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USING WRF-ARW DATA TO FORECAST TURBULENCE AT SMALL SCALES

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1. INTRODUCTION

The Army Research Laboratory (ARL) has an interest in high spatial and temporal resolution weather output with an emphasis on products that assist warfighter decision aids and applications in battlefield environments. This model study was done in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N) as well as for longer-range forecasting support. Thus, there was an emphasis on fine-resolution, short-range forecasts in complex terrain in an effort to support real-world combat weather and enhance battlefield planning. The model utilized to investigate fine-scale weather processes, the advanced research Weather Research and Forecasting model (WRF-ARW), was run with a triple nest of 18, 6, and 2 km grids over a 24-h period. One of the long-term intriguing model areas of study is clear-air turbulence due to the effects of turbulence on Army Aviation aircraft and on-board sensors. This study investigates the WRF-ARW output over northeastern New Jersey during the winter season of 2006- 2007. Using a combination of the Panofsky Index in the boundary layer and Turbulence Index (TI) above the boundary layer, a small sample of 75 pilot reports was compared to "YES/NO" turbulence forecasts over the 24-h forecast period. Results were very encouraging using both the 18-km and 2-km output, with a probability of detection over 0.70, although the testing was biased to days with a high probability of turbulence.

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However, it was also found on the 2-km grid that the forecasted intensity of turbulence was excessive in many cases. There was no evident term in the TI that seemed to cause the problem; however, in many of these cases one or two terms were an order of magnitude higher at 2-km than at 18-km. It became apparent that a variable such as turbulence would need to be parameterized at smaller scales.

2. TURBULENCE

Forecasting clear air turbulence (CAT) is a complicated problem because of the small timescale and resolution at which turbulence is often observed. Theoretical studies and empirical evidence have associated CAT with Kelvin-Helmholtz instabilities. Miles and Howard (1964) indicate that the development of such instabilities require the existence of a critical Richardson number (RI) <=0.25. Stull (1989) notes that the Richardson number is a simplified term or approximation of the turbulent kinetic energy equation where the RI is expressed as a ratio of the buoyancy resistance to energy available from the vertical shear.

The equation is expressed below:

$$RI = \frac{\frac{g}{\theta} * (\frac{\partial\theta}{\partial Z})}{(\frac{\partial V}{\partial Z})^{2}} \qquad (1)$$

where g is the gravitational acceleration, $\partial\theta/\partial Z$ is the change of potential temperature with height, and □V is the vector wind shear occurring over the vertical distance □Z.

Numerous scientists have attempted to use both theoretical and observational data to formulate techniques to forecast CAT. Dutton and Panofsky (1970) associated vertical shear instabilities with turbulence. Bacmeister et al. (1984) noted an obvious correlation between mountain waves and turbulence. Keller (1990) developed the “SCATR” index which relates the nonturbulent component of the tendency of the Richardson number to stretching deformation and shearing deformation. These are just a small sample of work in this very challenging area and McCann (1993) showed that correlation coefficients are rarely greater than +/- 0.35 when using the existing methods.

Boyle (1990) of The U.S. Navy Fleet Numerical Meteorological and Oceanography Center used the Panofsky index (PI) to forecast low-level turbulence, where the low level is considered to be below 4,000 ft AGL. The formula for this index is:

$$PI= (\text{windspeed})^{2} * (1.0-RI/RI_{crit}) \qquad (2)$$

where RI is the Richardson number and RI_{crit} is a critical Richardson number empirically found to be 10.0 for the FNMOC data. The higher the Panofsky index the greater the intensity of turbulence at low levels.

Meanwhile, Ellrod and Knapp (1992) listed environments where significant CAT was found to be prevalent. Their study associated vertical wind shear, deformation, and convergence into a single index as shown below in equation 3 which is called the Turbulence Index (TI).

$$TI = VWS * [DEF + CVG] \qquad (3)$$

where VWS is the vertical wind shear, DEF is the deformation term which is a combination of stretching deformation and shearing deformation and CVG is the convergence. This work by Elrod and Knapp was based on the Petterssen’s frontogensis equation and was ideal to utilize the gridded output of a mesoscale model.

Using the Panofsky index below 5000 ft AGL and the Richardson number above that level to the model top of 7000 magl, Passner (2003) found that the Panofsky index was most effective in the lowest 5000 ft while the Richardson number was generally ineffective between 5,000 to 10,000 ft AGL and more effective above 10,000 ft AGL. The results in the Passner study indicated a need for an improved routine above 5000 ft AGL. It was determined to implement the TI above 4000 ft AGL, since Knapp et al. (1995) in their study were able to prove that a combination of the features of the TI and the PI provided the highest correlation coefficients.

3. THE WRF MODEL CONFIGURATION AND EVALUTATION

Originally, the turbulence forecasts and evaluation were done using the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5). However, more recently, the Advanced Research version of the Weather Research and Forecasting (WRF-ARW) model was implemented as the model used by the ARL to determine how accurate and robust the model is under a variety of meteorological conditions. Much of this study centered on basic model output such as temperature, moisture, wind direction and wind speed; however, a study of turbulence forecasts was also conducted with the WRF-ARW.

The WRF models were run with version 2.1.2. All the models run were utilized with the WRF-ARW dynamical core and were initialized with 0000 universal time coordinate (UTC) 40-km WRF model data. The models were run for a period of 24 hours with model output available every hour. A triple-nest configuration was used, with the domain having configurations of 18-km, 6-km, and 2-km grid resolutions.

The physics packages used for all model runs were:

- Lin microphysics
- Rapid Radiative Transfer Model long-wave radiation
- Dudhia short-wave radiation
- MM5 similarity for surface-layer physics
- Noah land surface model
- Yonsei University scheme for planetary boundary layer

- Kain-Fritsch cumulus parameterization for 18-km grids only
- Four soil layers

An evaluation of the basic model output was completed during the period July 2006 to March 2007 at the Caldwell, NJ airport observation site. Table 1 shows the average forecast, average observation, average absolute temperature error, mean error, and correlation coefficient for the 18-km model output at all forecast hours through the entire 24-h forecast output.

Table1. WRF results at the Caldwell, NJ site from July 2006 to March 2007, 18–km resolution

	Ave Abs Error	Mean Error	Correlation
Temp (°C)	1.6	-0.1	0.99
Dew Point (°C)	1.9	0.2	0.99
Wind Dir (deg)	22	6	0.80
Wind Speed (knots)	1.0	0.3	0.77

As can be seen in the table, the WRF does show excellent skill and correlation for this location. However this is not unexpected given the lack of complex terrain and generally light wind speeds during much of the study.

Table 2. WRF results at the Caldwell, NJ site from July 2006 to March 2007, 2–km resolution

	Ave Abs Error	Mean Error	Correlation
Temp (°C)	1.6	0.3	0.98
Dew Point (°C)	1.8	0.4	0.97
Wind Dir (deg)	18	7	0.86
Wind Speed (knots)	2.5	0.7	0.77

The results in table 1 and table 2 show general agreement with only minor differences in the skill between the 18 and 2-km resolution output at the point tested. There are no strong biases noted in any of the parameters tested.

4. TURBULNCE EVALUTATION

The method used in this study to verify turbulence is to compare pilot reports (PIREP)s to model forecasts. Using the WRF output, verification is limited to a 1-h period surrounding the model forecast time. As an example, model forecasts of turbulence at 2100 UTC are compared to PIREPs from 2030 to 2130 UTC only. Any PIREPs that included two intensities, such as LGT to MDT, were classified as the more extreme intensity. As a standard, only pilot reports close in height to the model forecast were accepted. For levels below 10000 ft AGL, the forecasted turbulence had to be within 1000 ft of the PIREP. From 10000 to 20000 ft AGL, the forecast had to be within 1500 ft of the PIREP, and above 20000 ft AGL, the forecast had to be within 2000 ft of the observed turbulence.

The turbulence evaluation was done between August 2006 and April 2007 using a small sample of about 75 pilot reports over the New Jersey-New York metropolitan area. This time frame included a variety of weather conditions and seasons. Table 3 shows the results of this study for both the 18- and 2-km grid resolutions where POD is Probability of Detection, FAR is False Alarm Ratio, TSS is True Skill Score, and Bias is the bias to overforecast or underforecast an event.

Table 3. Turbulence “YES/NO” forecast skill using WRF output for 24-h forecasts over New Jersey grid

	18-km WRF	2-km WRF
POD	0.73	0.83
FAR	0.28	0.30
TSS	0.12	0.20
Bias	1.02	1.19

The results in table 3 are very encouraging using the WRF output and the combination of the TI (above 4,000 ft AGL) and PI (below 4,000 ft AGL). However, a closer investigation of these data indicated that the lower levels, using the PI, had higher skill than the TI. Table 4 shows the skill associated with the TI over the New Jersey grid for both the 18-km and 2-km WRF grids for points above 4000 ft AGL.

Table 4. Turbulence “YES/NO” forecast skill above 4000 ft using TI for WRF output for 24-h forecasts over New Jersey grid

	18-km WRF	2-km WRF
POD	0.68	0.80
FAR	0.37	0.45
TSS	0.15	0.23
Bias	1.31	1.56

As can be seen in table 4 the FAR is higher using the TI which leads to a lower TSS and much higher bias. This indicates that the turbulence is being overforecasted significantly using the TI using the WRF input. It does appear that while the POD is higher with the 2-km resolution data, the bias is even higher which shows that the program is forecasting turbulence in far too many cases.

In figure 1 and figure 2, the plots show the turbulence forecast for 1500 UTC 08 August 2006 over the New Jersey grid.

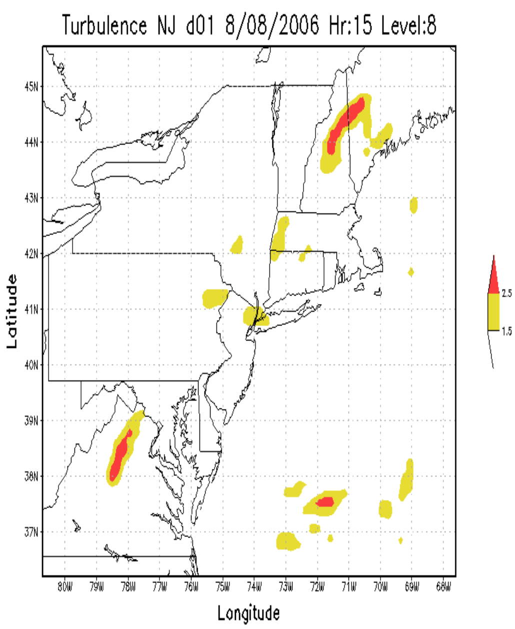

Figure 1. Turbulence forecast at 1500 UTC 08 August 2006 using 18-km WRF output at 4000 ft AGL.

In figure 1, the light turbulence or no turbulence is shown using the white shade, moderate turbulence is yellow, and severe turbulence is displayed in red. As can be seen in the plot, there is very little turbulence noted over the grid except over the higher terrain of New Hampshire and Virginia. The same colors are shown in figure 2, which is a 2-km resolution at the same time and day. As can be expected, the domain size is smaller, but clearly the inner domain has a large coverage of moderate and severe turbulence.

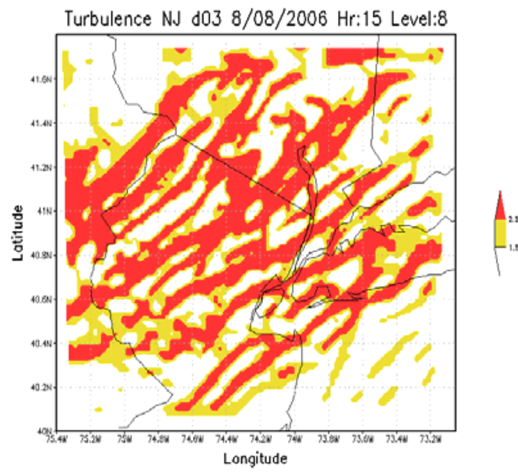

Figure 2. Turbulence forecast at 1500 UTC 08 August 2006 using 2-km WRF output at 4000 ft AGL.

Using the two plots, there are obvious differences between the 18-km and 2-km resolution data as there is far greater coverage of turbulence forecasted using the 2-km WRF output than the 18-km data, which agrees with the statistics shown in table 4. In general, these data for the entire experiment from August 2006 to April 2007 did show more intense and higher turbulence coverage at 2-km than at 18-km. For example, on the 18-km domain 40 percent of the forecasts were for moderate or severe turbulence while 43 percent of the observations were for moderate or severe turbulence. On the 2-km domain, 58 percent of the forecasts were for moderate or severe turbulence while 40 percent of the observations contained reports of moderate or severe turbulence. Overall, using the 2-km output, 25 forecasts were for severe turbulence but only four cases verified in the sample of 67 cases.

On the day in question, 08 August 2006, a small sample of pilot reports over the region indicated no turbulence except for some light chop or occasional light turbulence in the layer from 2,500 to 3,500 ft AGL. Based on the 1200 UTC upper-air observation at Upton, New York (KOKX) (not shown) the winds were from 330 degrees at 20 to 25 knots in this layer. There was some directional shear noted in the layer but little speed shear.

It becomes a question as to why this occurs; the strong bias for overforecasting turbulence and turbulence intensity at 2-km. A careful investigation of the TI equations at 9500 ft AGL on 08 August 2006 shows that all terms of the TI were larger in the 2-km domain with the shearing term showing the largest difference. Most of the terms were about one order of magnitude larger with the shearing term two orders of magnitude larger. The turbulence forecast at 18-km was "light" while the forecast at 9500 ft AGL on the 2-km grid was "severe" at 1500 UTC. Based on a pilot report at 1452 UTC over the White Plains, New York area at 8500 ft AGL turbulence was reported as "negative."

Several other cases such as the 1 December 2006 case show the shearing term to be as much as two orders of magnitude larger on the 2-km grid than the 18-km grid at 4200 ft AGL. At a higher level of 5100 ft AGL, this trend was still noted on the 1 December 2006 case. However, this trend was not noted consistently, as the 14 February 2007 case indicated that the stretching, shearing, and deformation terms were all larger on the smaller domain. Additionally, the case of 5 March 2007 over the LaGuardia, New York airport at 9200 ft AGL showed a larger difference in the stretching and convergence terms. This led to a forecast of moderate turbulence on the 2-km grid and no turbulence on the 18-km grid.

Based on these calculations, it is apparent that the terms are scale dependent; thus, a smaller grid size results in larger growth in the main terms in the TI. Many of the spurious cases of severe turbulence do appear to follow the terrain features; however, after careful study it is uncertain why this would be. Logically, the convergence of the wind field would be a cause, but the convergence term in the TI is the least significant term in the equation set. The vertical shear term did not show any significant difference the grids. Further studies were done to find a point where the terms in the TI expanded to the point where they started growing large enough to cause the increase in turbulence intensity. It was found that about 8-km grid resolution acted as a cut-off between effective and ineffective resolution of turbulence. This work follows some of the logic of a cumulus parameterization, where grid size does greatly influence the result of the convective development. It can be argued that below a certain grid size that turbulence can not or should not even be resolved. However, turbulence forecasts remain a very important forecasting issue and a smoothing or different approach at smaller scales is necessary. The idea of limiting the grid resolution to 8 km did provide better graphical results with less disparity between the 18-km and 2-km grids. However, very little validation or verification has been done using this new method and it is impossible to say if it truly provides accurate results.

5. TURBULENCE FORECAST FOR UAV OPERATIONS

Recently, there was an opportunity to expand the turbulence-forecasting evaluation by participating in an operation using a ScanEagle Unmanned Aerial Vehicle (UAV) at the Yuma Proving Ground (YPG). The ScanEagle is a light-weight, long-endurance UAV with a 10-ft wingspan developed by Insitu and The Boeing Company. The experiment was conducted in November and December 2007 and sponsored by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The Battlefield Environment Division of the Computational and Information Science Directorate, ARL, provided localized wind, vertical motion, and turbulence forecasts for the ScanEagle flight over YPG.

Unlike much of the previous work, these were forecasts at very low flying levels since the ScanEagle was flown at approximately 200 to 300 ft AGL. Thus, turbulence forecasts were derived using the PI rather than the TI for this test. The forecasts were made using the WRF-ARW as described in section 3 of this paper. However, in order to better resolve the lower levels, more sigma layers were placed in the lowest 1000 ft AGL and the model runs were conducted with 60 vertical levels. Additionally, the model was a two-nest case with 1-km resolution on the smaller, inner domain. The resulting forecasts were utilized to determine areas and times of adverse flying conditions and used by flight operations personnel and CRREL scientists.

Results of this work were very positive and the graphical displays provided much information for the flight operators. Figure 3 show an example of a wind and turbulence forecast for a very small area over the YPG where flights were tested.

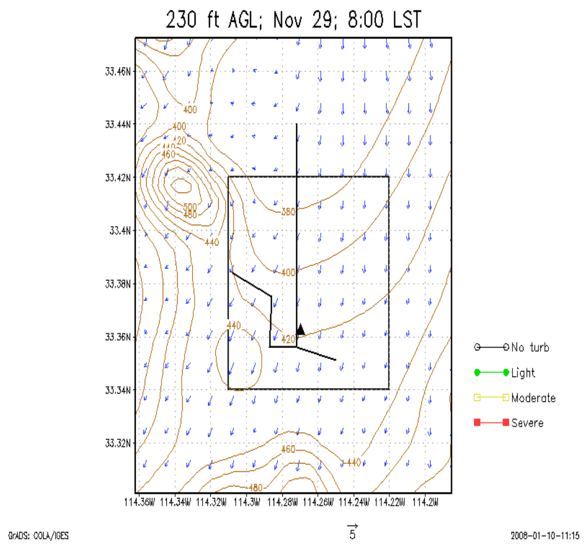

Figure 3. Wind (m/s) and turbulence forecasts at 1500 UTC 29 November 2007 over YPG

As can be seen in figure 3 the winds are light and from a northerly direction which is typical for an early morning in the region. No turbulence is forecasted on the grid area.

However, as the day progresses, more turbulence was forecasted as seen in figure 4.

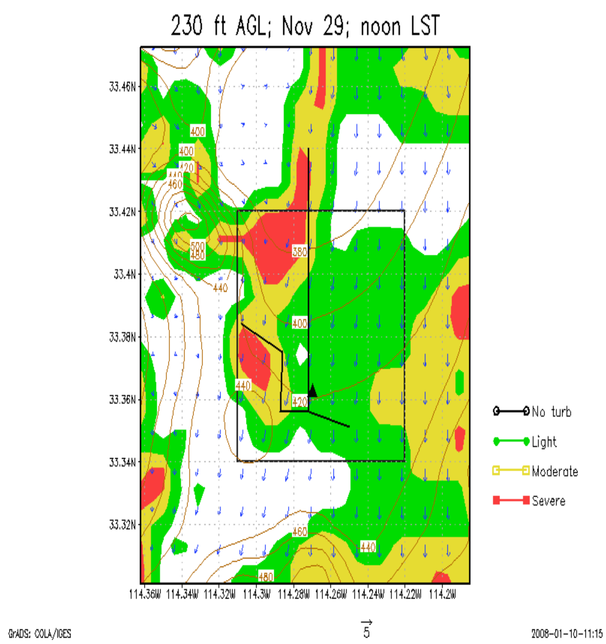

Figure 4. Wind (m/s) and turbulence forecasts on 29 November 2007 over YPG

This trend for areas of moderate or severe turbulence in small areas was prevalent each afternoon as solar radiation increased, although wind speeds and any wind shear did not appear to increase significantly. After researching the problem it became obvious that the height differences in the sigma levels were exceptionally small in the boundary and this led to significantly higher values of PI. The denominator in equation 1 became excessively large in the lowest four or five sigma levels due to the small values of ƏZ (change of height). This led to values of PI of over 1,000 in some cases when even values of 250 were considered to relate to severe turbulence.

Typically turbulence in the very lowest layers is a result of the terrain, wind, and thermals from the heat at the surface so adjustments near the immediate surface will need to be made in the forecasts with more emphasis on the slope of the terrain than on the height difference between layers.

6. CONCLUSIONS

The ARL, with an interest in high resolution mesoscale models for applications in the battlefield, has developed a forecast method to predict turbulence using 2-km and 1-km output of the WRF-ARW. While it is understandable that capturing clear-air turbulence is very difficult given the timescale and resolution involved, it still remains a goal to give a wide-ranging calculation of turbulence given the larger-scale conditions of the atmosphere. Verification was completed over a grid centered on northeast New Jersey since it contains a large number of airports and aviation traffic. Using a combination of the Panofsky Index in the lower atmosphere and the Turbulence Index in higher layers, comparisons were done for 18-km and 2-km output from the WRF-ARW. While the WRF did not show much difference between these two grids, there was a trend for more frequent turbulence forecasts at the smaller horizontal grid sizes. It was also noted that errors were more common using the TI than the PI with a higher FAR and stronger bias to overforecast turbulence.

It was determined that turbulence, due to its variable time and space scales, needed to be parameterized to prevent excessive amounts and intensity at the smaller grids. It was also found that increasing the number of layers in the vertical in the WRF created additional problems near the surface. Adjustments were made to account for this problem, but additional changes are needed to account for boundary-layer fluctuations. Upon completion, additional testing and comparison to PIREPs will give more detailed information about improvements made in turbulence forecasting as mesoscale models trend to smaller grid sizes and additional sigma levels to provide more detailed forecasts of the atmosphere. It is apparent that the empirical routines formulated for predicting turbulence at higher levels and larger grid sizes may not capture the true nature of turbulence in the atmosphere. Ongoing efforts to understand and forecast turbulence at very small scales are still being developed and will undoubtedly add insight in solving this problem. For now, the best approach is to adjust what does exist and find a fit that provides the best results and skill for aircraft.

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