacts the effective ground speed because the UAS must expend a portion of the airspeed in countering the crosswind.

A potentially important issue for determining the impact of wind forecast errors on UAS time of arrival is whether the UAS flight control systems has a closed loop mode in which it monitors progress to the intended destination and makes adjustments to the airspeed if it appears that the UAS will not arrive at the desired time. The degree to which such a "close loop" control system can significantly impact the sensitivity to errors in headwind and crosswind could not be assessed at this time due to lack of information on representative control systems.

Another factor that needs to be considered for round trip flights is that operating with a headwind and then with a tailwind of the same magnitude produces an overall longer flight time than would have been the case without the headwind. It can be shown that the fractional error in time flown = $1/[1-\left(\frac{Vw}{Vu}\right)2\ ]$. Thus, if there are strong headwinds (say a headwind that is 50% of the airspeed), the flight time will be about 33 % longer than would have been the case without the headwind even though the plane has a very sizable tailwind for half of the distance flow.

5.2.1.1 Winds Aloft UAS Safety Considerations

Safety considerations associated with strong wind changes (e.g., storm outflows) are even more serious for the winds aloft associated with low altitude UAS operations. As noted above, microburst and storm outflow winds are typically even stronger aloft than at the surface due to the lack of wind sheltering by buildings and terrain. Additionally, a UAS that encounters storm outflows aloft which exceed the horizontal airspeed capability of the UAS is more likely to transport far away from the intended location than is the case if the storm outflow is encountered near the surface. If the UAS then inadvertently crosses into a "geofence denied area" such as the approach and landing corridor for a major airport, there clearly could be a major safety hazard.

Note in Table 5-2 that some of the UAS classes have fairly short maximum flight times. For those cases, encountering unexpected strong winds aloft may lead to an UAS uncontrolled descent in an unplanned location which in turn carries the possibility of significant safety risks to people and property on the ground if the operations are being conducted in a highly populated area.

5.2.1.2 Winds Aloft Operational Efficiency Considerations

The winds aloft are a critical factor of UAS planning for flights whose anticipated duration is approaching the maximum shown in Table 5-2. In cases where an UAS will be flying a complicated path, accurate information on the spatial distribution of winds aloft are needed to determine the most appropriate path considering the wind.

5.2.1.3 Winds Aloft UAS Airspace Management Considerations

Time of flight is a key consideration for UTM especially for an UAS which operates in airspace with conventional aircraft. If the UAS low altitude traffic increases to a point such that traffic management becomes important in the low altitude UAS sector, then errors in flight time due to errors in the winds aloft used for flight planning become important.

5.2.2 Utility of Existing Products and Information

5.2.2.1 Non-Urban Environments

Winds aloft observations are provided by a number of systems:

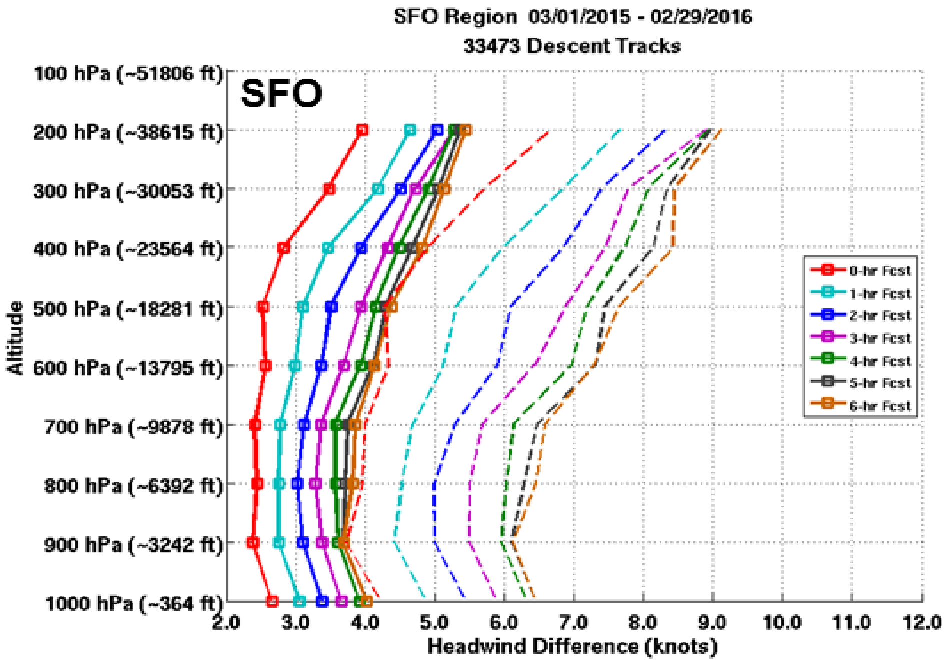
- Meteorological Data Collection and Reporting System (MDCRS)
- Radiosondes
- NEXRAD
- ITWS (terminal winds analysis using MDCRS, NEXRAD, and TDWR)
- The FAA wind shear detection systems (TDWR, LLWAS, ASR-9 WSP) and the NEXRAD detect outflows associated with microburst and gust fronts as well as forecasting gust fronts out to 20 minutes in the future.

The quality and quantity of winds aloft observations for higher altitude UAS operations (e.g., >3000 feet) are generally fairly good in regions that have significant conventional air traffic.

For low altitude UAS operations (e.g., 50–500 feet AGL) the availability of observations differs greatly with geographical location: near major airports and/or regions where the ITWS terminal winds have good coverage from at least two Doppler weather radars, the quality of the winds aloft observations can be fairly good (e.g., Root Mean Square (RMS) errors on the order of 5 knots). These regions of good Terminal Wind (TWIND) coverage are also regions where the wind shear detection systems have good detection of strong outflows from convective storms. When out of the ITWS terminal winds coverage and not near a major airport or NEXRAD, low altitude wind observations are very sparse.

Winds aloft are principally forecast by numerical weather models. On the following pages the HRRR and MDCRS observations are compared for aircraft operating into San Francisco International Airport (SFO), Chicago O'Hare International Airport (ORD), Phoenix Sky Harbor International Airport (PHX), and Newark Liberty International Airport (EWR).

The results in figures 5-4 and 5-5 illustrate differences between observed wind aloft and forecasted winds aloft for ORD, SFO, EWR, and PHX.



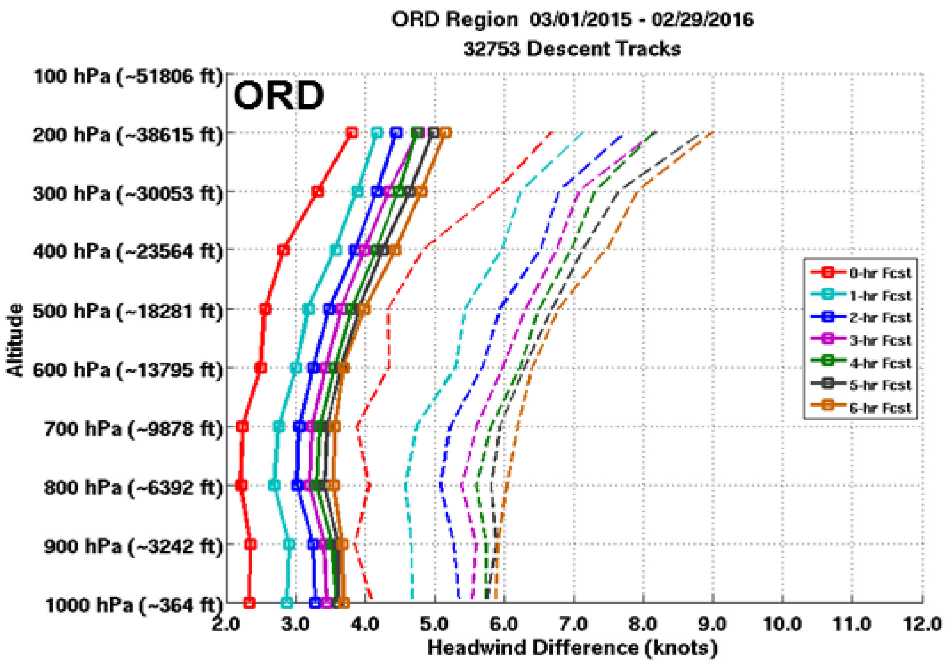
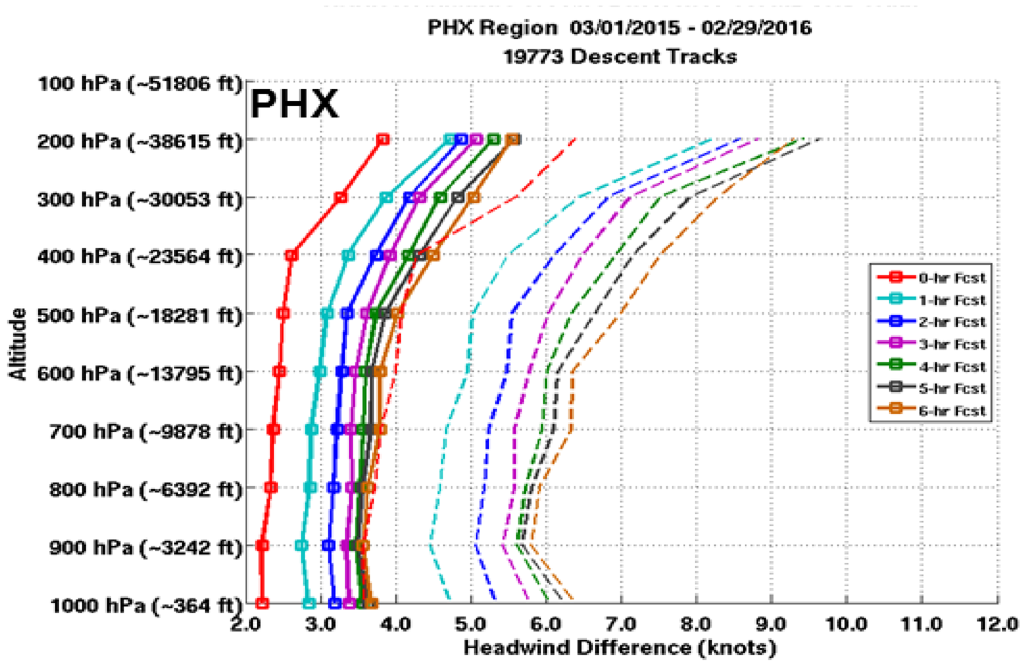


Figure 5-4 Mean headwind difference (solid curves) and mean plus one standard deviation (dashed curves) between HRRR forecasts and MDCRS wind observations by altitude, and forecast look ahead time for arrivals into SFO and ORD airports.



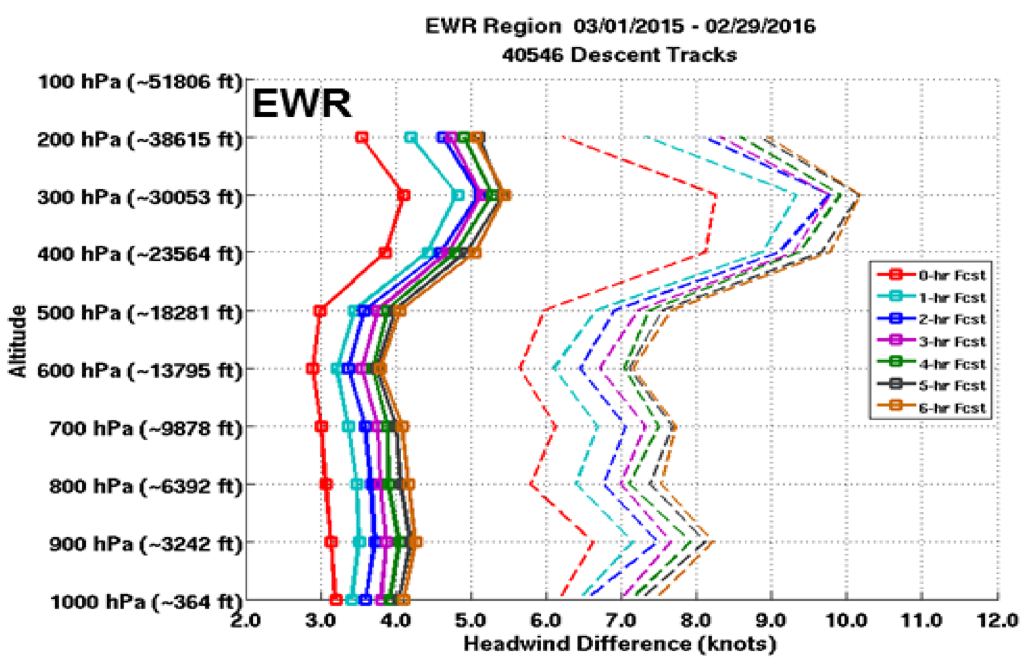


Figure 5-5 Mean headwind difference (solid curves) and mean plus one standard deviation (dashed curves) between HRRR forecasts and MDCRS wind observations by altitude, and forecast look ahead time for arrivals into PHX and EWR airports.

It is observed that EWR has a much larger RMS error, but lower mean error than the other three airports. In all cases, the magnitude of the wind error increases at higher altitudes (where the mean wind speed is higher).

Much higher vertical resolution observations at low altitudes have been made at SFO and MEM using a Doppler lidar. In Figures 5-6 through 5-9 HRRR forecasts aloft are compared with measurements by a lidar in support of the FAA wake vortex program. The poor agreement between HRRR and observations at SFO is believed to arise from inadequacies in the HRRR terrain representation for SFO. At Memphis, the HRRR accuracy seems good enough to support low altitude UAS operations.

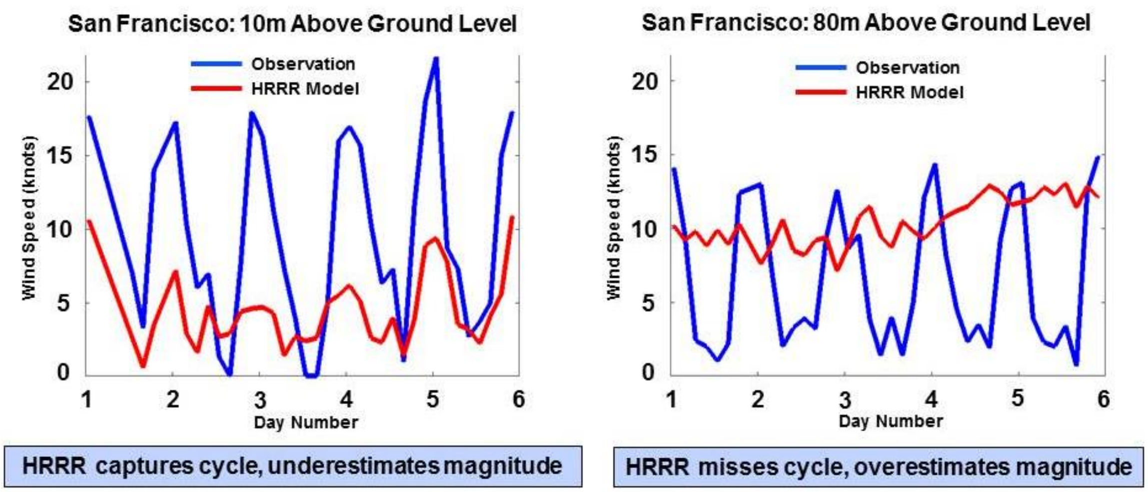


Figure 5-6 HRRR accuracy at 10 m and 80 m AGL over a six day period in the summer.

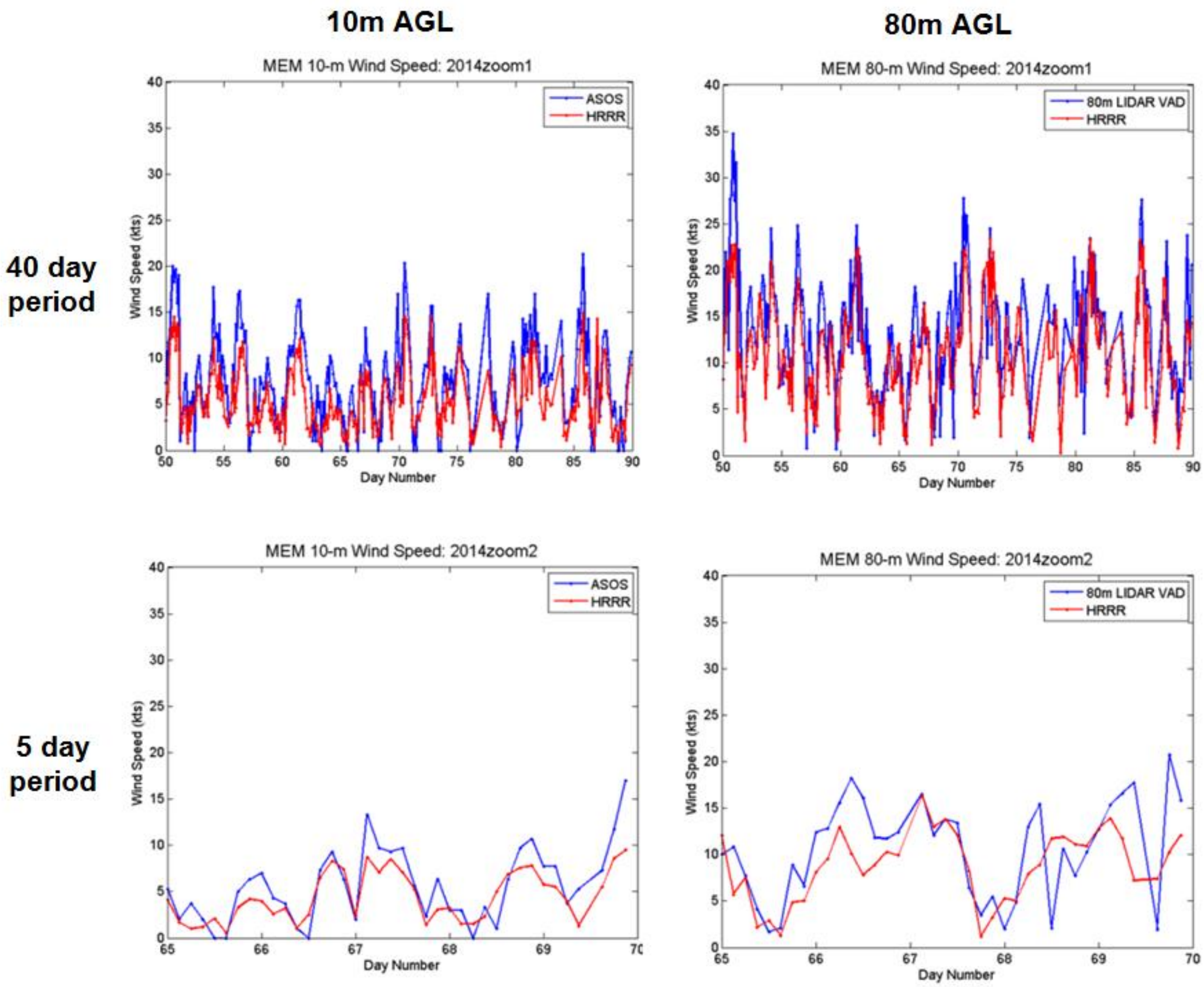


Figure 5-7 HRRR accuracy at MEM at 10 m and 80 m AGL over 5 and 40 day periods.

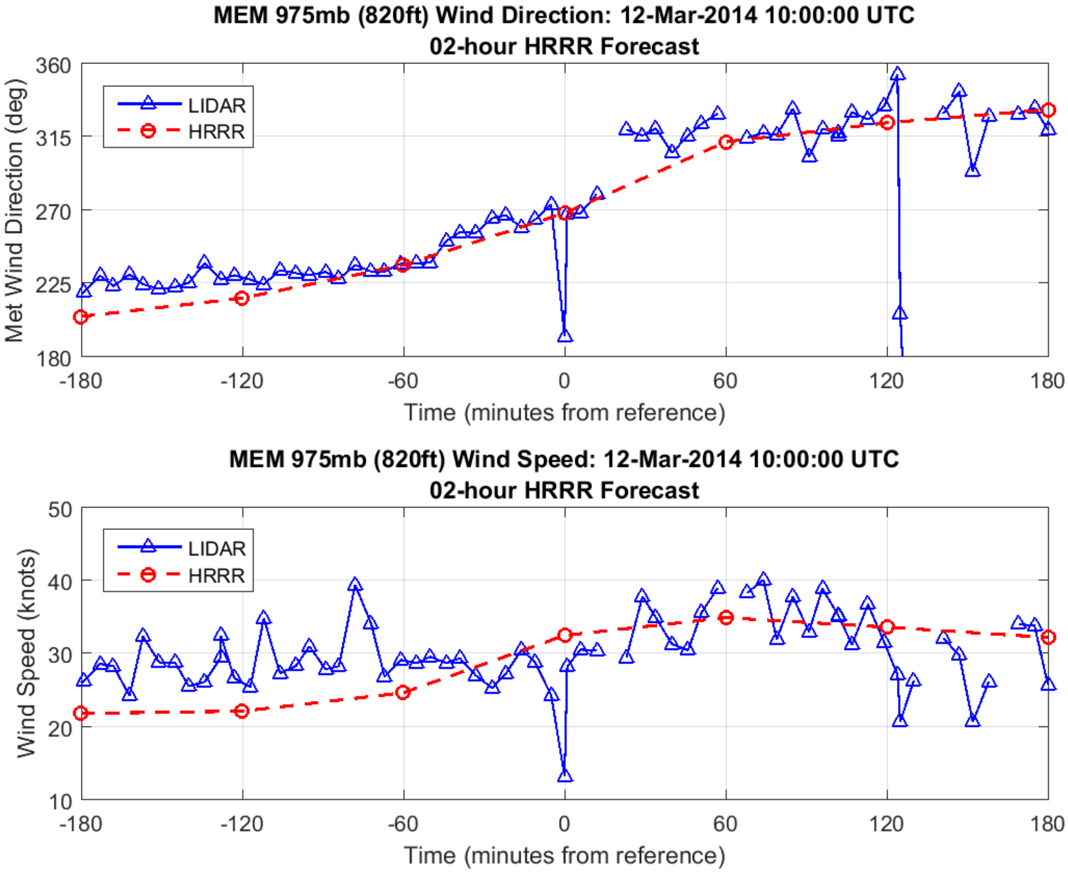


Figure 5-8 HRRR 2-hr forecast accuracy at MEM at 820 feet AGL when a surface wind shift was occuring.

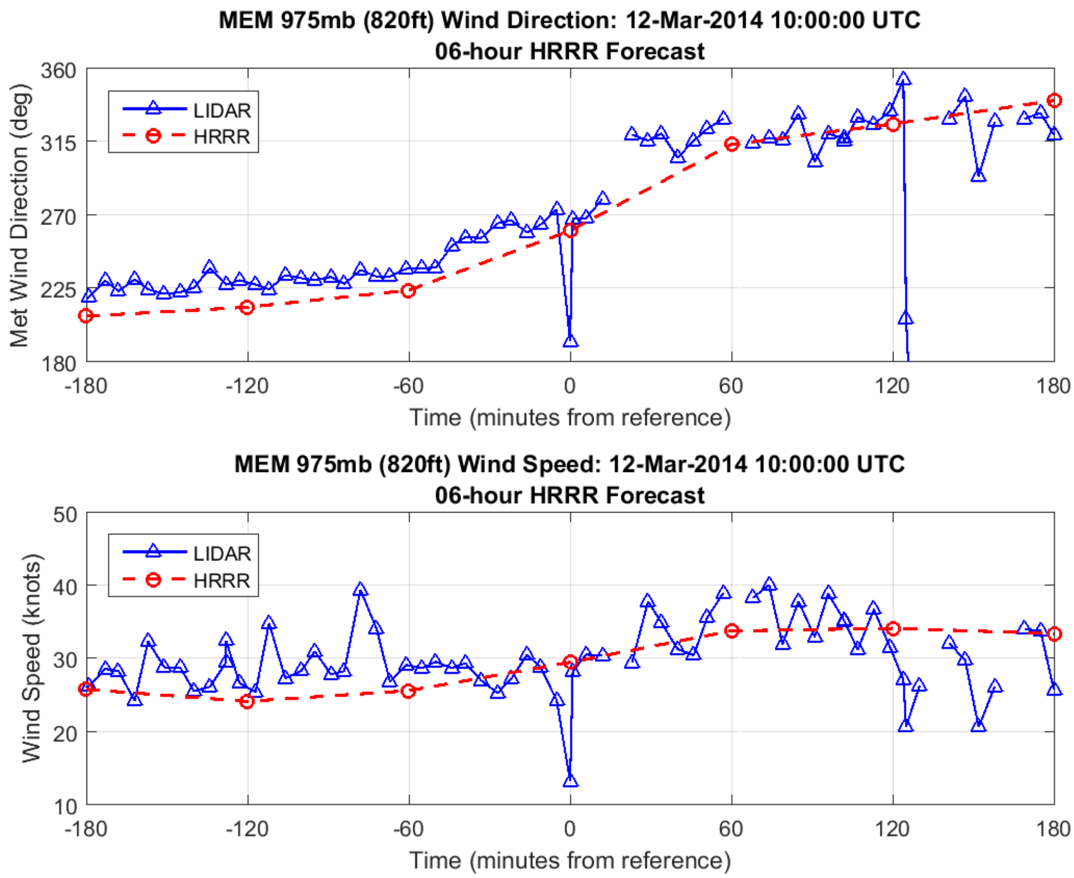


Figure 5-9 HRRR 6-hr forecast accuracy at MEM at 820 feet AGL when a surface wind shift was occurring. Note that the 6-hour forecast of wind speed was more accurate than the 2-hr forecast shown in the previous Figure 5-8.

5.2.2.2 High Rise Urban Environments

Dense urban environments with building heights comparable to or exceeding the UAS operating altitude pose a major challenge as it is difficult to either a) make representative observations of the very complicated wind patterns that occur, or b) use validated forecasts for the winds aloft.

A street canyon (also known as an urban canyon) where the street is flanked by buildings on both sides can modify both the speed and the direction of the ambient wind. The vertical wind velocity approaches zero at the roof level of the canyon. Shear production and dissipation are high at the roof level and a strong thin shear layer is created at the building height. Figure 5-10 shows an example of flow patterns in an urban environment.

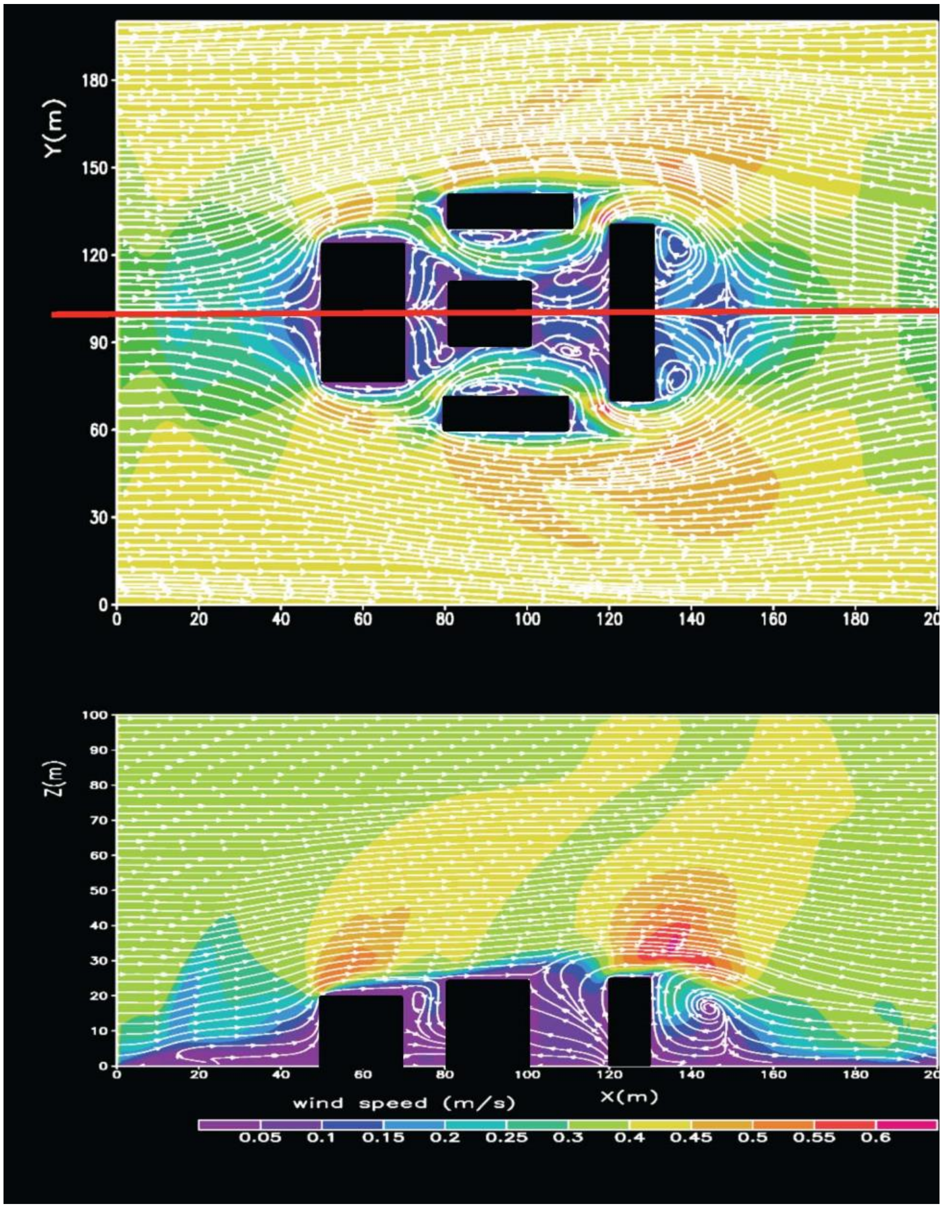


Figure 5-10 Wind patterns computed using Army Research Laboratory (ARL) microscale Atmospheric Boundary Layer Environment (ABLE) numerical model (Dave Knapp presentation at UAS-wx workshop NASA Ames, July 2016.)

Army Research Laboratory (ARL) found that the computed wind pattern can be very sensitive to small changes in the ambient wind direction during experiments using numerical models with very simple buildings. One suspects that the results also would be very sensitive to changes in the building profiles (e.g., actual buildings often differ significantly from shapes shown in the figures above). Clearly, the winds aloft weather product capability in dense urban environments is very poor.

The New York Fire Department provided interview feedback that the very complicated wind environment in the high building section of Manhattan is too challenging to warrant attempting low altitude UAS operations at this time.

5.2.3 Potential Shortfalls

Winds aloft are a very important element of low altitude UAS operations due to the much lower maximum airspeeds and endurance of the low altitude UAS (see Table 5-2). Observations are generally too sparse for the expected operations region for the low altitude UAS (e.g., away from airports). As a consequence, UAS operators will need to rely on:

(i) Inference from the surface winds at the UAS launch site, and/or
(ii) Numerical weather forecasts for the expected operations region

Extrapolation from surface winds at the UAS launch site may be fairly reasonable on flat terrain with no trees or buildings nearby (e.g., within 200 meters). However, in locations with trees and multi-story buildings near the launch site, wind sheltering can cause the surface winds to far underestimate the low altitude winds aloft (the LLWAS siting document FAA Order 6560.21A "SITING GUIDELINES FOR LOW LEVEL WINDSHEAR ALERT SYSTEM (LLWAS) REMOTE FACILITIES" has curves that show the degree of sheltering as a function of the geometry).

The HRRR commonly produces errors of about 5 knots in the low altitude regime, and 20 knot errors are not uncommon (see, e.g., the Memphis and SFO lidar comparisons to HRRR). Moreover, the HRRR accuracy does not seem to improve significantly if one uses short lead time forecasts (e.g., 2-hr as opposed to 6-hr).

The information gap is driven by strong, unexpected outflows from thunderstorms with no current easy access to FAA information on such strong outflows. This leads to the conclusion that current winds aloft weather products rarely meet the needs for what is anticipated to be the operations domain for most of the low altitude UAS operations (urban and suburban regions). There are UAS applications in rural areas with minimal terrain features (e.g., farm land, pipe line or train line inspection in the Great Plains) for which the currently available products may be adequate most of the time.

The winds aloft significance scores for all of the low altitude UAS operations are high due to the importance of winds aloft for planning of extended flights and the possibility of encountering strong outflows from storms with a potential of creating significant safety risks for conventional aircraft and/or persons and buildings on the ground.

For UAS operations at altitudes similar to those for conventional aircraft, the following is true:

a) The vehicles are much less sensitivity to 5–20 knot wind errors, and
b) The operators have access to far better information on the winds aloft due to the MDCRS reports and the nature of the winds aloft.

Hence, the winds aloft product gaps are much less for mission classes 5 and 6. Table 5-3 provides a summary of the weather information gaps related to winds aloft.

Table 5-3

Winds Aloft Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	3	2	5
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	3	2	5
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	3	3	6
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	3	3	6
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	3	0	3
Mission Class 6 FL250+ / 1-12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	3	0	3

Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	3	1	4

5.3 TEMPERATURE INFORMATION GAP

5.3.1 Impact and Operational Considerations

Cold temperatures may impact small UAS battery performance, and are an important factor for anticipating icing conditions. Operating temperature can become a concern for values less than 32°F (0°C). Hot temperatures may impact engine performance, and also have a negative effect on the performance of on-board electronics. Operating temperature can become a concern if greater than 86°F (30°C).

5.3.2 Utility of Existing Products and Information

The primary source of surface temperature information is via surface airport weather observations, routinely available in METAR reports. Contour maps of interpolated hourly surface temperature observations are widely available. Aloft temperature information is acquired via radiosonde profiles, and typically mapped to standard pressure level heights or flight altitudes. Surface and aloft temperature fields are also available as 0-hour analysis fields for most numerical models. Though these temperature fields tend to be smoothed, they typically provide sufficient information for UAS mission operation.

Most forecast temperature information is derived from numerical models or via MOS/LAMP. The National Weather Service provides point location plots of temperature (and other weather elements) in meteogram format out to six days (Figure 5-11). The Aviation Weather Center (AWC) web site, which is popular amongst UAS operators, provides forecast surface and aloft temperature contour plots (Figures 5-12 and 5-13), temperature contour plots, and wind/temperature tables at 6-, 12- and 24-hour forecast horizons for flight levels ranging from 3000 feet to 53,000 feet (Figures 5-12 and 5-13).

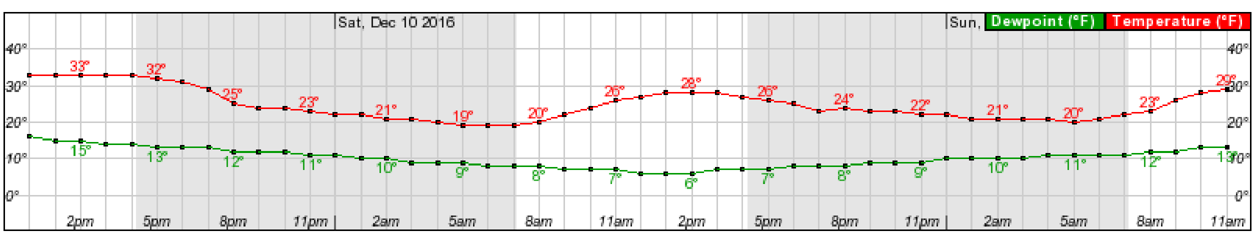


Figure 5-11 NWS 48-hour point location meteogram of temperature and dew point.

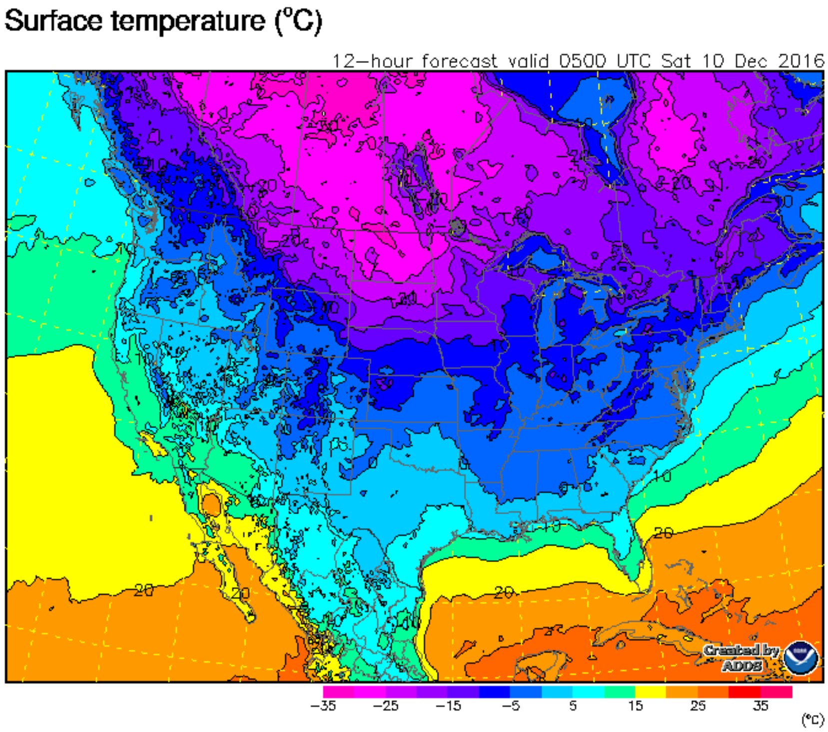


Figure 5-12 12-hour forecast surface temperature plot.

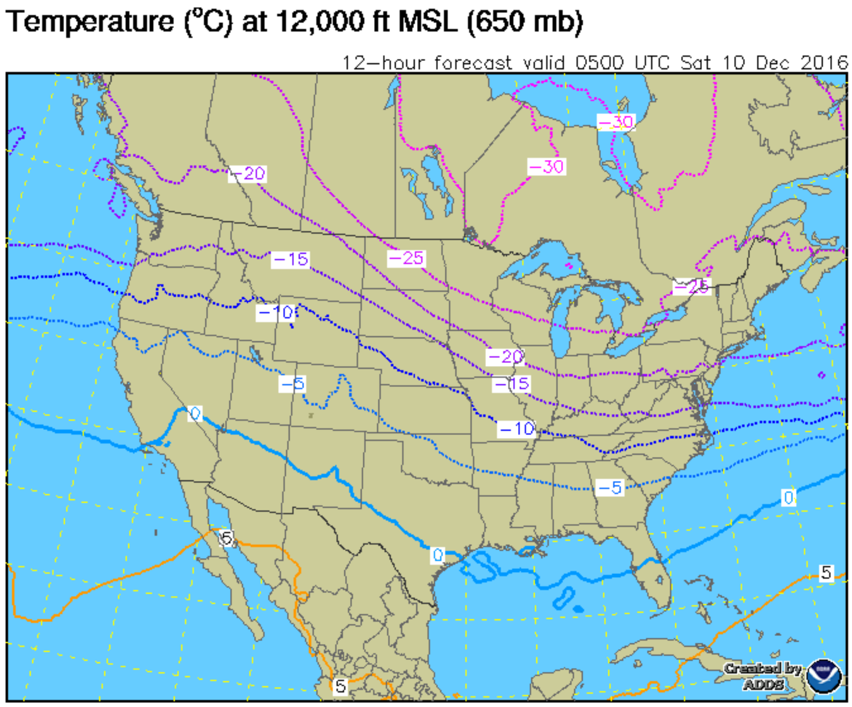


Figure 5-13 12-hour forecast temperature plot for 12,000 ft AGLs.

5.3.3 Potential Shortfalls

Since temperature impact is limited to extremes (less than 32°F/0°C or greater than 86°F/30°C), precise temperature information is typically not required, and most available sources of temperature information are adequate to meet UAS needs. This was reflected in the relative significance and utility scores from survey respondents. Lack of adequate temperature information would be most evident for off-airport small UAV operations where terrain or marine influences may discount the value of interpolated observations or forecasts, or for temperature information specifically in the 100–400 ft AGL altitude range where direct observations and forecasts are not specifically available. However, existing observations and forecasts provide suitable indication when extreme temperatures are a potential operational risk. The only other potential shortfall may be layered temperature information aloft as it pertains to icing, which is addressed in Section 5.10. Table 5-4 lists the temperature information gap scores.

Table 5-4

Temperature Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	1	1	2
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	1	1	2
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	1	1	2
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	1	1	2
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	1	0	1
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	1	0	1
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	1	1	2

5.4 BAROMETRIC PRESSURE INFORMATION GAP

5.4.1 Impact and Operational Considerations

The primary impact of barometric pressure information is its use in establishing the altimeter setting for a pressure altimeter. This is expected to only have an operational impact (safety risk) if there were to be a much larger than anticipated change in pressure during the duration of the flight at the launch/landing location(s).

5.4.2 Utility of Existing Products and Information

Barometric pressure reduced to sea level and altimeter setting routinely appears in METAR reports as observed from airport surface observing stations, and is also widely available as contour plots. Additionally, the locations of features associated with abrupt pressure change (such as synoptic scale fronts and circulation systems) are also identified on most widely available surface analysis maps and forecast maps. Numerical models in general do a good job at predicting pressure changes at the scale required for UAS operations.

5.4.3 Potential Shortfalls

The primary potential shortfall would be a large unanticipated change in surface pressure. For larger UAS operations at airports where observations and forecasts are routinely available, this is not a general concern. Even for smaller off-airport operations, there is sufficient information to anticipate potential changes associated with synoptic scale features. Furthermore, flight durations are short enough that large changes of local pressure (within VLOS during flight) are infrequent. There may, however, be risk of pressure changes associated with smaller scale features, such as that associated with localized convective outflow. However, in those circumstances, the altimeter-related concern would typically be less than the risk associated with the wind shear and precipitation accompanying the convective activity. As such, UAS operators (particularly small UAS) are already avoiding convection risks, and their information shortfall is more notably associated with detection and forecasting of convective weather (Section 5.5) and wind gusts/shear (Sections 5.1 and 5.2). Table 5-5 provides a summary of the barometric pressure information gap scores.

Table 5-5

Barometric Pressure Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	1	1	2
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	1	1	2
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	1	1	2
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	2	1	3
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	1	0	1
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	0	0	0
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	0	0	0

5.5 CONVECTIVE WEATHER INFORMATION GAP

5.5.1 Impact and Operational Considerations

Convective weather is a significant weather hazard for all mission classes and categories of UAS. For the purpose of this report, the term convective weather refers to areas of moderate or greater precipitation also associated with turbulence and/or hail. Wind phenomena such as microbursts, and gust fronts or wind shear associated with thunderstorms are discussed in Section 5.2. While convective weather is largely a seasonal phenomenon, it affects all areas of the country. Figure 5-14 depicts the annual severe weather frequency across the Contiguous United States (CONUS).

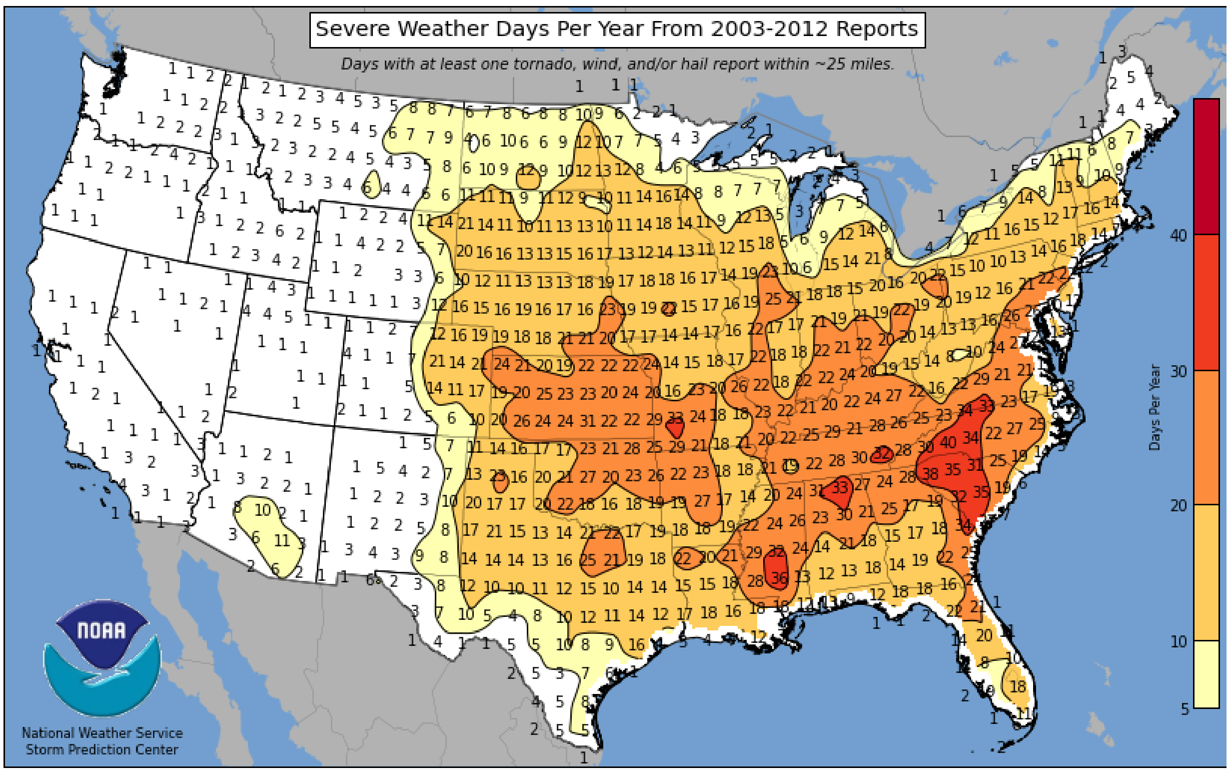


Figure 5-14 Average number of severe weather days per year (www.noaa.gov)

5.5.1.1 UAS Safety Considerations

The most obvious impact of convective weather is the safety hazard caused by the associated precipitation, turbulence, and hail. Precipitation and hail can damage the airframe of a small UAS and result in an uncontrolled descent to the ground. Convective induced turbulence can overwhelm the ability of a small UAS flight control system to maintain position. Large UAS airframes are impacted by convective weather in a similar fashion as manned aircraft. In certain cases, convective-induced turbulence can cause structural failure or at a minimum, deviations from assigned altitude or headings. For UAS with a satellite-based control and communications link, convective weather can interrupt the signal or convective-induced turbulence can overwhelm the SATCOM controller and result in lost link. If operating BVLOS, there are additional considerations if the UAS encounters convective weather during a mission. Most UAS are not equipped with onboard weather radar; therefore, if a tactical deviation around convective weather is required, it must be done with reference to ground-based information unless the UAS has a camera system that could identify convective weather in the vicinity.

5.5.1.2 UAS Operational Efficiency

BVLOS operations require significant planning to ensure that the anticipated flight path and any contingency routing remain clear of convective weather. Any uncertainty in the convective weather forecast results in added conservatism to the plan, sometimes cancelling a mission that would have been otherwise unaffected by the weather. Moreover, unanticipated convective weather can result in aborted missions and significant mission cost if a mission objective is not accomplished.

5.5.1.3 UAS Airspace Management

The hazardous nature of convective weather generally results in airspace that is unusable for normal flight. This manifests itself in weather deviations that cause airborne delay and can result in the infeasibility of time-based operations. Moreover, when weather limits the capacity of airspace, constraints should be implemented to either limit or preclude flight through the area. The constraints must be robust to UAS with different operational capabilities in order to maximize efficiency. In many ways this is a similar framework to the current traffic management system for manned aircraft except the constraints need to consider a range of UAS-specific convective weather sensitivities.

5.5.2 Utility of Existing Products and Information

Convective weather products can be classified by the decisions they are intended to influence. In general, tactical weather products are mostly observation-based or are forecast products with very short forecast horizons and fast update rates to capture dynamic changes in the weather. Strategic products are mostly model-based, with some input from observations and human observers. The purpose of a strategic product is to inform high-level routing decisions, go/no-go decisions, and contingency plans that are implemented well in advance of the weather impact.

5.5.2.1 Tactical Convective Weather Products

Mission classes 1 and 2 are characterized by VLOS operations with durations between 0 and 1 hour, and typically rely on tactical weather products due to the short duration of the flights and the ease of recovery if the conditions become unfavorable. Most UAS operators for this type of mission rely on visual observation of convective weather to make their go/no-go decision and for any premature mission cancellation. Outside of visual identification, the most common generally available tactical weather product for convective weather information is NEXRAD ground-based weather radar. NEXRAD provides a map of precipitation levels, where higher levels of precipitation can indicate convective activity. NEXRAD can be viewed from a number of websites, where the precipitation image is typically updated every 10 minutes. While NEXRAD is popular for convective weather situational awareness, a number of general aviation accidents have been caused by inadvertent penetration of convective weather due to latency in NEXRAD information. Additionally, there are gaps in NEXRAD coverage over select areas in the mountain west and off of the coast, where terrain interferes with the radar beams. Figure 5-15 illustrates the coverage areas of NEXRAD.

Figure 5-15 NEXRAD coverage areas.

Operators familiar with manned aviation also utilize tactical aviation weather products such as Convective SIGMETs, which are issued hourly and are valid up to 2 hours, and provide advisories on thunderstorms and severe surface weather including high winds, hail, and tornadoes. The primary drawback to Convective SIGMET information is that it is a very broad warning that might not be relevant to local VLOS UAS operations. Figure 5-16 shows a typical convective SIGMET.

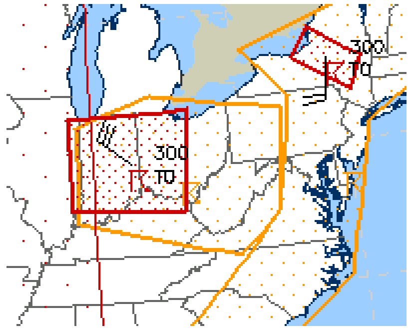


Figure 5-16 Depiction of Convective SIGMET (red polygon).

METARs provide airport observation of cloud type and are issued hourly and updated if conditions change significantly during the hour. The primary drawback to METARs is that it is a point observation over an airport, not necessarily the local area what the UAS is operating. There is a remarks section that can provide more information on thunderstorm beginning and ending times as well as a storm motion vector. Another drawback to METARs is the possibility that a METAR will not be issued when there is convective weather is near the airport [6].

The FAA Air Traffic Control (ATC) facilities and major airlines currently have real time access to information provided by the ITWS, CIWS and CoSPA systems. These systems provides air traffic managers and controllers with a graphical display of airport terminal-impacting weather via synthesis of data from FAA and NWS sensors (especially the NEXRAD, ASR-9 and TDWR radars as well as the Canadian meteorological service Doppler weather radars), numerical models, and aircraft-derived weather data. Derived convective weather products include mosaics of VIL precipitation, storm cell information, the motion of storm cells, and high spatial resolution gridded forecasts of VIL and storm echo tops.

ITWS, CIWS, CoSPA and NWP all have several short term forecasts for tactical planning. Storm leading edge extrapolated positions are shown for 10 and 20 minutes in advance. Explicit forecasts of VIL and echo tops are available every 15 minutes from 0 to 2 hours along with quantitative metrics for the accuracy of the 1-hour and 2-hour forecasts. In addition, ITWS, CIWS, CoSPA and NWP all show regions of current growth and decay of the convective weather.

The FAA convective weather information is currently unavailable to the average UAS operator. As noted earlier, one of the NextGen improvements will be significantly enhanced access to the FAA convective information through the CSS-Wx system which offers a mechanism for private industry UAS weather providers to access NOAA and FAA NWP weather products.

5.5.2.2 Strategic Convective Weather Products

Mission classes 3 thru 7 are characterized by BVLOS missions with durations greater than one hour. These mission classes rely on the previously discussed tactical convective weather products in addition to strategic convective weather products that incorporate longer forecast horizons. There are a variety of strategic convective weather products available to UAS operators that have a varying degree of usefulness. For example, NWS point forecasts available on www.weather.gov provide hourly thunderstorm percentages for a given latitude/longitude position. While this forecast provides local weather to the operator, it is generally unclear how the information translates into an operational decision. TAF provides a 24–30 hour forecast of airport weather, which includes a convective weather component; however it is only valid within 5 miles of the airport. The Collaborative Convective Forecast Product (CCFP) and Significant Weather (SigWx) prognostic charts provide broad forecasts of convective weather areas, but the information might not be specific enough to support efficient UAS operations across the spectrum of UAS types. Figures 5-17 and 5-18 illustrate examples of the CCFP and SigWx charts, respectively.

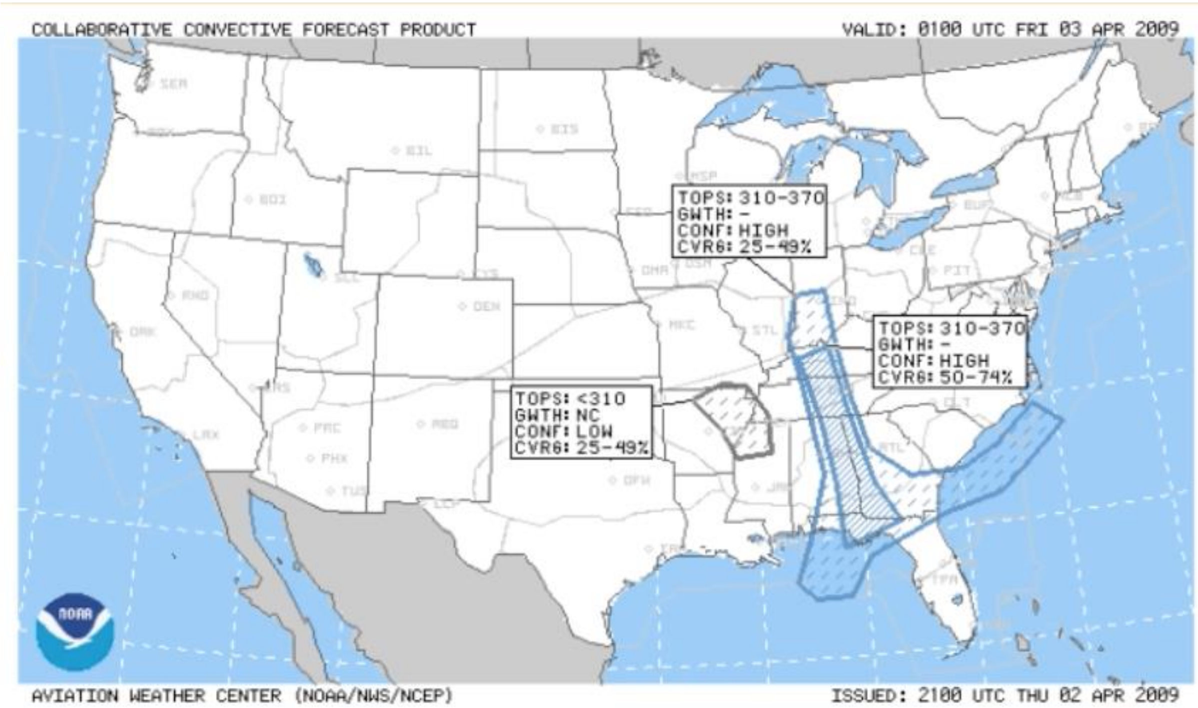


Figure 5-17 Example of the Collaborative Convective Forecast Product. (www.aviationweather.gov)

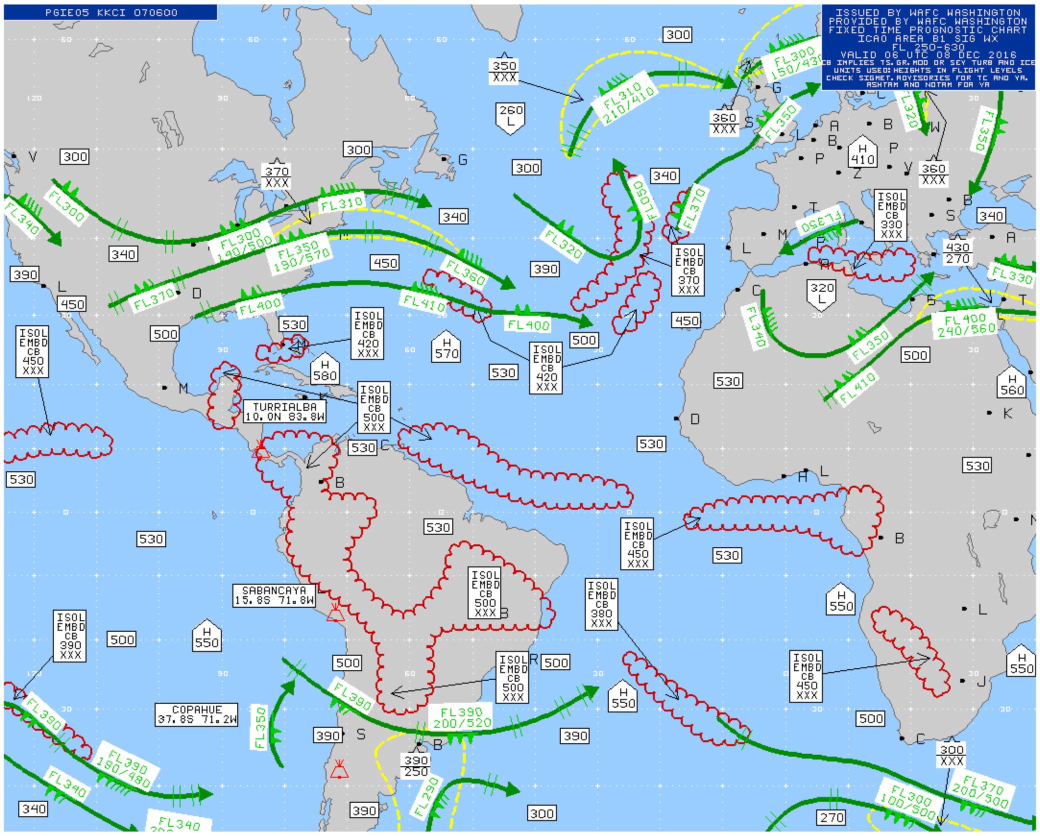


Figure 5-18 Example of SigWx Prog chart. Convective weather regions shown by red scaling. (www.aviationweather.gov)

The FAA's deterministic forecasts generated by CIWS, CoSPA, and the planned NWP provide a set of specific weather products and a detailed picture of forecasted convective weather features (precipitation, radar echo tops, and weather avoidance regions for manned aircraft) every hour, with a maximum forecast horizon of 8 hours. These forecasts use radar data alone for 0–2 hours, blend HRRR and radar based forecasts for 2–4 hours and use HRRR forecasts for 4–8 hours.

The value of deterministic tools is that they provide a realistic looking weather picture that can be easily translated into specific decisions. The drawback to deterministic forecasts is that their performance decreases with forecast lead time.

An alternative to a deterministic convective weather forecast for strategic planning is a probabilistic convective weather forecast such as LAMP or MOS, which provide forecasts of the probability of convection for a spatial grid (currently 2.5 km) every 3 hours out to 192 hours. If an UAS will operate only within a single grid point, the LAMP/MOS guidance should be helpful. However, if the UAS will operate over a number of grid points, the current LAMP/MOS products do not provide enough information to determine whether the mission probably can be carried out.[3]

Overall, the tactical weather products are more useful than the strategic weather products. This is largely due to the increase in forecast uncertainty with longer forecast horizons that impacts the effectiveness of flight and contingency planning. The convective weather products were given a score of ‘1’ for mission classes 1 because of the short mission durations and the ability to visually observe the weather. With mission class 2, the possibility of being surprised by a fast moving convective weather system such that the UAS cannot be safely recovered is a significant concern and results in a score of ‘2’.

The currently available weather products (excluding non-public sources) do not completely meet the tactical operations need because there are cases in which the latency of NEXRAD and/or a visual obscuration and/or lack of access to reliable short term forecasts results in a fast moving convective weather system surprising the UAS operator. The convective weather products to support mission classes 3–7 are rated ‘2’ based on a need for a better representation of forecast uncertainty to aid in risk-based flight planning. Moreover, no weather products currently meet the need to translate convective weather into airspace impacts for UAS operations.

5.5.3 Potential Shortfalls

The ability of current convective weather products to support UAS needs is dependent largely on whatever the operation is, VLOS or BVLOS. In general, the weather products mostly meet the needs of VLOS missions due to the ability of the UAS operator to visually observe the surrounding weather in conjunction with more detailed tactical weather products, such as commercially available NEXRAD images. The primary shortfall associated with VLOS operations occurs during nighttime operations or quickly changing conditions where the operator does not recognize changing weather in time to recover the UAS.

There are a number of shortfalls in convective weather products that affect BVLOS operations. First, there are BVLOS missions with durations greater than many of the currently available strategic convection forecast horizons (e.g., CCFP). Moreover, current convective weather forecasts do not sufficiently convey convective weather uncertainty such that it can be used to manage risk in lost link contingency planning.

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[3] The problem is handling of statistical correlations that may exist between nearby grid points. For example, if an UAS were to fly over five grid points each with a probability of 0.25 of convection and, what happens in each grid point is independent of what happens in the other grid points, the probability of the route being entirely free is 24%. In practice, however, convective weather is much more likely to occur in a given grid cell if convection occurs in an adjacent cell.

If an UAS encounters convective weather on its route, it is unclear how the tactical management should occur without the aid of onboard weather radar. NEXRAD has long been frowned upon for tactical weather avoidance in the manned aircraft community, but it may be the only current option for BVLOS operations without airborne radar.

Additionally, there is a lack of understanding in how convective weather will impact the spectrum of UAS operations such that the impact can be modeled and used to determine airspace management constraints.

There are weather products currently in operational use by the FAA and airlines that would be very helpful for tactical decision making by the average UAS operator. For example, the rapid update rate and wealth of products within CIWS/CoSPA (and planned for NWP) could provide superior tactical decision support to all of identified mission classes for UAS operations. Table 5-6 provides a summary of the scoring for the convective weather information gaps. Note that the significance of convective weather is rated '3' for all mission classes for the reasons mentioned above.

Table 5-6

Convective Weather Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	3	1	4
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	3	2	5
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	3	2	5
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	3	2	5

Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	3	2	5
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	3	2	5
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	3	2	5

5.6 PRECIPITATION INFORMATION GAP

5.6.1 Impact and Operational Considerations

The precipitation weather element is defined by liquid precipitation that is not associated with a convective core. This generally includes light to moderate precipitation, although occasional instances of non-convective heavy precipitation (e.g., stratiform rain) are included in this definition. Precipitation associated with convective weather is handled in Section 5.5.

5.6.1.1 UAS Safety Considerations

Precipitation has a varied impact on different UAS platforms and mission classes. In general, small UAS are not waterproof, which means they have to avoid any amount of precipitation. If they do get wet, there is risk for an electrical failure and uncontrolled descent into the ground. On the other hand, large UAS can tolerate precipitation as long as it is not severe enough to overwhelm the combustion in the engine.

5.6.1.2 UAS Operational Efficiency

The efficiency of large UAS operations is generally unaffected by precipitation unless the precipitation interferes with takeoff or landing by either decreasing visibility or breaking action on the runway. It is unclear how small UAS will operate BVLOS with regard to precipitation. If the vehicles are sealed to water they are significantly less sensitive to precipitation than vehicles that are not sealed. If the vehicles are not sealed, precipitation will impact operations significantly – both nominal flight plans and contingency flight plans would be required to remain clear of rain.

5.6.1.3 UAS Airspace Management

Precipitation represents a no-fly area for a subset of UAS platforms and would therefore require an airspace constraint in a UAS traffic management concept. It is important for the constraint to reflect the specific capabilities of the UAS (e.g., precipitation tolerance) and not overly constrict the airspace.

5.6.2 Utility of Existing Products and Information

The weather products for precipitation are almost identical to the weather products for convective weather listed in Section 5.5. In general, the most sensitive UAS platforms to precipitation conduct VLOS operations; therefore the operator is located at the mission site and would be able to recover the UAS at the first sign of precipitation (i.e. the operator can abort the mission if they feel rain). Outside of physical observation, the operator can easily check NEXRAD for developing conditions.

5.6.3 Potential Shortfalls

The currently available weather products mostly meet the precipitation need. The primary shortfalls are related to VLOS operations, where a quickly moving system could surprise an operator and overwhelm the UAS before it can be recovered. There are also shortfalls over the ocean and in some mountainous areas where NEXRAD coverage does not exist. The vast majority of BVLOS operations are robust to precipitation, especially given the wealth of weather products available to support. Table 5-7 provides the precipitation gap ratings for each mission class.

Table 5-7

Precipitation Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	3	1	4
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	3	1	4
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	2	1	3
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	2	1	3

Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	1	1	2
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	0	1	1
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	0	1	1

5.7 CLOUDS AND CEILING INFORMATION GAP

5.7.1 Impact and Operational Considerations

This weather element refers to areal cloud coverage that provides an obstruction to visibility, and cloud ceiling height which, along with visibility, contributes to determination of Visual Meteorological Conditions (VMC) / Instrument Meteorological Conditions in terminal airspace. Primary impact on small UAS is the Part 107 Flight Rules for VLOS, which require vehicles to maintain 500 feet below and 2000 feet horizontal distance from clouds. For BVLOS operations, UAS are expected to be subject to Instrument Flight Rules. As such, the availability of quality cloud observations and forecast information greatly impacts terminal area traffic management of large UAS which may be integrated with manned traffic, since airport operational capacity is largely influenced by cloud/visibility conditions (IMC versus VMC). Presence of clouds for BVLOS operations may also contribute to lost communication link between vehicle and controller. For UAS missions that require favorable visual conditions (survey, mapping, photography, inspection, etc.), the presence of cloudiness also has a mission impact beyond that associated with safe vehicle operation and air traffic management.

5.7.2 Utility of Existing Products and Information

The primary observation of cloud amount and ceiling height is acquired through standard airport surface observation ceilometer instrumentation. Cloud amounts are reported in layers, with ceiling height established as the lowest layer with at least 5/8 area cloud coverage. The surface observation determines the ceiling component of an airport's IMC/VMC status. (The standard requirement for VMC is ceiling not less than 1000 feet AGL). Cloud layers and base heights can also be inferred via temperature/humidity measurements from twice-daily balloon Rawinsonde profiles. Additionally, inferred cloud layers can be determined from most numerical model analysis fields. Pilot reports may contain cloud height information at altitude, though reporting is irregular in time and space. Another major source of cloud information is via visual and infrared satellite imagery, which provides excellent spatial coverage, but is not able to discern layers or cloud base heights necessary to determine cloud ceiling.

For cloud forecast conditions, manned and unmanned aircraft pilots rely most heavily on TAFs. Cloud conditions are also a component of other derived products, such as SIGMETs, AIRMETs, and Area Forecasts. For specific airport locations, forecasts of cloud amount and categorized ceiling height are included in statistically-based MOS/LAMP guidance, which is often a source forecast for other derived forecast products (e.g., TAFs, Area Forecasts, etc.) Forecast cloud layer information is currently an output product of most numerical models, which provides for good horizontal resolution to address off-airport conditions, though product reliability requires further validation. The Aviation Weather Center provides a National Ceiling and Visibility (C&V) Analysis product (Figure 5-19) which uses interpolation of METAR reports with cloud masking techniques to estimate cloud coverage between surface reporting stations. It also includes a model-derived ceiling forecast out to 15 hours.

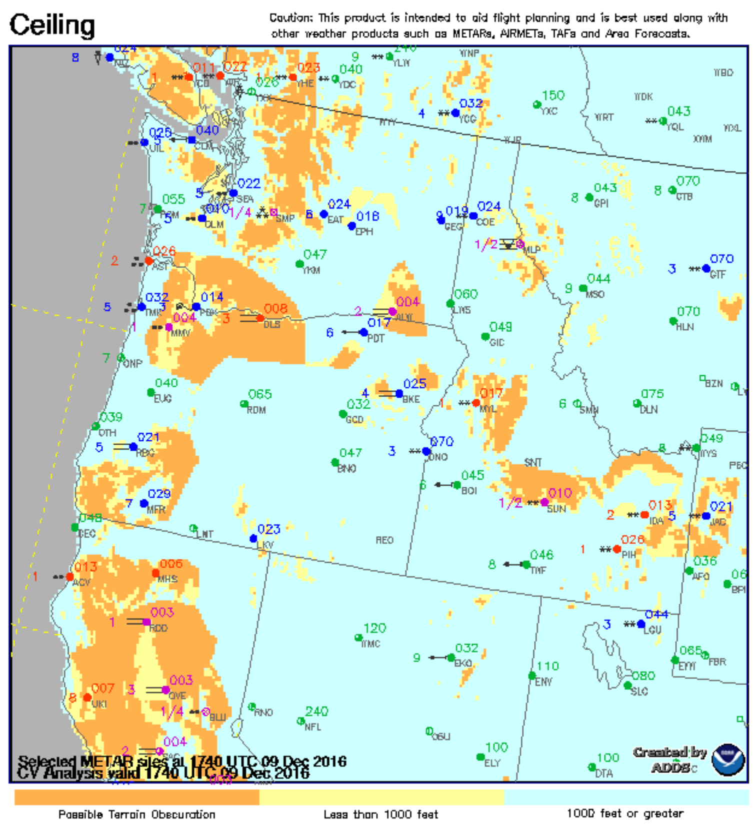

Figure 5-19 Ceiling analysis for Northwest U.S. region, from Ceiling and Visibility Analysis (CVA). (www.aviationweather.gov)

A substantial Research and Development (R&D) effort was sponsored by FAA AWRP to provide an approach zone cloud/ceiling forecast tailored specifically for San Francisco International Airport. The frequent occurrence of diurnal stratus has a major impact on SFO's arrival capacity on many days each summer. Due to the high volume of traffic and interconnectivity with Pacific Rim flights, air traffic management's ability to anticipate clearing (capacity increase) is critical for efficient operations, making SFO a good candidate for development of an airport-specific ceiling solution. This required deployment of a number of special system sensors in the Bay area (Figure 5-20), and development of multiple statistical and physical models for accurate ceiling prediction. A similar concentrated investment at other key airports for either manned or unmanned aircraft operations would, of course, depend upon potential benefits. The stratus forecast system at SFO continues to be an integral part of the SFO approach forecast delivered by the Oakland Center Weather Service Unit and NWS Forecast Office at Monterey, with key information shared with national airspace managers and commercial airlines.

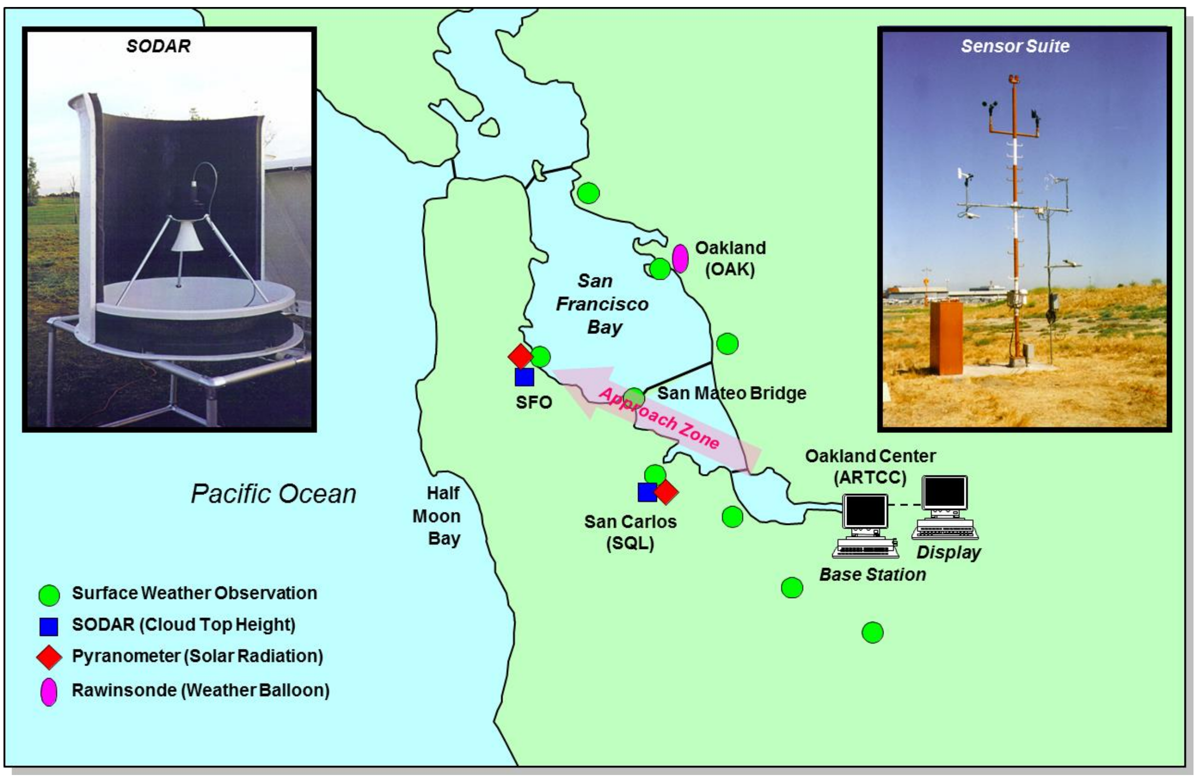

Figure 5-20 Sensor suite in support of specialized Marine Stratus Forecast System at SFO.

5.7.3 Potential Shortfalls

The sufficiency of currently available cloud observation and forecasting information varied largely between on-airport and off-airport UAS operators. There is extensive coverage of surface observing stations at airports across the CONUS, and most automated and derived forecast products (e.g., TAFS, MOS/LAMP, etc.) are tailored for terminal airspace from where validating reports to support forecast development are widely available. The primary shortcoming at airport locations is the timing of a lowering or lifting ceiling, for which the skill varies by location and time horizon. Survey respondents were more dissatisfied with the availability of ceiling information for launch/landing operations taking place at a distance from an airport, where the representativeness of the nearest airport cloud/ceiling observation is in question. This is cited as particularly significant for small UAVs, as seen by the Significance Score of shorter range missions in Table 5-8, which tend to be smaller aircraft requiring VLOS, or unobstructed visibility in order to successfully complete a mission that requires inspection or survey of some type. In these instances, reliability of nearest airport observation or forecast is often inadequate, with UAS pilots often waiting until launch to make a local cloud estimate by visual inspection. Inter-airport cloud/ceiling estimates and forecasts are a long-standing research challenge due to local influences which do not lend themselves to simple interpolation methodologies. The CVA product available via the Aviation Weather Center attempts to overcome this challenge via satellite masking and weighted numerical model forecast techniques. Current operational models provide derived high spatial resolution (3 km) derived estimates of cloud amount, base height, and top height. However, model performance between airport observing stations require further validation, and may present an opportunity for additional research.

Table 5-8

Clouds and Ceiling Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	3	2	5
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	3	2	5
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	1	2	3

Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	1	2	3
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	2	1	3

5.8 VISIBILITY INFORMATION GAP

5.8.1 Impact and Operational Considerations

This weather element refers to obstruction to horizontal or slant range visibility. Near-surface measurement of horizontal visibility, along with cloud ceiling height, contributes to determination of VMC / Instrument Meteorological Conditions in terminal airspace. Primary impact on small UAS is the Part 107 Flight Rules for VLOS operations. For BVLOS operations, UAS are expected to be subject to Instrument Flight Rules. As such, the availability of visibility observations and forecast information greatly impacts terminal area traffic management of large UAS which may be integrated with manned traffic, since airport operational capacity is largely influenced by cloud/visibility conditions (IMC versus VMC). For UAS missions that require favorable visual conditions (survey, mapping, photography, inspection, etc.), suitable visibility conditions also have a mission impact beyond that associated with safe vehicle operation and air traffic management.

5.8.2 Utility of Existing Products and Information

The primary source of observed visibility conditions is via instrumentation within standard surface observing stations (e.g., ASOS), typically located at airports. Most such instrumentation relies on forward scattering measurements across a projector-detector lens span of approximately 3.5 feet in order to compute an extinction coefficient that provides an estimate of human visibility. As such, the geographical representativeness of the estimate is limited by the small sampling volume, which presumes some homogeneity in visibility conditions across airport terminal airspace. Some airports are also equipped with Runway Visual Range (RVR) instrumentation which provides runway-specific visibility. RVR is provided along with airport visibility in standard METAR reporting. The FAA also operates an extensive network of several hundred cameras across Alaska to deal with the localized visibility conditions associated with that state's rugged terrain. Research is currently being sponsored to convert camera imagery to a visibility observation equivalent.

As with cloud coverage and ceiling, manned and unmanned aircraft pilots rely most heavily on TAFs for visibility forecasts. Visibility is also a component of other derived products, such as SIGMETs, AIRMETs, and Area Forecasts. For specific airport locations, forecasts of categorized visibility are included in statistically-based MOS/LAMP guidance, which is often a source forecast for other derived forecast products (e.g., TAFs, Area Forecasts, etc.) Surface visibility information is currently an output product of most numerical model (Figure 5-21), which provides for good horizontal resolution to address off-airport conditions, though product reliability requires further validation.

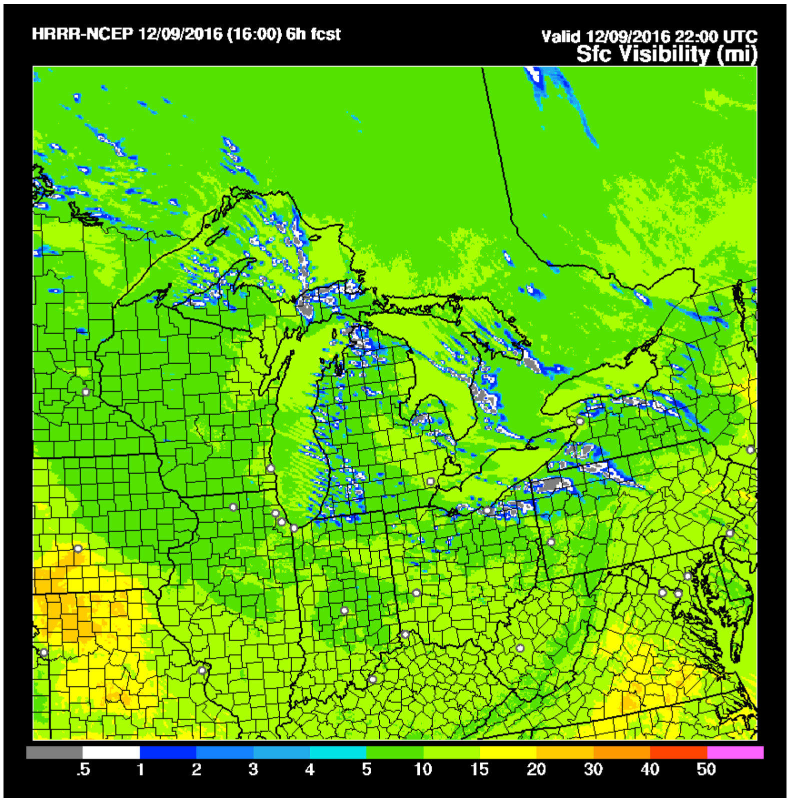

Figure 5-21 6-hour visibility forecast for Great Lakes Region from High Resolution Rapid Refresh (HRRR) Model.

The Aviation Weather Center provides a National C&V Analysis product that uses interpolation of METAR reports to estimate surface visibility between surface reporting stations, as well as a model-derived ceiling forecast out to 15 hours.

5.8.3 Potential Shortfalls

The biggest challenge to providing adequate surface visibility information and forecasts is the high spatial variability of conditions, which are largely influenced by local effects such as terrain and marine/water influence. Visibility may even vary by runway within a single terminal area. As such, surveyed users particularly emphasized the deficiency of off-airport visibility information, often having to rely on nearest-station observations and forecasts to estimate off-airport conditions. High resolution forecasts of visibility are available as output from numerical models, but reliability has not been sufficiently validated. Since off-airport operations tend to impact smaller UAS (see Table 5-9), often times mission decisions are deferred until time of launch by visual inspection of local conditions.

Table 5-9

Visibility Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	3	2	5
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	3	2	5
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	1	2	3
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	1	2	3

Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	2	1	3

5.9 TURBULENCE INFORMATION GAP

5.9.1 Turbulence Impact and Operational Considerations

For purposes of this study, "turbulence" refers to wind patterns (e.g.,, eddies) that change quickly in time and space. Persistent vortices that arise from winds impacting urban structures (Section 5.2) have been addressed in the discussion above on winds aloft in urban areas. Convectively induced turbulence has been considered in Section 5.5.

Turbulence is a significant weather hazard for the mission classes operating above 20,000 feet. This arises from jet stream induced turbulence that is typically characterized by a von Karman model with a turbulence intensity parameter (energy dissipation rate, $\varepsilon\varepsilon$) and a correlation length scale. For UAS equipped with SATCOM, turbulence can affect the ability of an onboard satellite antenna to maintain a connection to a satellite. If the satellite connection is broken, the UAS loses communication and control link and is forced to abort to its contingency procedure.

At lower altitudes, the situation is much more complicated for both the weather and the impact on an UAS. Sharman [7] suggests two major generating mechanisms that are challenging to characterize for quantitative predictions:

(1) a roughness layer where the flow is highly irregular; strongly affected by the nature of the individual roughness features such as grass, trees and low buildings, and

(2) a surface layer up to about 150 feet characterized by relatively strong vertical wind shear with the possibility that there might be more intense small scale turbulence generated by surface roughness, and very small scale localized convective plumes (e.g., from a warm parking lot).

There is major uncertainty as to the response of the most common low altitude UAS – the quadcopter – to such turbulence. First, it is not clear how turbulent eddies impact such an UAS (unlike the situation with fixed-wing aircraft). Second, an autopilot is essential for quadcopter stability and control, and autopilot performance along the spectrum of available technology is not currently understood.

In the absence of any published studies of the impact of low altitude (e.g., between the surface and 150 feet) turbulence on quadcopter performance, interviews were conducted with Lincoln Laboratory staff who routinely use quadcopters in support of Homeland Security applications. Their experience has been that the quadcopters are very stable when landing or launching in situations where there is an appreciable roughness in the terrain. The main impact has been higher energy consumption due to a greater use of the four blades when the boundary layer is turbulent.

The Lincoln Laboratory researchers have conducted a number of tests with a quadcopter flying low over building debris (Appendix C), and not noted significant problems with random turbulence.

5.9.1.1 Turbulence UAS Safety Considerations

Clear air turbulence (CAT) in the vicinity of the jet stream, and arising from "mountain waves" near the tops of mountains, where there is a strong ambient flow over the mountains, have been long standing safety issues for commercial aircraft. The principal safety hazard for commercial aircraft is to the passengers and cabin attendants who may be thrown around and/or impacted by objects flying within the aircraft when CAT is encountered as opposed to the aircraft itself suffering major damage. Given that a high altitude UAS has no passengers aboard, the question of safety revolves around the degree to which turbulence excites sensitive modes of the aircraft motion and the nature of the control system for the UAS. The largest safety concern is turbulence causing abrupt changes in attitude that result in a lost communication/control link. If an operation becomes lost-link, it flies autonomously on a preprogrammed route.

For low altitude UAS quadcopters, the safety impact of low altitude turbulence appears to be relatively minor. The safety impact of low altitude turbulence on fixed-wing low altitude UAS is unclear at this point in time.

5.9.1.2 Turbulence UAS Flight Planning Considerations

There are current techniques for flight planning around areas of CAT (see, e.g., Kim, et al., 2015) [8] that can be applied to high altitude UAS operations. Commercial conventional aircraft also use pilot reports from other aircraft in their vicinity to determine airspace with less turbulence as a courtesy to their passengers. If an UAS can safely handle the CAT, it is unclear that such flight adjustments would be required for UAS operation. It is not clear at this time whether low altitude turbulence is a significant issue for low altitude UAS flight planning.

5.9.2 Utility of Existing Products and Information

Current turbulence weather products are intended to support manned aviation applications, which typically operate between 1000 feet and FL450. SIGMETs and AIRMETs provide broad warnings and forecasts of light, moderate, severe, and extreme turbulence, where the turbulence levels are calibrated on conventional aircraft. The GTG model provides a heat map of Eddy Dissipation Rate (EDR) at different altitudes and forecast periods. PIREPs supplement turbulence models and forecasts by introducing observational data that is used by pilots to validate and refine their understanding of the models. Some aircraft are equipped with atmospheric measuring equipment and downlink turbulence information to the ground for use by pilots and as input to turbulence prediction models. Figure 5-22 shows the graphical output of the GTG model.

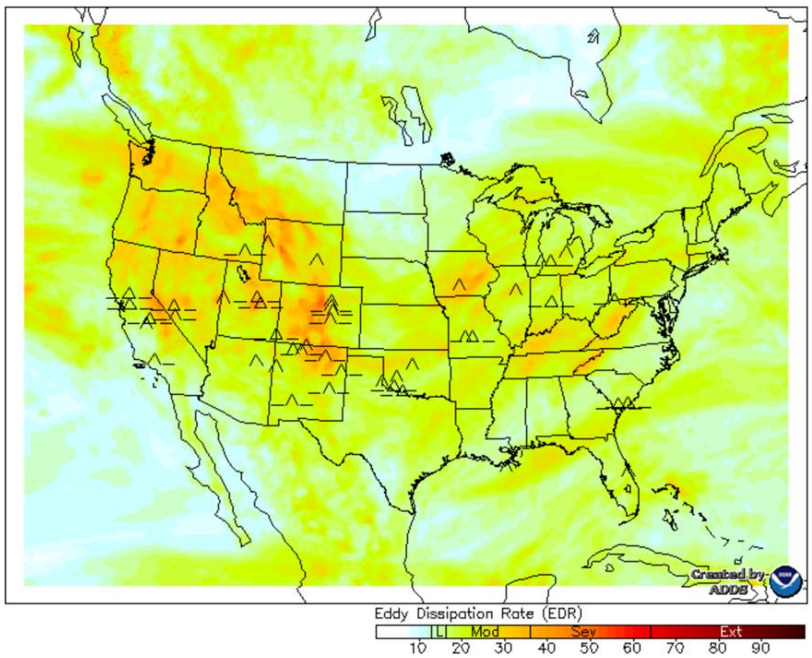

Figure 5-22 Graphical Turbulence Guidance (GTG) model output (www.aviationweather.gov).

The heat map depicts EDR values that can be used to predict turbulence levels. PIREPS are overlaid on the map to provide information on observed turbulence. In general, current turbulence products are sufficient in supporting operations between 1000 feet and FL450. Operations below 1000 feet and above FL450 are outside the typical operating range of conventional aircraft and have significantly less information available for support.

5.9.3 Potential Shortfalls

There is significant uncertainty in how turbulence affects the stability of small UAS and the ability of satellite communications and control links to maintain signal during turbulence. There is also a lack of turbulence information below 1000 feet and above FL450. The turbulence environment in the boundary layer is complicated, and it is important to distinguish between the potential sources of turbulence such that appropriate turbulence prediction models can be used to support operations. Above FL450 there are few aircraft observations to feed into turbulence forecasting models. Furthermore, it is unclear if the current turbulence categorizations of (light, moderate, severe, extreme) are sufficient to support all classes of UAS (i.e., light turbulence might indicate severe turbulence in a small UAS). Table 5-10 provides a summary of the turbulence information gaps.

Table 5-10

Turbulence Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	1	2	3
Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	1	2	3
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	1	2	3
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	1	2	3
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3

Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	2	2	4

5.10 ICING INFORMATION GAP

5.10.1 Impact and Operational Considerations

5.10.1.1 UAS Safety Considerations

Airframe icing impacts UAS operations in a similar fashion as manned aviation. Ice accretions on the airframe and propeller decrease aerodynamic efficiency, thrust capability, and add weight to the vehicle. In general, icing is a concern when flying in clouds where the local temperature is between 0°C and -20°C, in freezing rain, or if a UAS descends from high altitude and encounters liquid precipitation while the surface of the airframe is still below freezing. Small UAS are especially susceptible to icing due to the higher accretion efficiencies on surfaces with small radii of curvature. Many large UAS are not equipped with deicing equipment and are restricted from flying in icing conditions.

5.10.1.2 UAS Operational Efficiency

Icing is a significant hazard to flight safety, and for UAS without ice protection any flight into icing conditions can be dangerous. Therefore, most operations are restricted from flying in icing conditions, which results in operational inefficiency if the conditions are over-forecasted. Much like convective weather, knowledge of forecast uncertainty is critical to maintaining robust flight planning, including contingencies for lost link operations.

5.10.1.3 UAS Airspace Management

One method to manage airspace containing icing conditions is to establish constraints or geofences to preclude flight in the area. The geofences would need to be highly dependent on altitude due to the stratification of icing conditions.

The significance of icing in VLOS operations is small due to the restriction to stay out of the clouds and the ability of the operator to physically observe any freezing rain and quickly discontinue the mission. BVLOS missions are envisioned to be operated under IFR flight rules, meaning it is possible to fly in the clouds and meet the necessary conditions for icing. Because icing is at least partially seasonal, it is given a rating of ‘2’ for the BVLOS mission classes.

5.10.2 Utility of Existing Products and Information

The most basic icing weather product is a combination of cloud ceiling and freezing level information (i.e., icing is anticipated if the UAS enters the clouds below the freezing level). The only available icing observation is given by PIREP information, although icing on a manned aircraft might be significantly different than icing on a small UAS. AIRMETs and SIGMETs provide broad icing forecasts and warnings that are intended for manned aircraft. Due to the spectrum of UAS types and sizes, this information may over or under-estimate the severity of UAS airframe icing. The CIP and FIP are icing prediction models that provide a graphical representation of icing levels for a forecast horizon of 0–18 hours. However, because the CIP/FIP are designed to inform manned aviation, it is unclear how well the information can be used to support UAS operations.

The weather product scores in Table 5.10 are primarily driven by the uncertainty in current weather products being able to predict accurate icing levels for small UAS. Mission classes 1–4 are assigned ‘2’ because they are predominately operated by small UAS. Mission classes 5–7 are assigned ‘1’ because they are operated by aircraft roughly similar in size to manned aircraft, although most are not equipped with ice protection.

5.10.3 Potential Shortfalls

There are two primary shortfalls associated with the icing weather element. First, many of the models and current icing products are based on ice accretion rates with larger aircraft (at least the size of a small general aviation aircraft). Ice accretes much differently on a small UAS compared to a manned aircraft, meaning that the current product might not be sufficient for small UAS use. Secondly, BVLOS missions require robust contingency planning to ensure there is feasible routing for lost link events. The currently available icing products do not include forecast uncertainty information that would aid in more efficient flight and contingency planning. Table 5-11 provides a summary of the icing information gap.

Table 5-11

Icing Gap Summary

Mission Class Altitude / Duration / Range	**Operational Considerations**	**Significance Score**	**Weather Product Score**	**Total Score**
Mission Class 1 0–500 ft / 0–1 hr / 0–3 mi	Visual line of sight (VLOS). Typically operate away from airport areas.	0	2	2

Mission Class 2 0–500 ft / 0–1 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas.	1	2	3
Mission Class 3 0–500 ft / 1–12 hr / 3–25 mi	Extended VLOS and BVLOS. Typically operate away from airport areas. Interactions with urban terrain.	2	2	4
Mission Class 4 0–500 ft / 1–12 hr / 25+ mi	BVLOS. Typically operate away from airport areas. Large potential variation in terrain and weather.	2	2	4
Mission Class 5 500-FL250 / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 6 FL250+ / 1–12 hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports.	2	1	3
Mission Class 7 FL250+ / 12+ hr / 25+ mi	BVLOS. Typically larger UAS operating out of airports. Altitudes extend up to FL600.	2	1	3

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6. UAS WEATHER INFORMATION GAPS SUMMARY

The objective of this study is to identify information gaps in UAS operations. The gap identification process is built on survey and interview feedback from the UAS operational community. Airspace management strategies and BVLOS operational concepts are extracted from the FAA UAS Integration Roadmap and the NASA UAS Traffic Management Concept of Operations. The focus of the analysis is to determine the ability of *currently available weather products* to meet the needs of the UAS operator or airspace management authority. For the purpose of this work, a *currently available weather product* is defined as information available to the UAS operational community through publicly available websites (e.g., www.weather.gov), aviation weather sources (e.g., www.aviationweather.gov), and flight planning applications (e.g., Foreflight). This is an important distinction to make, as the availability of weather information can be categorized as

(1) information readily available to an UAS operator today (e.g., www.aviationweather.gov), or

(2) information that exists and is in use operationally today, but not readily available to an UAS operator (e.g., ITWS), or

(3) information that will be available with coming systems (e.g., GOES-R, NWP).

In this paper, information in categories (2) and (3) are not considered to be available to the UAS operator, and recorded as gaps if the information is important for operational decision making. Moreover, it is assumed that operators have the ability to view web-based weather information in the field via smartphone or tablet weather applications. For example, an operator can view updated ASOS or NEXRAD information during operations.

A very important element of assessing the relative importance of weather information (especially winds and turbulence) is equipage and capability of UAS within a UAS class. First, all UAS are assumed to have Global Position System (GPS) capability and closed-loop flight control such that UAS automatically correct for disturbances such as unsteady wind. Based on operator feedback, quadrotor UAS platforms are assumed to be robust to small-scale boundary layer turbulence. Small fixed-wing UAS are assumed to maintain trajectory but not attitude during small-scale turbulence. Large UAS are assumed to operate outside of the boundary layer and are therefore unaffected by small-scale boundary layer turbulence. Moreover, small UAS are assumed to operate away from airport locations whereas large UAS are restricted to launch and recovery from an airport. All classes of UAS are assumed to not have de/anti-icing or onboard weather radar. BVLOS operations occurring under IFR are assumed to not have requirements for minimum visibility or cloud clearance.

UAS mission classes are established to group similar UAS missions by altitude, mission duration, and mission range as listed in Table 2-1. The ability of current weather products to meet the needs of each mission class is rated for each weather element listed in Table 2-2. The corresponding rating is used to highlight the most significant weather information gaps. However, when assessing the significance of gaps based on current operations, it is important to also anticipate the widespread implementation of UAS. For example, certain operations will be realized before others (i.e., it is reasonable to assume that first responder drone use over people will occur before package delivery over people). Moreover, the majority of current operations (and reflected in the survey feedback) are VLOS. As operations move to BVLOS there are a number of additional weather concerns that will be realized. This study attempts to project weather gaps in BVLOS, however it should be noted that there is significant uncertainty in the capability of future UAS platforms and how BVLOS airspace will be managed. Moving forward, it is important for the weather research community to keep an active role in assessing evolving UAS operational needs as operations become more mature.

It is also important to understand that not addressing the information gaps could delay or preclude the many unique benefits of UAS operations. For example, weather-induced safety incidents not only risk damage to people, property, and other aircraft, but they also degrade the public perception of UAS. Moreover, the life-saving benefits of certain first responder UAS missions are dependent on the ability of the mission to be completed in a variety of weather conditions. Lastly, successful UAS integration is contingent on the ability of future airspace management strategies to remain both feasible and efficient in different weather situations.

Table 6-1 ranks the weather elements based on the total weather gap score across all of the mission classes. The list is divided into four groups to highlight similar weather gap scores. In other words, weather elements with similar scores are grouped together (e.g., 1a, 1b, …) to establish levels of weather gap importance. The ranking within the groups is less important than the ranking of the groups. Each weather element entry in Table 6-1 provides the aggregate weather significance and weather product effectiveness scores, a description of the gaps assuming access to currently available weather products, and notes on the opportunity to leverage FAA weather products to address the gaps.

There are several trends in the information gaps which surfaced repeatedly. A key item is the availability of weather observations and forecasts tailored for on-airport operations are not necessarily sufficient for off-airport operations. Surveyed users indicated that airport-specific weather information (e.g., METAR, TAFs, etc.) did not readily translate to conditions at remote launch locations, which may be 10–30 miles from the nearest airport, and influenced by local terrain, vegetation, and water sources. Moreover, the results showed significantly less weather information available to support low-altitude flight than for typical manned-flight profiles. This is especially true in urban areas or in areas with complicated terrain.

This brings to light the utility of numerical weather models, which continue to be developed at increasingly high resolution. Model skill would help to resolve the off-airport issues, but more widespread and rigorous validation of the models would likely be necessary. This is particularly true for weather elements that are largely impacted locally, like cloud ceiling, visibility, and low altitude wind/gusts which are heavily influence by local obscurations.

BVLOS operations have higher need for weather forecasts, uncertainty information, and contingency planning than VLOS operations. For example, tactical convective weather products lack short term forecasts and can give an erroneous depiction of current storm location due to latency. Strategic convective weather products lack precision, especially at long forecast horizons, and do not provide sufficient uncertainty information to support contingency planning. Moreover, winds aloft products do not provide information to support low-altitude or super high-altitude operations. Similarly, turbulence forecasts and models are not designed to support low-altitude or super high-altitude operations, which has an impact on UAS that rely on a satellite communications link. Lastly, icing is a relatively rare event, but can have a catastrophic impact on flight safety, especially for small UAS. Icing prediction models lack uncertainty information necessary for contingency planning and may not be designed to properly reflect the icing risk to small UAS.

Table 6-1

Ranking of Weather Condition by Information Gap Score and Product Availability

Rank	Weather Condition	Gap Score (Significance/ Product/Total)	Information Gap Description Assuming Access to Currently Available Weather Products	Opportunity to Leverage FAA-current and near term Weather Products
1a	Convective Weather	21/13 34	Tactical products lack short-term storm forecasts and are susceptible to latencies. Strategic products lack precision at long forecast horizons and need better uncertainty information to support decision making.	FAA products (CIWS, CoSPA, NWP) would reduce the weather gap.
1b	Winds Aloft	21/11 32	Current wind aloft forecasts lack precision and winds aloft observations are lacking in the low-altitude and super high-altitude regions.	FAA ITWS and ASR-9 WSP products provide significant improvements in wind aloft and wind shift information for major metropolitan areas.
2a	Visibility	14/11 25	Sparse off-airport observation field. Models are often inadequate, especially where there is a large variation in terrain and soil moisture	N/A
2b	Clouds and Ceiling	14/11 25	Sparse off-airport observation field. Models need evaluation in off-airport areas, especially where there is a large variation in terrain. Also, cloud layers are not resolved well, especially away from airports.	N/A
2c	Surface Winds	14/10 24	Sparse off-airport observation field. Rapid changes in surface winds (e.g., due to microburst outflows, gust fronts and sharp synoptic fronts) are not alerted. Urban wind effects are uncertain.	FAA ITWS and ASR-9 WSP products provide significant improvements in wind shift information for major metropolitan areas.
3a	Turbulence	10/12 22	Lack of validated stratospheric and low-altitude turbulence information. Models not calibrated for small UAS. Forecasts lack uncertainty element.	N/A

3b	Icing	11/11 22	Ice will build up faster on a small airframe. Models not calibrated for small UAS. Models do not account for ‘cold soak’. Forecasts lack uncertainty element.	N/A
3c	Precipitation	11/7 18	Only significant for small UAS.	FAA products (CIWS, CoSPA, NWP) would reduce the weather gap.
4a	Temperature	7/5 12	No significant gaps identified.	N/A
4b	Barometric Pressure	6/4 10	No significant gaps identified.	N/A

Airspace management strategies are also affected by the weather information gaps. For example, low-altitude time-based operations require validated winds aloft models and forecasts below 500 feet. Additionally, the feasibility of time-based operations (e.g., time-based metering for UAS) depends on an understanding of UAS weather impact models that are highly dependent on UAS type. Weather-based geofences will require similar UAS weather impact models for a spectrum of UAS platforms and weather conditions.

Table 6-2 distills the information in Table 6-1 into twelve specific weather information gaps that are prioritized based on current operational need. The information gaps listed in Table 6-2 are the basis for the research roadmap. The ranking of the gaps listed in Table 6-2 is generated from the ranking of the weather conditions in Table 6-1, but also the maturity of the operation that the gap affects. For example, consider two gaps that are scored equally in Table 6-1. If one of the gaps influences VLOS operations and the other affects BVLOS operations, the VLOS gap will be prioritized higher than the BVLOS gap because VLOS operations are currently more mature and common than BVLOS operations.

Table 6-2

Prioritized Ranking of Specific Weather Information Gaps

	Weather Information Gap	Impacted UAS Operation
1	Numerical weather model performance is uncertain, especially where there is a large variation in terrain	All UAS missions, especially in the low-altitude domain
2	No mechanism to alert operators to rapid changes in winds (e.g., due to microburst outflows, gust fronts, and sharp synoptic fronts)	Primarily small UAS operations
3	Off-airport weather observations (visibility, ceiling, wind) are sparse	All UAS missions that operate off-airport, especially VLOS operations (Part 107)
4	Tactical convective weather products lack short-term storm forecasts and are susceptible to latencies	Primarily BVLOS missions for UAS without onboard weather radar
5	Current wind aloft forecasts lack precision and winds aloft observations are lacking in the low-altitude and super high-altitude regions	Primarily BVLOS mission planning, especially for time-based operations
6	Strategic convective weather products lack precision at long forecast horizons and need better uncertainty information to support decision making	Primarily BVLOS missions with durations greater than 2 hours
7	Urban wind products are not sufficient and are not available to the public	All UAS missions in an urban environment
8	Lack of validated stratospheric and low-altitude turbulence information	Very high-altitude missions / low-altitude missions in the boundary layer
9	Icing and turbulence forecasts lack an uncertainty element to support contingency planning	Primarily BVLOS missions
10	Icing models do not account for ‘cold soak’ effect	High-altitude BVLOS missions

11	Turbulence and Icing models not designed for small UAS	Primarily BVLOS missions with small UAS
12	Weather impact models do not exist for UAS	Airspace management, including geofences, airspace capacity balancing, time-based ops

The most significant gap is validation of numerical weather model performance in UAS domains. This is driven by the significance of low level winds aloft (Table 6-1, Rank 1b) for all types of UAS operations, and the importance of local ceiling and visibility (Table 6-1, Ranks 2a and 2b) to VLOS operations. The second gap is hazardous weather alerting of convective weather and winds (Table 6-1, Ranks 1a, 1b, and 2c), primarily for VLOS operations (i.e., the UAS operator cannot continuously monitor weather information due to the need to maintain visual contact with the UAS). The third gap is related to the sparse network of airport observations for ceiling, visibility, and wind (Table 6-1, Ranks 2a, 2b, and 2c) to determine if local Part 107 (VLOS) weather requirements are met. The information gaps ranked four through seven are lower priority than the first three, mainly due to their emphasis on BVLOS and urban operations, which are far less operationally mature than VLOS operations. Gaps eight through twelve address turbulence and icing (Table 6-1, Ranks 3a and 3b), and weather impact models for far-term UAS traffic management concepts. No specific weather gaps are listed for precipitation, temperature, and barometric pressure due to their low significance scores (Table 6-1, Ranks 3c, 4a, and 4b).

Lastly, there were several issues identified as a result of the research process that should be addressed in follow on work to address the gap analysis needs that became apparent late in the analysis effort reported here:

1. First, there should be more interaction with operational users who have “pushed the envelope” in operating with low altitude surface winds, surface wind gusts and turbulence. Examples of this type of operation are introduced in Appendices B and C.

2. Also, more thought should be put into differences in the flight control ability of different UAS platforms. Although this information is typically proprietary, it is necessary to understand the operational impact of low altitude/near-surface turbulence and, the ability of the UAS to complete the envisioned UTM procedures such as time-based operations.

3. Assess NOAA/NWS products currently not being utilized for aviation purposes (e.g., products not available on the AWC WWW site) to see if they might have applications for UAS weather decision support

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APPENDIX A
ITWS TERMINAL WINDS LOCATIONS AND COVERAGE

The ITWS low altitude wind shear/gust front products and high resolution terminal winds analysis are a potentially very useful source of wind information especially for low altitude UAS operations in and near major metropolitan areas. Figure A-1 shows the locations of the ITWS. Figure A-2 shows the data sources used in the ITWS gridded analysis while Figure A-3 shows the algorithms used to generate the ITWS gridded winds analysis. Figure A-4 shows an example of the DFW ITWS terminal wind surface wind grid. Table A-1 shows the areas of the ITWS terminal winds grids. The ITWS terminal winds gridded analysis covers a much larger area than the area immediately around major airports. This is because the gridded winds analysis was intended as an input to terminal time based flow management (TBFM) systems such as Travel Management Advisor (TMA) which operate throughout the full extent of the terminal area and, in the en route airspace just outside the terminal area.

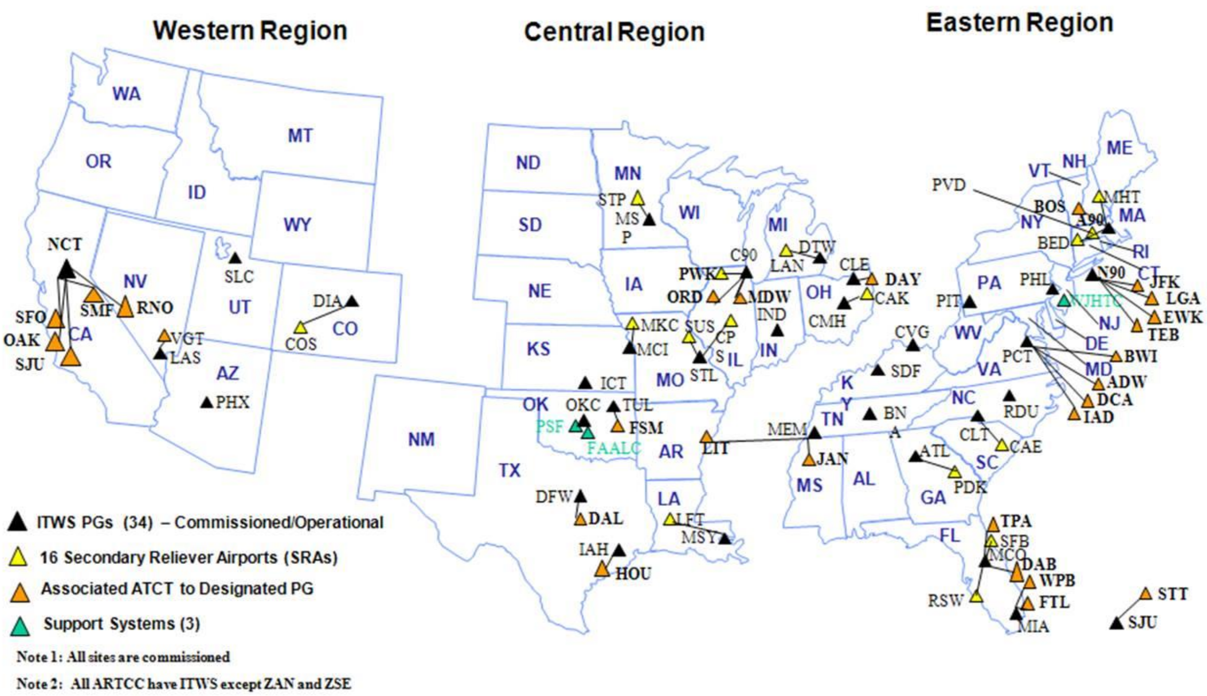


Figure A-1 Locations of the ITWS systems including ATC facilities served.

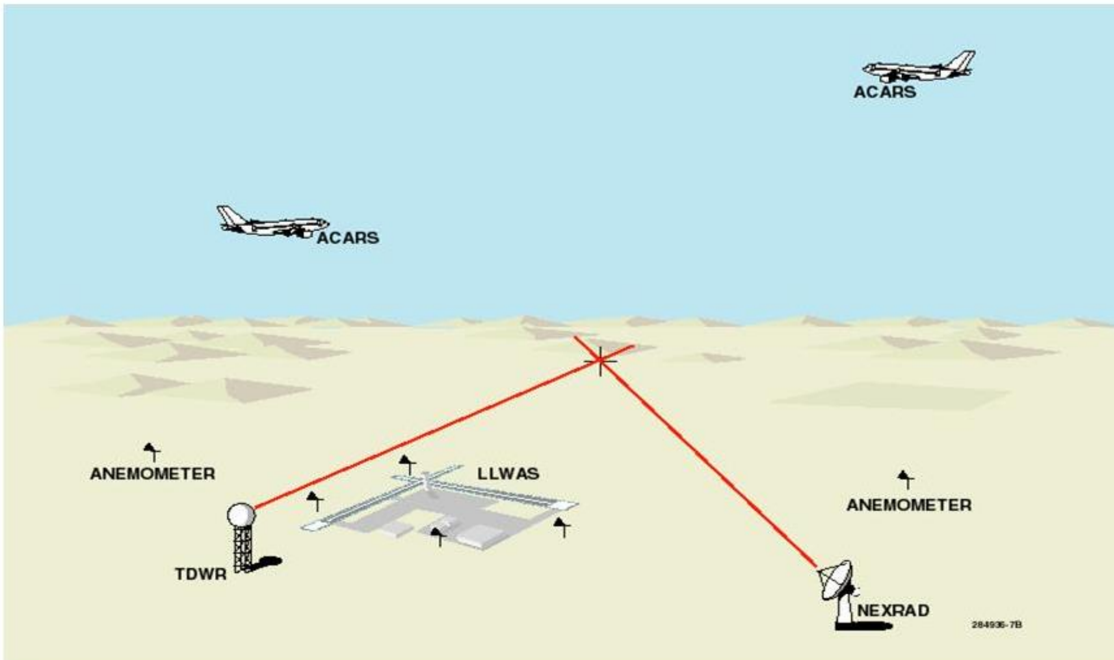


Figure A-2. The number of radars used for the ITWS gridded winds analysis depends on the ITWS. For example, the Washington-Baltimore ITWS accesses 2 NEXRADs and 4 TDWRs. The anemometers shown include the ASOS. In addition to the sensors depicted above, the analysis uses numerical weather forecast wind fields as a starting point.

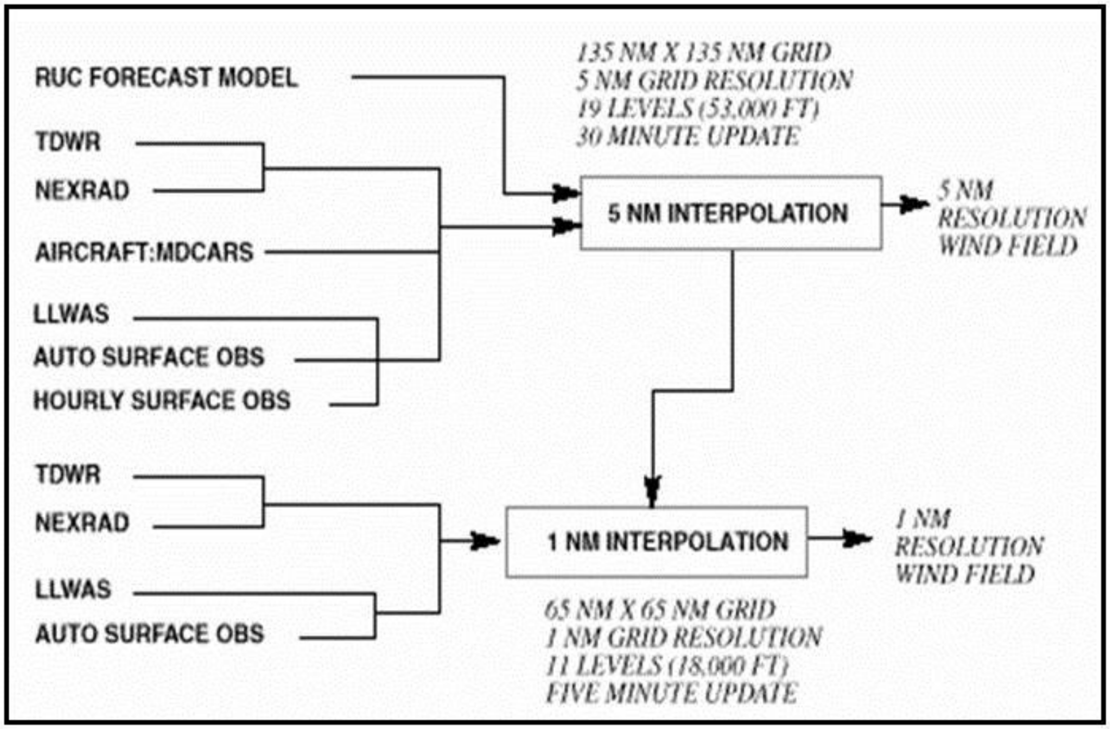
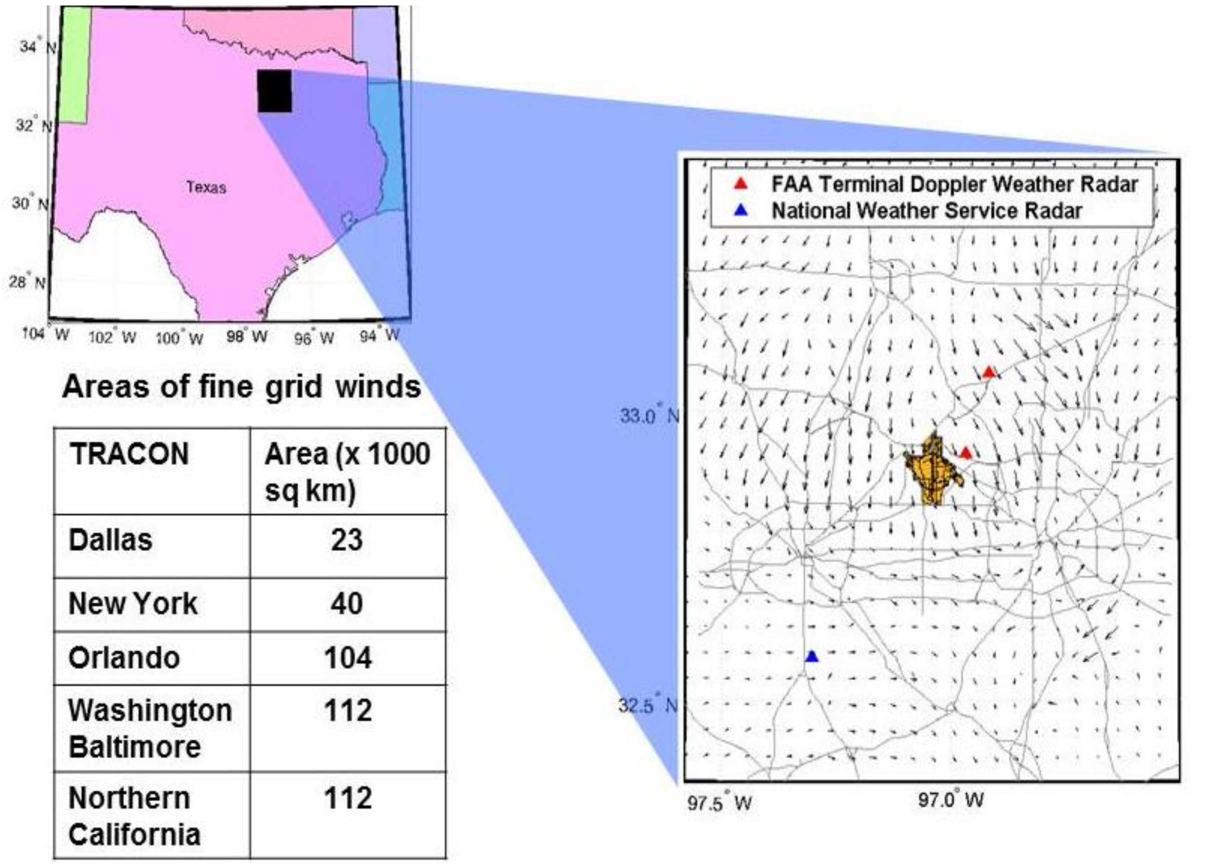


Figure A-3 Data analysis algorithms for the ITWS terminal winds product.[9] [10]



TRACON	Area (x 1000 sq km)
Dallas	23
New York	40
Orlando	104
Washington Baltimore	112
Northern California	112

Figure A-4 Example of ITWS surface wind gridded analysis at DFW

Table A-1
Surface Area of ITWS Terminal Gridded Winds Analysis

Metropolitan area		X-Distance (km)		Y-Distance (km)		Area (1000 km^2)	
	TRACON	Coarse	Fine	Coarse	Fine	Coarse	Fine
Atlanta	ATL	410	**310**	390	**298**	159.9	**92.4**
	BNA	250	150	230	138	57.5	20.7
Chicago	C90	270	**174**	350	**254**	94.5	**44.2**
	CLE	310	214	290	206	89.9	44.1
	CLT	270	178	270	178	72.9	31.7
	CAE	210	126	250	162	52.5	20.4
	CMH	390	294	310	222	120.9	65.3
	DAY	310	218	310	222	96.1	48.4
	CVG	250	158	230	146	57.5	23.1
Denver	D01	270	**186**	330	**230**	89.1	42.8
	COS	190	102	190	106	36.1	10.8
Dallas Ft Worth	D10	250	**150**	250	**150**	62.5	22.5
	DTW	370	274	270	190	99.9	52.1
	F90	310	210	310	214	96.1	44.9
Houston	I90	270	178	290	206	78.3	36.7
	ICT	270	174	250	162	67.5	28.2
	IND	270	182	290	194	78.3	35.3
	LAS	250	154	210	110	52.5	16.9
Minneapolis	M98	250	162	250	158	62.5	25.6
	MCI	250	154	270	190	67.5	29.3
	SGF	250	154	290	206	72.5	31.7
Orlando	MCO	410	**314**	430	**330**	176.3	**103.6**
	RSW	270	174	250	166	67.5	28.9
	MEM	250	166	250	166	62.5	27.6
	LIT	250	158	270	190	67.5	30.0
	JAN	210	122	210	118	44.1	14.4
	MIA	270	170	350	258	94.5	43.9
New Orleans	MSY	310	**222**	290	**190**	89.9	42.2
	LFT	230	138	270	186	62.1	25.7
New York	N90	270	**182**	310	**226**	83.7	**41.1**
Northern California	NCT	370	**286**	490	**394**	181.3	**112.7**
	RNO	190	102	230	150	43.7	15.3
	OKC	270	178	230	142	62.1	25.3
Washington/Baltim	PCT	430	**338**	430	**334**	184.9	**112.9**
	PHL	250	158	210	110	52.5	17.4
	PHX	290	190	250	166	72.5	31.5
	PIT	250	162	230	138	57.5	22.4
	RDU	250	154	230	134	57.5	20.6
Louisville	SDF	270	174	250	166	67.5	28.9
San Juan	SJU	370	**282**	**270**	186	99.9	**52.5**
	STT	230	146	270	186	62.1	27.2
	SLC	210	122	290	202	60.9	24.6
St. Louis	T75	270	186	270	174	72.9	32.4
	TUL	250	170	250	158	62.5	26.9
	FSM	250	166	330	242	82.5	40.2

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APPENDIX B
FIREFIGHTER USE OF UNMANNED AIR SYSTEMS (UAS)

Nearly all of the UAS uses considered in the survey were situations where the desired objective of using an UAS could be accomplished later that day or on a later day if need be, i.e., there was not a high time urgency for use of the UAS.

Firefighter decision support for an active fire is an application for the use of an UAS which is highly time urgent given that human lives may be at risk. Hence, fire department use of an UAS (especially low altitude UAS) will need highly capable tactical decision support to support UAS use when strategic forecasts suggest that there is a likelihood of significant weather impacts.

An article "Rise of the Machines" by J. Roman in the National Fire Protection Association (NFPA) Journal, July-August 2015 makes the following points about firefighter UAS usage:

(1) The Association for Unmanned Vehicle Systems International (AUVSI) predicted in 2015 that there will be 1 million unmanned drone flights per day in the United States within the next 20 years.
(2) After agriculture, industry experts believe public safety and first responder applications will be the largest civilian market for UAS.
(3) The NFPA and the National Institute of Standards and Technology (NIST) are actively investigating standards and operating procedures for UAS to support firefighter decision support.
(4) A number of fire departments and universities are actively investigating UAS use for fire fighter decision support including Austin, Texas.

The Austin, Texas fire department WWW site (http://www.afdredteam.com/about) notes that Austin is the first major metropolitan department in the country to obtain authorization to operate an UAS in the national airspace system. The applications they are actively investigating for UAS use are:

- Wildfire Mitigation Flood Response
- High-Rise and Commercial Fires
- Hazardous Material Mitigation
- Search and Rescu
- Structure Collapse, and Confined Space Rescue
- Pre-Incident Fire Planning
- Post-Incident Fire Review
- Creating Communication Networks during disaster response

An important issue in determining the extent to which the FAA should consider assisting in the development of weather support for firefighter UAS is the potential benefits associated with improved firefighter use. An NFPA fact sheet on fire impacts on the U.S. in 2015 notes the following:

> 1,345,500 fires were reported in the U.S. during 2015 resulting in 3,280 civilian fire deaths, 15,700 civilian injuries, $14.3 billion in property damage with department responding to a fire every 23 seconds. There were 501,500 structure fires with 2,685 civilian deaths and $ 10 B in property damage and 639,500 "outside and other fires".

The extent to which the impact of fires might be reduced through better response to fires is under study, but results were not available at the time of writing.

A case study of the possible use of a low altitude UAS was conducted for an event of opportunity. In particular, there was a significant fire at the Berkeley, California First Congregational church on September 30, 2016 (http://www.dailycal.org/2016/09/30/3-alarm-fire-breaks-berkeley-church-channing-way/). Visibility on the street was reported as incredibly low as smoke billowed from the building beginning about 12:30 p.m. Its roof had collapsed as of 1:50 p.m.

The Daily Californian newspaper article on the fire contained the following quote: "It looked really containable at first, like it was 1 square foot, and then it quickly spread to the entire building," said UC Berkeley sophomore Stephanie Miller, who lives at the nearby Rochdale Village on Haste Street. "One second it's on fire, and then 45 minutes later, it's halfway burned down to the ground."

An interview was conducted with a Berkeley fire department assistant chief who was the incident commander for that fire. The incident commander commented that because the fire had started in the roof (Figure B-1), he had relatively poor situational awareness from the street as to what was going on in the roof of the building that collapsed and the adjacent building as shown in Figure B-2. By contrast, aerial views obtained by local TV stations (Figure B-3) provided a much better sense of the fire extent at the roof. For this case, it would seem that having a low altitude UAS with both a camera with conventional imaging and a separate thermal imager (to help when smoke was obscuring things plus spot hot spots) to use as soon as firefighters arrived at the fire could have been very helpful for the incident commander.

Figure B-1 Start of fire at Berkeley, CA First Congregational Church (from a cell phone).

Figure B-2 Street level views of fire at Berkeley, CA First Congregational Church.

Figure B-3 Aerial view of Berkeley First Congregational Church fire obtained by the ABC News helicopter.

The Berkeley fire department assistant chief also noted the value of drones for real time incident management of fires at the urban–wild land interface. This October was the 25th anniversary of the Oakland hills firestorm of 1991 (see https://en.wikipedia.org/wiki/Oakland_firestorm_of_1991).

The Oakland firestorm of 1991 was a large suburban urban–wild land interface conflagration that occurred on the hillsides of northern Oakland, California, and southeastern Berkeley on October 20, 1991. The fire ultimately killed 25 people and injured 150 others. The 1520 acres (620 ha) destroyed included 2843 single-family dwellings, and 437 apartment and condominium units. The economic loss has been estimated at $1.5 billion.

The fire started on Saturday, October 19, 1991, from an incompletely extinguished grass fire in the Berkeley Hills northeast of the intersection of California State Routes 24 and 13 (0.5 mi (0.8 km) north of the Caldecott Tunnel west portal). Firefighters fought the 5 acre (2.0 ha) fire on a steep hillside and by Saturday night they thought everything was under control. However, the firefighters had missed some embers in the area of the fire. The fire re-ignited shortly before 11 a.m. on Sunday, October 20, 1991 when the surface winds picked up as a brush fire and rapidly spread southwest driven by wind gusts up to 65 mi (100 km) per hour.

This case of the Oakland hills firestorm illustrates the potential value of a low altitude UAS with both visual and thermal imaging in assessing whether a wild-land fire has in fact been put out.

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APPENDIX C
USE OF LOW ALTITUDE UAS FOR DISASTER RESPONSE

Nearly all of the UAS uses considered in the survey were situations where the desired objective of using an UAS could be accomplished later that day or on a later day if need be, i.e., there was not a high time urgency for use of the UAS.

Disaster response is an application for the use of an UAS which is highly time urgent given that human lives may be at risk. Hence, fire department and other first responder use of an UAS (especially low altitude UAS) will need highly capable tactical decision support to support UAS use when strategic forecasts suggest that there is a likelihood of significant weather impacts. The potential importance of low altitude UAS usage for US disaster response operations has been highlighted by the 2017 hurricanes in Texas and Florida.

The Department of Homeland Security Science and Technology Directorate (S&T) is conducting a five year program, Next Generation First Responder (NGFR) geared towards making first responders better protected, connected and fully aware. Under the NGFR Apex program, Lincoln Laboratory researchers are developing technologies that can enable UAS drones to provide emergency responders with the information needed to establish situational awareness at disaster sites that are nearly inaccessible or dangerous, e.g., the 2016 disaster in Amatrice, Italy shown in Figure C-1. Low altitude UAS operations at disaster sites such as this or those which occurred in Texas and Florida after the 2017 hurricanes clearly indicate a potential need to “push the weather envelope” due to the importance of timely response.

Figure C-1 Photograph of search for survivors of earthquake in Amatrice, Italy August 2016 (ABC news).

Figure C-2 shows the test site in Fairfax, VA being used for NGFR testing of techniques to more rapidly and safely find survivors of disasters such as figure C-1.

Figure C-2 Search underway for test subjects at NGFR test site for disaster recovery R & D (Fairfax, VA)

The approach taken by Lincoln Laboratory to locate victims under the building debris is to search for cell phone signals with a low flying UAS as shown in figures C-3 and C-4. Figures C-3 and C-4 do not capture the very dynamic low altitude trajectory used for the cell phone signal search. It is recommended that the reader view the video at (https://www.youtube.com/watch?v=PzcMNyGiQ6s&feature=youtu.be). From the video, it is clear that surface winds and wind gusts will be an important factor in mission success in finding victims.

One issue that arises with such a system is the fraction of victims that might be found using cell phone signals. In 2013, nearly 90% of U.S. adults had cell phones.[4]

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[4] Italy also has a very high fraction of the population with cell phones: it is estimated that there are 50 M cell phones in use in Italy, which has a total population of 62 M people.

Figure C-3 Close-up of Lincoln Laboratory developed low-altitude UAS, seeking cell phone signals by flying low over building rubble.

Figure C-4 Low altitude UAS searching in area of building collapse.

Low altitude and surface wind, and wind gusts are clearly a major concern for search and rescue operations of this type, as well as convective weather. The Laboratory's experience with UAS thus far at the Fairfax, VA test site has been that turbulence and wind gusts at test altitudes have *not* been a significant problem operationally, once the rotor blades were enclosed in a cage (Figure C-3).

It would be useful to have test sites such as the Department of Homeland Security (DHS) Fairfax, VA, NGFR site instrumented with weather observation systems to better quantify the impacts of low altitude weather phenomena on low altitude UAS operational use.

Additionally, it will be important to have ongoing in-depth discussions with current disaster response and first responder low altitude UAS operators to determine the importance of the identified weather information gaps for their operations, as well as how they have attempted to fill those gaps from available information.

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APPENDIX D
COMMON UAS WEATHER SOURCES IN THE FIELD

UAS operators typically use smartphone or tablets to access weather information in the field. There are a variety of pilot's weather applications designed for manned aviation that have value for UAS operations. Figure D-1 is a screenshot of Foreflight, one of the mobile application on the market.

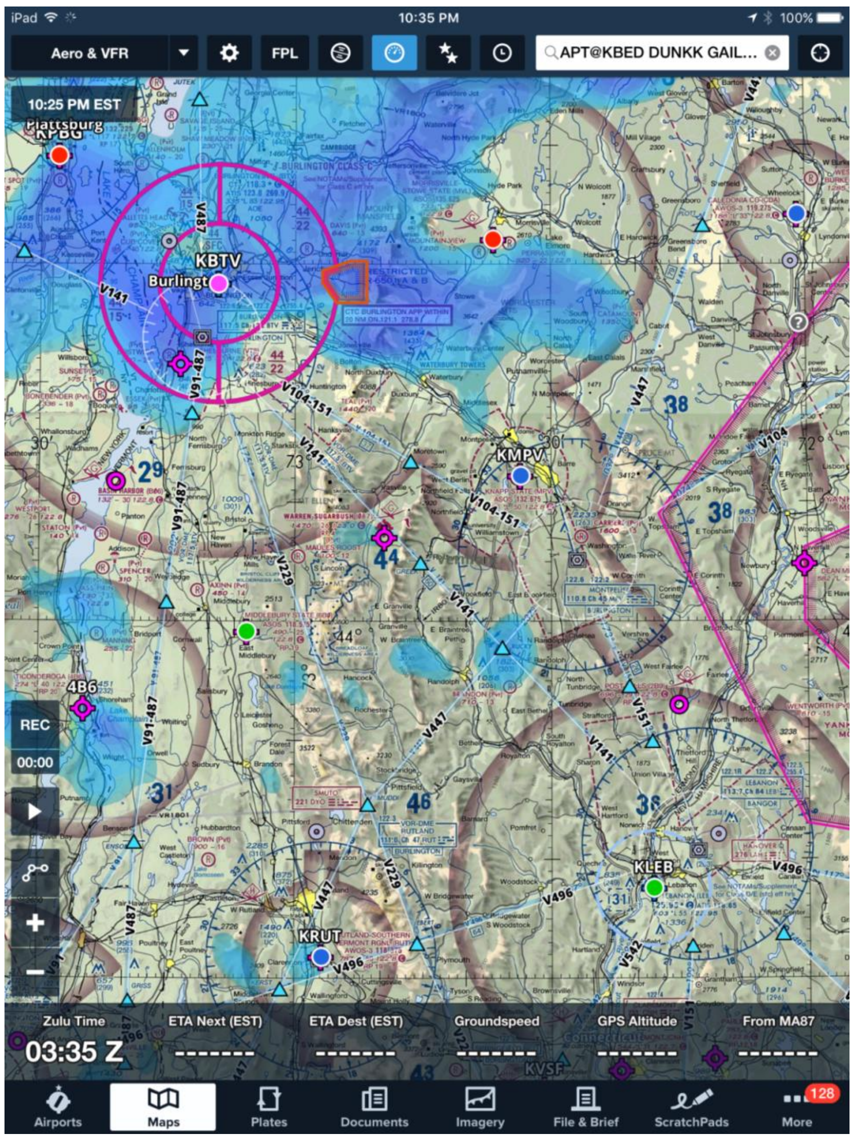

Figure D-1 Foreflight precipitation overlay (10 minute NEXRAD latency).

The application can display any of the weather information available on www.aviationweather.gov overlaid on a set of aviation maps. Figure D-1 shows an area of winter weather in the Vermont area, where it is important to note that the precipitation image is 10 minutes old (10:25 PM issue time and 10:35 PM current time). Figure D-2 shows the MOS ceiling graphical forecast available on Foreflight.

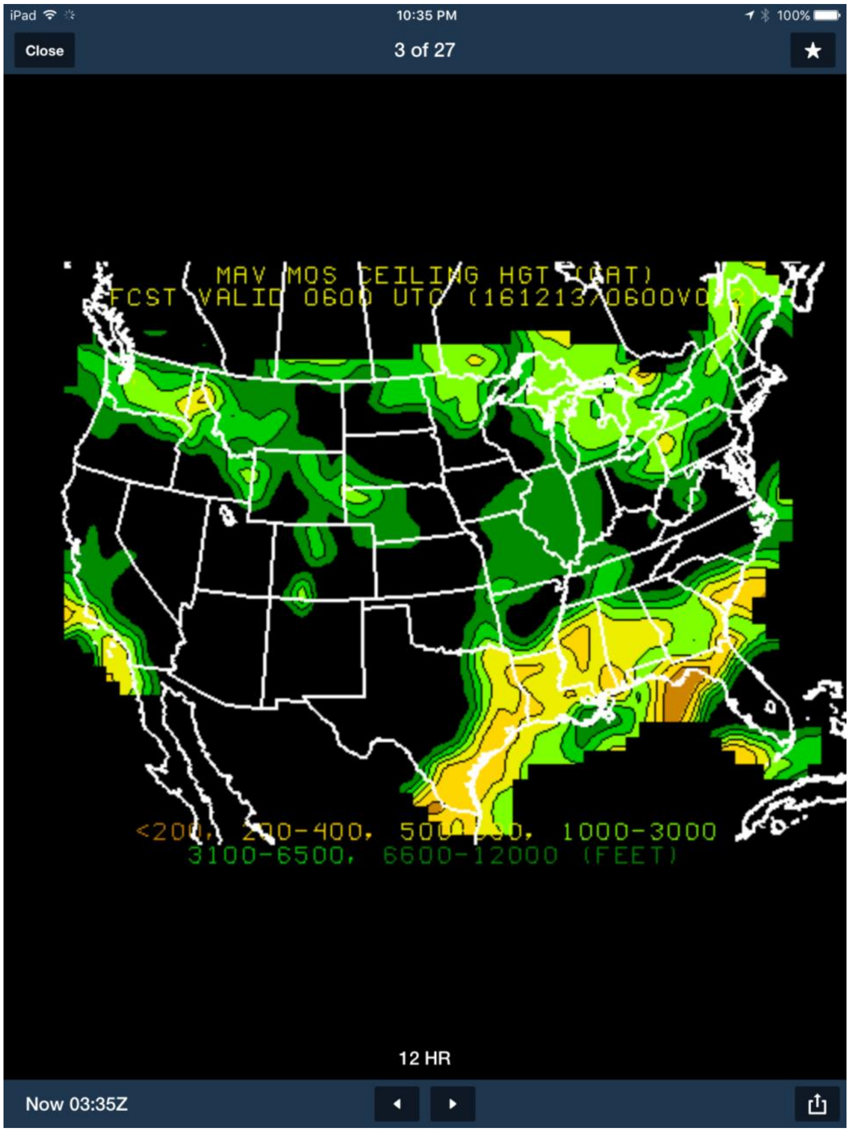

Figure D-2 Foreflight MOS ceiling graphical forecast.

The ceiling forecast provides contours of ceiling height; however, the map cannot be zoomed-in to see details on the scale needed by small UAS VLOS operations. Figure D-3 shows the graphical turbulence AIRMET on the Foreflight application.

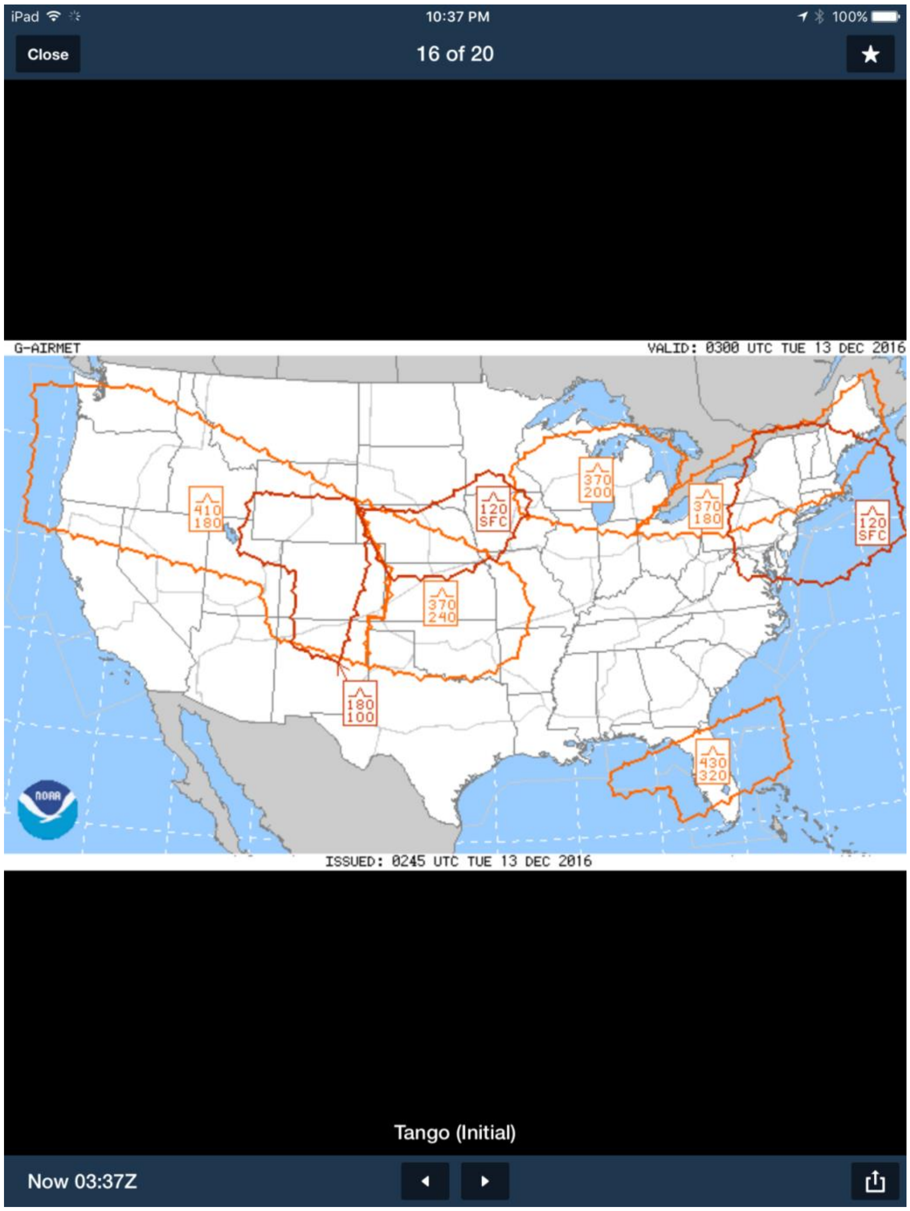

Figure D-3 Foreflight turbulence AIRMET imagery.

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GLOSSARY

ABLE	Atmospheric Boundary Layer Environment
AGL	Above Ground Level
AIRMET	Airmen's Meteorological Information
ARL	Army Research Laboratory
ASOS	Automated Surface Observing Stations
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
AUVSI	Association for Unmanned Vehicle Systems International
AWC	Aviation Weather Center
AWD	Aviation Weather Display
BVLOS	Beyond Visual Line of Sight
CAT	Clear Air Turbulence
CCFP	Collaborative Convective Forecast Product
CIP	Current Icing Product
CIWS	Corridor Integrated Weather System
CONUS	Contiguous United States
CoSPA	Consolidated Storm Prediction for Aviation
CVA	Ceiling/Visibility Analysis
DHS	Department of Homeland Security
DoD	Department of Defense
ECMWF	European Center for Medium-range Weather Forecasting
EDR	Eddy Dissipation Rate
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FIP	Forcast Icing Product
GF	Gust Front
GFS	Global Forecast System
GFS/AVN	Global Forecast System/Aviation
GOES	Geostationary Operational Environmental Satellites
GPS	Global Position System
GTG	Graphical Turbulence Guidance
HRRR	High Resolution Rapid Refresh
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ITWS	Integrated Terminal Weather System
LAMP	Localized Aviation MOS Program
LLWAS	Low Level Windshear Alert System

MB	Microburst
MDCRS	Meteorological Data Collection and Reporting System
METAR	Meteorological Terminal Aviation Routine Weather Report
MOS	Model Output Statistics
NAM	North American Model
NAM/WRF	North American Mesoscale/Weather Research & Forecasting
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NEXRAD	Next Generation Weather Radar
NextGen	Next Generation Air Transportation System
NFPA	National Fire Protection Association
NGFR	Next Generation First Responder
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NWP	NextGen Weather Processor
NWS	National Weather Service
ORD	Chicago O'Hare International Airport
PHX	Phoenix Sky Harbor International Airport
PIREPS	Pilot Report
R&D	Research and Development
RAP	Rapid Refresh
RMS	Root Mean Square
RVR	Runway Visual Range
S&T	Science and Technology
SATCOM	Satellite Communications
SFO	San Francisco International Airport
SIGMET	Significant Meteorological Information
SigWx	Significant Weather
SWIM	System Wide Information Management
TAF	Terminal Aerodrome Forecast
TBFM	Terminal Time Based Flow Management
TDWR	Terminal Doppler Weather Radar
TMA	Travel Management Advisor
TWIND	Terminal Wind
UAS	Unmanned Aircraft System
UTM	UAS Traffic Management
VIL	Vertically Integrated Liquid
VLOS	Visual Line of Sight
VMC	Visual Meteorological Conditions
WSP	Weather Systems Processor

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