1.4 TARGETED WEATHER FORECASTS FOR SMALL UNMANNED AIRCRAFT SYSTEMS

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1. INTRODUCTION

The number of small Unmanned Aircraft Systems (sUAS) in the United States National Airspace System (NAS) is rapidly growing. The Federal Aviation Administration (FAA) predicts that the number of commercial and hobby unmanned aircraft (drones) will be around 4 million by 2022 (Lukacs and Bhadra 2017). Many of these operations will likely take place over heavily populated areas, presenting a significant risk for human injury and property damage when sUAS crash. Many studies have addressed the challenges and risks of integrating commercial and hobby drones into the NAS (Rao et al. 2016; Rios et al. 2017; Clarke 2014). Few studies have specifically addressed the challenges and risks associated with how weather phenomena will affect sUAS operations.

Ranquist et. al. (2016) investigated the range of impacts that weather has on sUAS operations. That study outlined the many negative impacts that weather can have on sUAS operations including limiting aircraft controllability, decreasing visibility, and knocking the aircraft off its flight path. Many of the commercial applications of drones will require flight in urban environments and heavily populated areas. FAA regulations require that most small drones have a flight ceiling 400 ft above ground level. When flying over people, sUAS must maintain a high degree of control to ensure an acceptable risk to people and property. In these populated areas, buildings can cause highly unpredictable gusts. This section of the atmosphere above the surface is largely overlooked by current forecasting. Surface level data is only useful for drone operations within about 30 ft of the ground, and most model forecast data is above the level at which drones fly. Additionally, the horizontal and temporal resolution of operational forecast data is about 3-km and 1 hour, respectively. As such, the space and time scales resolved by these models are much larger than the typical distance and time span of sUAS operations.

There is a current effort at the National Center for Atmospheric Research (NCAR) to develop very high-resolution (~100 m) simulations using WRF-LES to inform sUAS operations. These simulations will likely be necessary for safe drone flight in areas with significant terrain height and/or land surface type variations. Terrain variations can cause wind streams and strong turbulence that could significantly impact drone flight. In addition, boundary layer structures such as rolls and convective cells that can be resolved by LES can adversely impact sUAS operations. Extremely high-fidelity simulations, however, require super computing power to perform them over a useful amount of area. In addition, these fine scale forecasts could benefit from some quantification of forecast uncertainty either through building an ensemble of forecasts at more coarse resolution or through model post processing techniques (such as spatial filtering). As computer technology advances, it is likely that WRF-LES simulations will be commonplace, but for now, such high-resolution forecast data is not accessible to the public and there will still be a need for methods of quantifying forecast uncertainty.

The current study seeks to address the growing need for better weather information for a wide range of sUAS operations. This report will first briefly assess what weather resources are currently available to sUAS operations. In an effort to explore new ways to obtain weather data, the possibility of running targeted weather forecasts to provide on-demand weather information for sUAS operators is investigated. Finally, based on the results of the present work, research questions for both the meteorology and aerospace industries will be presented. These research areas need to be addressed to prepare for the growing number of sUAS.

2. CURRENT WEATHER RESOURCES

2.1 *Common Weather Information*

There are many sources from which people obtain their daily weather information. The weather data that most people access every day have a relatively low resolution. For instance, a mobile weather application may give a single value for the forecasted wind speed over all of Boulder, CO for a given time. Boulder, however, has variable terrain which can lead to significant differences in wind speed from one side of town to the other. Using only conventional weather information, a sUAS operator may be led to believe that it is safe to fly over any part of Boulder on a given day, even though the mountain or valley they are flying next to will create gusts that can damage their aircraft.

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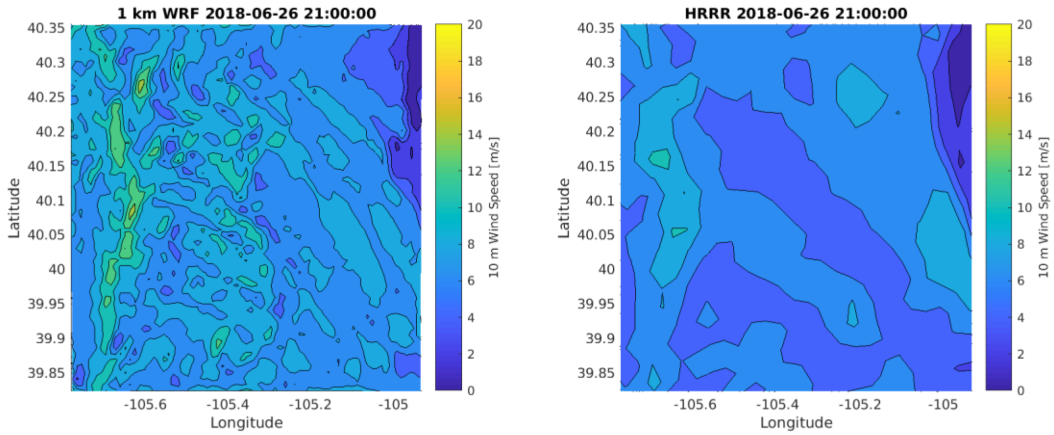

Figure 1: Weather simulation results for 10-m wind magnitude over Boulder County, CO. The left figure shows the results of a 1-km resolution WRF simulation with a 73 km x 61 km. The right figure shows 3-km resolution HRRR data for the same time.

2.2 *High Resolution Rapid Refresh*

The High-Resolution Rapid Refresh (HRRR) weather forecast is the highest resolution forecast that is run operationally over the United States. The HRRR model is run by the National Oceanic and Atmospheric Administration (NOAA) (Benjamin et al. 2016). This model has a 3-km grid with hourly output data and some field variables available every 15 minutes. A new 18-hour forecast is computed every hour. This model is well established and is continually being improved. The HRRR data is available for download from the NOAA website. Only data from about the past two days is available at any time, but this is not a concern for sUAS operations that are only concerned with the most up-to-date forecasts. NOAA is also developing visualization tools that display the data. The HRRR is a great resource but does not provide the resolution necessary for sUAS applications.

2.3 *Commercial Weather Products*

There are several companies who have products that supply weather information to drone users. One of these commercial products is Sferic DroneFlight from Earth Network. This product provides ~4 km hourly wind data (www.earthnetworks.com). Another company called UAV Forecast (www.uavforecast.com) provides hourly weather data for a specified location. This site allows users to input limitations of their drones, and it issues warnings accordingly. On top of the weather data, it provides warnings for any airspace restrictions in the area. This cite serves as a good model for what everyday sUAS operations will need to know for safe operations.

2.4 *Other Potential Weather Resources*

The research and knowledge in other areas could help satisfy the weather demands of sUAS operations. The rise of wind energy has been accompanied by the rise of research in wind estimations for wind farms (Wu and Hong 2007; Soman et al. 2010). These studies are focused on improving wind forecasts near the ground, the same area that is relevant to sUAS operations (Mahoney et al. 2012). Structural engineers have long been developing wind models and maps that help inform engineers of the loads that buildings will likely experience (Ellingwood and Tekie 1999; Holmes 2015). Structural engineering is less concerned with forecasting, but the wind maps they use could help inform the drone industry of areas where wind will, or will not, be a big risk. It is important that the emerging sUAS industry leverages these and other well-established weather research areas.

3. TARGETED WEATHER FORECASTING

The weather information that is currently available to the public is generally insufficient for the many sUAS operations that will be taking place in the very near future. Even the commercial products mentioned above have a relatively limited spatial and temporal resolution. To improve the weather data that people have access to, the current study investigated using the Weather Research and Forecasting (WRF) Model to calculate weather forecasts over a small, targeted area.

The simulations for this study were run on an 8-core desktop computer with 16 GB of RAM. The goal was to show that improved weather data could be obtained using a very accessible amount of computing power. The weather simulations were initialized using HRRR data downloaded from the NOAA website. This was done because the HRRR data is readily available to anyone. The simulations were run with a 1-km resolution. This grid spacing was used because it is three times finer than the HRRR and is expected to provide more detailed wind field data for the two cases chosen.

The 1-km WRF model was run over two different locations, Boulder County, CO and the Colorado San Luis Valley to assess the applicability of small domains in areas characterized by different terrains. The Boulder County simulation was for the day of June 26, 2018. On this day, Boulder County was dominated by an upper level ridge centered over Colorado which resulted in relatively weak upper level flows, allowing local forcing to

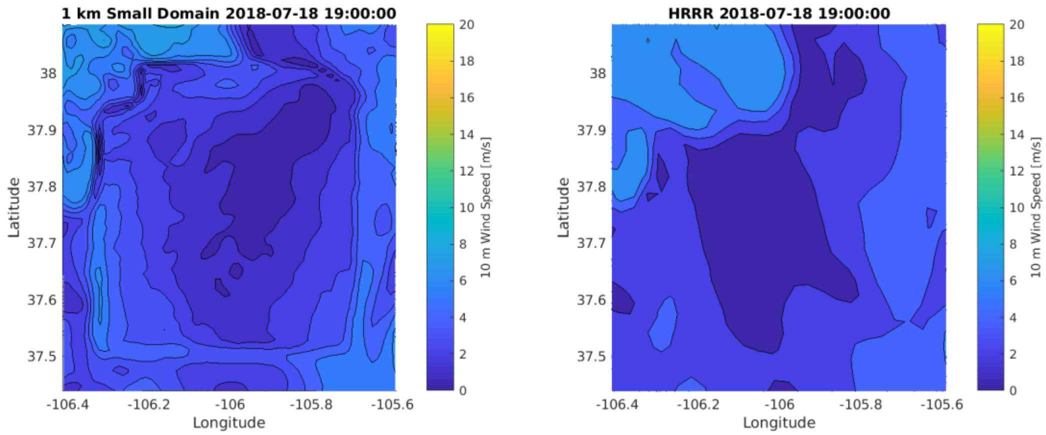

Figure 2: Weather simulation results for 10-m wind magnitude over the Colorado San Luis Valley. The left figure shows the results of a 1 km WRF simulation with a 73 km x 73 km domain. The right figure shows the HRRR data at the same time.

dominate. This weather regime is ideal for very small, coarser resolution domains. The San Luis Valley simulation was for the day of July 18, 2018. On this day, the San Luis Valley was under the influence of an upper level anticyclone with relatively weak upper level winds. Thus, weather within the valley was predominantly driven by solar heating, locally-driven terrain-induced circulations. Results for these two simulations are presented below.

3.1 *Boulder County Simulation*

The simulation over Boulder County was a 7-hour forecast with output data every 15 minutes and was initialized at 17:00 UTC. The lateral domain was 73 km x 61 km and surrounded Boulder County, CO. The physics settings used in the simulation were based on a previous study over the Salt Lake City area (Blaylock et al. 2017). The WRF simulation took less than a half hour to run on the 8-core desktop computer mentioned above. The results for the 10-m wind magnitude at one forecast time are shown in Figure 1. The results shown have a 4-hour lead time. The 10-m wind magnitude was the focus of this study because it is one of the more relevant weather parameters for small drones. A qualitative assessment of the two plots shows decent agreement in the overall behavior of the two models. The 1-km data, however, clearly provide much more detail than the HRRR. There are some locations where the WRF model predicts as much as 5-10 m/s higher wind magnitudes than the HRRR. Depending on the capabilities of the drone, this information would be critical for safe operations. Boulder County has a very diverse terrain with mountain peaks exceeding 10,000 ft to the west that flatten into rolling hills across most of the city and to the east. The mountains cause significant temporal and spatial variations in weather. It is evident from the results in Figure 1 that the 1-km simulation has the ability to capture many of these details that the HRRR cannot.

3.2 *San Luis Valley Simulation*

A weather simulation was performed over the San Luis Valley in south-central Colorado. This simulation was for an 18-hour forecast with output data every 10 minutes. On the 8-core desktop computer, this simulation took approximately 1 hour to run. The San Luis Valley is a difficult region for weather prediction because of the terrain. The high-altitude (>8,000 ft) valley is a large flat area with little vegetation aside from farm crops and is surrounded by mountain ranges. The forecast was run for July 18, 2018. During this time, the International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA) had a flight week where many sUAS operations were conducted in the San Luis Valley. Data collected during these flights could be used in a future study to further validate and improve the simulations of the current study. In support of ISARRA flight week, NCAR ran high fidelity weather simulations over the San Luis Valley. These simulations were run using WRF-LES. A parent domain of 1-km grid spacing was nested with a smaller domain that had ~100 m grid spacing. The 1-km resolution domain was approximately 487 km x 687 km and centered around the valley. The current study ran a 1-km weather simulation over the valley with a 73 km x 73 km domain. Both the large domain simulation and the small domain simulation were initialized with the HRRR, and they both used nearly the same WRF physics settings. The small domain simulation was initialized at 12:00 UTC while the NCAR simulation was initialized at 4:00 UTC. The results of the small domain simulation are compared with HRRR data and the larger domain realtime simulation produced by NCAR in Figures 2 and 3, respectively.

As was shown with the Boulder County simulation, the 1-km grid spacing simulation shows the ability to capture many more details than the 3-km HRRR. However, the small domain in this case appears to suffer from significant edge effects near the domain boundaries. Because the domain is small, it appears that these edge effects impact much of the domain which is manifest in unrealistic looking gradients near each lateral boundary.

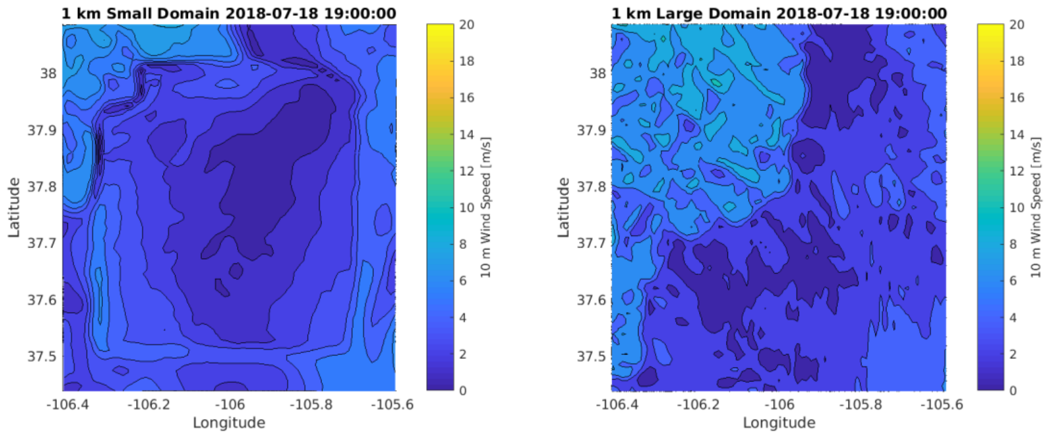

Figure 3: Weather simulation results for 10-m wind magnitude over the Colorado San Luis Valley. The left figure shows the results of a 1-km WRF simulation with a 73 km x 73 km domain. The right figure shows a sub-region of the 1-km NCAR simulation with a 487 km x 687 km domain.

It is interesting that these boundary influences did not appear in the Boulder County simulations. This is likely due to the fact that the domain in the San Luis Valley simulation is largely contained within the flat valley. Little of the surrounding mountainous terrain is within the small domain. This means that the simulation saw unexpected input data caused by the mountains that the simulation did not know were there. For the Boulder simulation, more than half of the domain contains mountains. This allowed the simulation to more accurately know the terrain of the area and therefore appropriately model its effects on the weather.

In addition to the different topographical conditions of the two simulations, the weather regimes of the two locations were different. For the Boulder County case, relatively weak upper level winds allowed local forcing effects to dominate. The small and coarse resolution domain has the ability to reasonably predict the weather because local forcing has the primary effect on the local weather. This local forcing is adequately captured with the small 1-km resolution domain. In contrast, the weather regime for the San Luis Valley simulation was not ideal for a small and coarse resolution domain. Significant convection formed outside the domain and propagated in. The small domain simulation did not capture that convection nor its influence inside the domain. This, along with topographical effects mentioned above, resulted in the observed edge effects.

The results of the small domain were also compared to the large domain 1-km simulation. These results are shown in Figure 3. At the time shown, the small domain simulation had a 6-hour run-up time while the large domain simulation had a 15-hour run-up time. The large domain simulation captures many details that the HRRR and the small domain cannot and removes the edge affect seen in Figure 3. Based on these results, it appears that the reason for the improved simulation results with the large domain is likely because the large domain captures all of the important topography and large scale weather phenomena not capture by the small domain. This means that the simulation captures more of the terrain effects on the weather that propagates into the valley. The small domain does not contain information of the surrounding geography so does not capture the same weather phenomena. A future study will further address this by running a weather simulation with a domain size between the two presented here.

The results presented show how the 1-km simulations provide more information about local weather than the 3-km HRRR can. It is also apparent that these targeted forecasts may need to be modified and adjusted for the specific region over which they are being run as well as the weather regime. Future studies will work to validate these simulations with real data and investigate how domain size and physics settings need to be adjusted for specific geographic areas.

3.3 *Pros and Cons of Targeted Forecasting*

There are several benefits to running targeted forecasts compared to large scale forecasts like the HRRR. The physics models used in targeted weather simulations can be tuned for the specific region over which they are being run. Large scale simulations need to make significant compromises to produce acceptable results for a wide range of geographical areas. Targeted weather forecasting also concentrates computing resources only on areas that are of interest. Forecasts over larger areas may waste computational resources computing high-resolution forecasts in areas where it is unnecessary. If weather data is not generally available in a given region (likely to be the case rural, sparsely populated areas), the concentrated computing power would allow many people with access to moderate desktop computers to compute their own weather data when needed. Developing a system for performing targeted weather forecasts could also be beneficial for companies that wish to develop proprietary sUAS networks that are independent of outside resources. This, however, could result in issues of situational awareness for sUAS operations as mentioned in the next paragraph. Using smaller more coarse domains also could enable running an ensemble which could be used to characterize uncertainties in the positioning of larger-scale flow features.

There are several drawbacks to targeted high-resolution weather forecasts. Tuning physics models for a certain region takes expertise and forecasts need to be extensively validated with the error statistics being well known for optimal decision making. Unless targeted forecasts are performed in a highly coordinated manner, it is possible that many different groups will perform their own weather simulations over the same region, resulting in potential conflicts and misunderstanding. Different targeted forecasts over the same area could lead to sUAS operations that do not have a common situational awareness, which is important for ensuring safe coordination between two operations in close proximity. Another challenge for targeted forecasting is obtaining the forcing data which are embedded within very large HRRR files requiring significant bandwidth to be obtained.

4. FUTURE METEOROLOGICAL AND AEROSPACE RESEARCH AREAS

Both the meteorological and the aerospace communities need to address the challenges presented by the growing sUAS industry. For the meteorological community, the following research questions need to be answered.

- The meteorological community has always done a remarkable job of making weather information available to the public. The high-fidelity information that is necessary for small drone flights is a totally different scale than what has previously been made available. The community needs to assess if this high-resolution data should be locally computed, made available to the public, or will be available by purchase. Ultimately, how can high-fidelity weather data be readily available to a wide range of users?
- In order to optimize computational resources, high-resolution forecasts should be focused on areas and times that will be most important for sUAS operations. Drone traffic as well as local weather variability will help determine where high-fidelity simulations are necessary and where they are not. The forecast model for a given region will be a function of the local terrain and dominant weather regime. How should simulations be adjusted for different geographic areas given terrain, weather regime, and demand from drone traffic?
- Urban and mountainous environments cause highly unpredictable wind gusts. Gusts that can damage drones may be on the scale of just a few meters. Capturing these gust scales directly would require very high forecast resolution and excessive amounts of super computing power. How can accurate wind gust estimates be obtained for urban and mountainous areas?

In collaboration with the above meteorological research areas, the aerospace industry needs to address the following questions.

- There are many factors that can influence sUAS operations from sun glare, precipitation, wind, turbulence, visibility and more. What weather information is most relevant for sUAS operations and how should the information be conveyed?
- Commercial and hobby drones need to be thoroughly tested to quantify their limitations regarding different weather phenomena. Most drones that are purchased only give basic information about weather limitations. They do not give maximum allowable turbulence, maximum or minimum temperature, whether or not they can withstand flying through precipitation, etc. Different sUAS have different performance capabilities as well. Should testing and quantification of sUAS limitations be standardized, and if so, how?
- The weather data needed may vary with different sUAS operations. Short duration flights may need general estimations of wind gusts to ensure that the sUAS can handle the gusts expected. Longer flights may need accurate wind speed and direction data over a large area to appropriately allocate battery power. What temporal and spatial forecast resolution is necessary to sufficiently inform sUAS operations?
- Given an accurate weather forecast and aircraft model, there need to be established ways to assess the risk of any given flight. Can weather related flight risks be standardized and quantified?

5. SUMMARY

The growing sUAS industry requires significant development in weather forecasting technology and in the current understanding of how drones respond to weather phenomena. A review of current weather resources showed that while some companies are beginning to address the need for weather data, much higher resolution data will be needed soon. The current study provided a proof of concept for 1-km resolution targeted weather forecasting to support sUAS operations. It was shown that reasonable amounts of computational power can be used to produce meaningful weather information that may otherwise be unavailable. The results show that these targeted simulations may need to be adapted for the specific location over which they are being run. Future studies will need to validate this type of targeted weather forecast. Both the aerospace and meteorological community have many research questions to address to ensure safe sUAS operations.

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