4.3

Feasibility Study on Using High Resolution Numerical Models to Forecast Severe Aircraft Turbulence Associated with Thunderstorms

Donald W. McCann*
McCann Aviation Weather Research, Inc., Overland Park KS

1. INTRODUCTION

Many of the most severe turbulence encounters by aircraft occur in thunderstorms. This is not surprising since up- and downdraft speeds typically exceed 20 m s^{-1} and sometimes exceed 40 m s^{-1}. Since draft diameters are usually less than 10 km, wind shears in all directions can be easily one to two orders of magnitude greater than the vertical wind shears in the free atmosphere.

Avoiding thunderstorms is not difficult with today's modern radar networks, although, if the statistics gathered for this study can be projected to an entire year, hundreds if not thousands of aircraft still experience severe turbulence in storms.

While some aircraft simply cannot avoid convection cores, many careful pilots are buffeted by severe turbulence anyway. Adequately advising aircraft of severe turbulence is a twofold problem. One is the turbulence in the convection itself and the other is turbulence on a storm's periphery.

Thunderstorm avoidance rules commonly recommend a buffer around radar reflectivity maxima (Air Safety Foundation), but turbulence in convection is best correlated with draft speed (Byers and Braham 1949). Up- and downdrafts often are not always co-located with high radar reflectivity. This explains the recommended buffer and may explain encounters outside this buffer. Therefore, predictions of thunderstorm drafts can better predict thunderstorm turbulence.

Furthermore, turbulence on storm peripheries is due to phenomena such as low level gust fronts and high level outflow jets. These can exist tens of km from radar reflectivity centers. McCann et al. (2010) showed that high level unbalanced flow can lead to severe turbulence in areas thought to be safe.

Successful thunderstorm-associated turbulence forecasts will have to predict both storm drafts and storm unbalanced flow. Today's operational numerical forecast models cannot explicitly resolve convection, but some experimental models can. These new models have the potential to forecast drafts and unbalanced flow.

On nearly every day in the spring, 2009, the Environmental Modeling Center of the National Centers of Environmental Prediction ran two experimental models over the eastern two-thirds of the United States, the 4-km Advanced Research WRF (ARW) model and the 5-km Non-hydrostatic Mesoscale Model (NMM) both initialized at 0000 UTC and 1200 UTC (EMC-NCEP). These were not posted until about four hours after initialization. Since there were no grids specifically predicting storm drafts, I created storm draft grids with the VVSTORM algorithm (McCann 1999). I created similar unbalanced flow grids with the ULTURB algorithm (Knox et al. 2008 and McCann et al. 2010).

I gathered 122 pilot reports of moderate-severe or greater turbulence during April, May, and June, 2009 then compared each report with each algorithm's corresponding turbulence forecast. The results show that the high resolution models predicted many more pilot reports than similar algorithm output from the 13-km RUC2 forecast model.

2. REVIEW OF THE VVSTORM AND ULTURB ALGORITHMS

Human meteorologists predict convection using an "ingredients-based" method summarized by Doswell et al. (1996). Introduced in 1999, VVSTORM objectively quantifies these necessary ingredients from numerical models and produces forecast grids of storm drafts (McCann 1999). Since turbulence intensity is correlated to draft speed, I created the following empirical relationships between draft speed and eddy dissipation rate (edr) from aircraft data in Byers and Braham (1949):

* *Corresponding author address:* Donald McCann, McCann Aviation Weather Research, Inc. 7306 157th Terrace, Overland Park, KS 66223; e-mail: don@mccannawr.com

$$edr = (.014w)^{1/3} \quad w < 10 \text{ ms}^{-1}$$

$$edr = (.14 + .0064[w - 10])^{1/3} \quad w \geq 10 \text{ ms}^{-1}$$

where w is the draft speed. Table 1 shows edr values at various draft speeds.

w (ms^{-1})	edr ($m^{2/3}s^{-1}$)	subjective turbulence
1	.24	light
5	.41	moderate
10	.52	moderate-severe
20	.59	severe
30	.65	severe
50	.73	extreme

Table 1. Edr and subjective turbulence estimates at various draft speeds.

VVSTORM outputs edr values at every model level.

Forecasting clear-air turbulence can also be "ingredients-based" (McCann 2001). Knox et al. (2008) found a very good relationship for clear-air turbulence using an indicator of flow imbalance and the environmental Richardson number. This relationship resulted in the ULTURB algorithm. McCann et al. (2010) presented two cases of high altitude severe turbulence diagnosed by ULTURB. Theoretically, ULTURB should also be able to diagnose turbulence with low level outflow boundaries although this has yet to be tested.

3. METHODOLOGY

I gathered moderate-severe or greater turbulence pilot reports (PIREPs) from +30min to +4hr30min after 0000UTC and 1200UTC each day during April, May, and June, 2009. To qualify as thunderstorm-related, the PIREP location had to be within a distance double the nearest storm's diameter from that storm's center as viewed on radar imagery. Additionally, the PIREP location had to be over the eastern two-thirds of the contiguous United States, the domain of the ARW and NMM models. The database consisted of 122 PIREPs representing all altitudes from near the surface to FL450.

Whenever a PIREP qualified, I computed edr values from both VVSTORM and ULTURB algorithms run on the high resolution ARW and NMM forecast models and the 13 km resolution RUC2 model at the forecast valid time nearest the PIREP. I also compared the ARW and NMM forecast base reflectivity to the PIREP location.

I counted any PIREP as a "hit" whenever the forecast edr was greater than .50 $m^{2/3}s^{-1}$ at any grid point within 20 km of the PIREP location. Otherwise, it was a "miss." For radar reflectivity a "hit" was whenever the model forecast reflectivity was greater than 30 dBz within 20 km of the PIREP location. The data only allows for a report on the probability of detection (POD).

4. RESULTS

Figure 1 shows the algorithm detection skill with the RUC2 model. The total hit rate for both algorithms combined was only 26%. Compare these PODs with the results below for the ARW and NMM models.

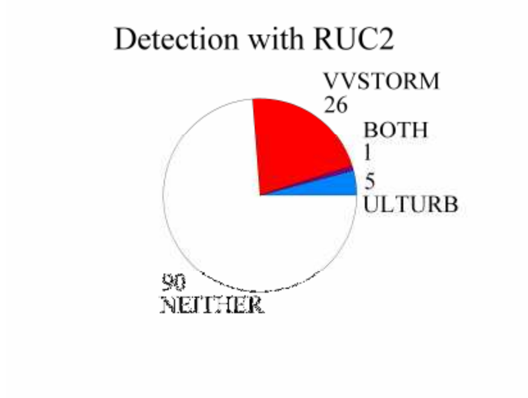

Figure 1. Detections of moderate-severe or greater turbulence with the VVSTORM and ULTURB algorithms run on the RUC2 model.

Both high resolution models' hit rates were higher than the RUC2's as viewed in Figures 2 and 3. Although the ARW's 59% hit rate is higher than the NMM's (43%), most of the time, edr output from ULTURB on both models was within ± .05 $m^{2/3}s^{-1}$ of each other 64% of the time, and edr output from VVSTORM on both models was within ± .05 $m^{2/3}s^{-1}$ of each other 78% of the time.

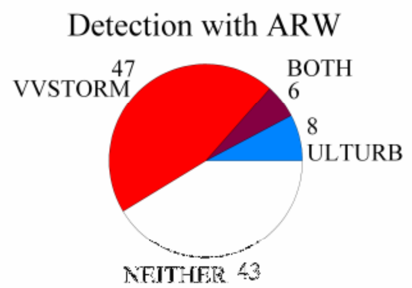

Figure 2. Same as Fig. 1 except algorithms run on ARW model.

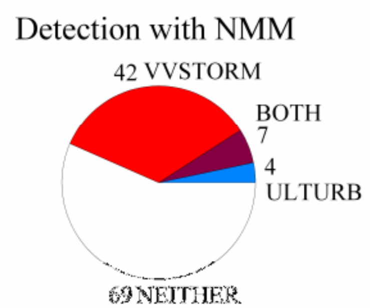

Figure 3. Same as Fig. 1 except algorithms run on NMM model.

Forecast model radar reflectivity was a poor detector of the PIREPs as indicated in Figure 4. The likely shortcoming with radar reflectivity is that it does capture the forecast up- and downdraft locations very well. It also cannot capture the peripheral features such as low level gust fronts and high level outflow jets.

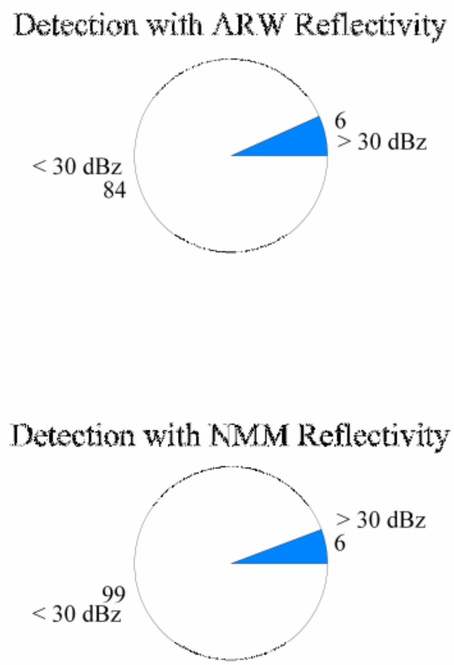

Figure 4. Detections of moderate-severe or greater turbulence with the forecast ARW and NMM model radar reflectivity.

Finally, Table 2 shows the detection rates by altitude and model. While all models did better at higher altitudes, the ARW model did significantly better at low altitudes than the other models. This best explains the ARW's skill over the NMM.

Flight level	RUC2	ARW	NMM
000-090	16%	46%	19%
100-250	22%	56%	52%
260-450	38%	68%	65%

Table 2. Total detection rates of moderate-severe or greater turbulence at various altitudes with VVSTORM and ULTURB run on the RUC2, ARW, and NMM models.

5. CONCLUSIONS

High resolution models show promise of improving aviation safety in and near thunderstorms. The primary challenge is to run these models in near real time. While the experimental NCEP models are run twice a day and post about +4 hours after model initial time, the 3 km High Resolution Rapid Refresh (HRRR) model output run hourly at the Earth Systems Research Laboratory Global Systems Division presently posts 2-3 hours after initial time (ESRL-GSD)[1].

In addition to the time taken to run the model, there is also post-processing time. This paper concluded that radar reflectivity is a poor detector of severe turbulence; therefore the models must be post-processed to compute the parameters that have skill in detecting severe turbulence. If model output includes storm draft speeds, there will be no need for a VVSTORM-like parameterization of up- and downdrafts. That will cut post-processing time. However, unbalanced flow indicators are not likely to be model output. Therefore, ULTURB will likely to remain necessary to predict thunderstorm peripheral turbulence.

REFERENCES

Air Safety Foundation (Aircraft Owners and Pilots Association): Thunderstorms and ATC, Safety Advisor Weather No. 4, webpage http://www.aopa.org/asf/publications/sa26.pdf

Byers, H.R. and R.B. Braham, 1949: *The Thunderstorm, Report of the Thunderstorm Project*, U.S. Dept. of Commerce, 287 pp.

Doswell, C.A., H.E. Brooks, and R.A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560-581.

EMC-NCEP: NCEP HiRes forecast window page. Webpage http://www.emc.ncep.noaa.gov/mmb/mmbpll/nestpage_4km/

ESRL-GSD: ESRD HRRR webpage http://ruc.noaa.gov/hrrr/Status.cgi

McCann, D.W., 1999: VVSTORM – Convection diagnosed from numerical models. *Proc. 8th Conf. on Aviation, Range, and Aerospace Meteorology*, Dallas TX, Amer. Meteor. Soc., 240-243.

McCann, D. W., 2001: Gravity waves, unbalanced flow, and clear air turbulence. *Nat. Wea. Digest*, **25(1,2)**, 3-14.

McCann, D.W., J.A. Knox, and P.D. Williams, 2010: Severe high altitude aircraft turbulence on thunderstorm peripheries. Proc.14th Conf. on Aviation, Range. and Aerospace Meteorology, Atlanta, GA, presentation P1.4

[1] HRRR grids were unavailable for this study.