J14.5 MESOSCALE MODELING EFFECTS ON OPTICAL TURBULENCE PARAMETERIZATION PERFORMANCE

Frank H. Ruggiero[1]
Air Force Research Laboratory
Hanscom AFB, MA

Daniel A. DeBenedictis
Titan/SenCom Corporation
Billerica, MA

Randy J. Lefevre and Stephen A. Early
Airborne Laser Element Office
Kirtland AFB, NM

1. INTRODUCTION

While there have been thousands of papers and scores of books written about the modeling of turbulence in the planetary boundary layer (PBL), there is a much more limited amount of material pertinent to turbulence modeling in the stably stratified free atmosphere. This is understandable since in the turbulent PBL model layers are thinner than the vertical depth of the mixing and there is significant turbulent exchange of heat and momentum between the layers that has to be numerically represented in the model. Generally in the stably stratified free atmosphere, the vertical depth of the turbulent mixing is smaller than the thickness of the model layers and thus not as important to the model solution.

While not as important to the model solution, turbulence in the stably stratified free atmosphere does have important implications. Mechanical turbulence can be very dangerous to aircraft, particularly those flying at very high altitudes (> 15 km). Optical turbulence (i.e. variance of refractive index fluctuations), can cause problems for optical seeing by astronomers as well as hinder laser propagation.

Since existing NWP turbulence parameterizations do not adequately resolve stably stratified free atmospheric turbulence, other parameterizations must be used. For optical turbulence, defined as the refractive index structure constant (C_n^2), the following equation was developed by Tatarski (1961):

$$C_n^2 = 2.8\left(\frac{\left(79x10^{-6}P\right)}{T^2}\right)^2 L_o^{4/3}\left(\frac{\partial T}{\partial z}+\gamma\right)^2$$

where P is pressure, T is temperature, z is height, γ is the adiabatic lapse rate, and $L_o^{4/3}$ is the outer length scale for the flow. Pressure and temperature are model prognostic variables and easily retrieved. In order to solve the equation a parameterization for $L_o^{4/3}$ is needed. One such parameterization was developed by Dewan et al. (1993) based on highly resolved vertical wind shear observations. There are two equations, one for the troposphere and one for the stratosphere:

$$L_o^{4/3} = 0.1^{4/3}\, x10^{(1.64+42.0xS)} \qquad \text{(Troposphere)}$$

$$L_o^{4/3} = 0.1^{4/3}\, x10^{(0.506+50.0xS)} \qquad \text{(Stratosphere)}$$

where S is the vertical wind shear. These relationships were originally designed to be used with radiosonde measurements and thus it was assumed that the vertical wind shear would be resolved to 300 m intervals. Roadcap (personal communication) compared computed C_n^2 values from the above equations with coincident observations of C_n^2 from two experiments in New Mexico and found good agreement suggesting reasonable estimates of C_n^2 could be achieved with correct input data.

Ruggiero and DeBenedictis (2000) adapted the Dewan model to run with data produced by Fifth Generation Penn State University/ National Center for Atmospheric Research Mesoscale Model (MM5; Grell et al. 1995). In a subsequent validation study (Ruggiero and DeBenedictis, 2002) they found that while the MM5/Dewan approach showed some skill, it still needed some improvement. One of the issues that Ruggiero and DeBenedictis (2002) noted was that the vertical profiles of the MM5 winds did not produce features at the resolution required

1 *Corresponding author address:* Dr. Frank H. Ruggiero, AFRL/VSBYA 29 Randolph Road, Hanscom AFB, MA 01731-3010

by the Dewan model (300 m) even when the vertical resolution of the model in the free atmosphere was close to that spacing.

The objective of this project is to study the effect of varying vertical and horizontal resolutions of MM5 on the predictions of optical turbulence. The goal of this effort is to come up with an optimum selection of both horizontal and vertical resolution that produces reasonable forecasts as well as can be considered computationally feasible in a real-time situation. This work builds upon the recent work of Lefevre et al. (2003) who performed a similar study using with a limited set of resolution configurations with data collected on Mauna Kea, Hawaii in December of 2002.

2. MESOSCALE MODEL RESOLUTION STUDIES

With increasing computational resources, it has become routine to run mesoscale models at increasingly higher horizontal resolutions. For example, to support optical seeing work at the Mauna Kea Observatory, Businger et al. (2002) run MM5 with a horizontal resolution in the innermost nest of 1 km. However, previous research has cautioned users about increasing horizontal resolution without sufficient increases in vertical resolution. In their study of an upper tropospheric front, Pecnick and Keyser (1989) came up with the relationship

$$\Delta z = s\Delta y$$

where Δz is the recommended vertical grid spacing, Δy is the horizontal grid spacing, and s is the frontal slope. Assuming an average frontal slope of 0.012, then for a Δy of 10 km Δz should be 120 m and for Δy of 1 km Δz should be 12 m. Lindzen and Fox-Rabinovitz (1989) came up with similar relationships for cases of quasi-geostrophic flow and gravity waves near critical levels. Later work by Ola et al. (1991) and McQueen et al. (1995) confirmed these findings for horizontal grid spacing of 10 km.

3. EXPERIMENT

For the mesoscale model in this experiment, MM5 was chosen because it is currently the operational model used by the Air Force Weather Agency (AFWA). AFWA will soon transition to the Weather Research and Forecast (WRF) model and it may have made sense to use that as the model for the experiment. However at the time of this work WRF did not have the capability of nesting and would have made testing various horizontal resolutions difficult.

Table 1. Specifics of model grids used in this study.

Model Grid	Horizontal grid spacing	Domain size	Convection Parameterization
1	27	118x118	Grell (1993)
2	9	178x178	Grell (1993)
3	3	268x268	None
4	1	400x400	None

Model runs were made for seven different days during a field experiment that was held at the White Sands Missile Range during September of 2002. During this period thermosondes were launched. Thermosondes are balloon-borne instruments that measure the horizontal temperature variation across a 1 m distance (Brown et al. 1982). This data can then be used to compute C_n^2 (Jumper and Beland, 2000). Along with the thermosonde, the payload also includes a radiosonde capable of measuring temperature, pressure, and winds. On each day of the field experiment 3 to 4 balloons were launched approximately at 2-hour intervals beginning near 0000 UTC.

For each day of measurements, three MM5 runs were made. The first run contained 42 vertical levels. The number and locations of the vertical levels were chosen to closely mimic the current operational setup at AFWA. The second MM5 run contained 61 vertical levels. The third run contained 81 vertical levels. The number and location of the vertical levels for the 81 level runs were chosen to give the approximately 300 m spacing above the PBL that the Dewan model was designed for. Other than the number and location of the vertical levels, all the model runs were configured the same. Specifications for each nest are given in Table 1. The 2-way feedback-nesting feature was turned off for all nests so that the results in the outer nests could be considered independent of what was occurring in the inner nests. For each grid, terrain data was utilized that was a resolution finer than that of the particular nest. The model runs were initialized using global forecast analysis from the NOAA Global Forecast System (GFS). The GFS analyses had a horizontal resolution of 1° at 24 pressure levels up to 10 mb. GFS analyses were also used as the lateral boundary conditions for the outermost nest during model integration. All four nests were initialized at 1200 UTC the day before each set of balloon launches so that comparisons of model data and balloon measurements were carried out approximately 12-18 hours into the model's integration.

For each balloon flight, its trajectory was computed using the radiosonde wind observations. Corresponding data from the model, including C_n^2 forecasts, were then computed via spatial and temporal interpolation along the same trajectory for comparison. The metric for conducting the comparison was path-integrated C_n^2, called the Rytov variance. For the comparisons, a sample path was used that went from 12 km to 17 km in the vertical.

4. INITIAL RESULTS

At this time two days of model runs corresponding to seven balloon flights have been processed. Figure 1 shows the RMS of the Rytov variance for the path from 12 km to 17 km. The results show that except for the 27 km horizontal resolution nest, the best results are found by running the 61 level model. The evident improvement from the 42 level runs to the 61 level runs makes sense given the previous resolution sensitivity studies referenced above, including the similar effort of Lefevre et al. (2003) who showed that going from 26 to 52 vertical levels resulted in an increase of accuracy. It is at first puzzling that this trend doesn't continue on with the 81 level run. However this may be due to numerical damping that is present in MM5 that prevents features that one would expect to appear with approximately 300 m vertical spacing from being realized. However while this would suggest a possible plateau in improvement with 61 levels it doesn't explain why the forecasts would degrade from the 61 to 81 level runs. Another noteworthy aspect in these initial results is that for each set of vertical resolution runs, the 3 and

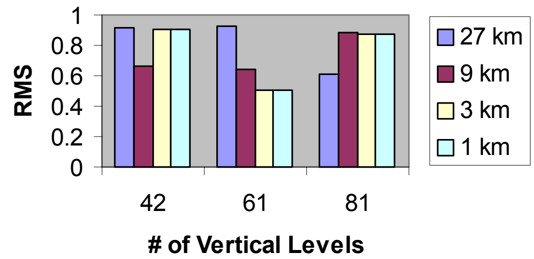

Figure 1. Root-mean-square error of Rytov variance predictions for various combinations of model resolutions.

1 km runs are nearly identical, indicating that running with a horizontal resolution of 1 km does not bring any additional value to the model solution.

One should be cautious about drawing too much of a conclusion from the partial data presented here. There are 12 more balloon flights from five other days in the campaign that will help make the results more representative.

Acknowledgements. Computer time for the project was provided the Department of Defense's High Performance Computing Modernization Office Program through the ABL II Challenge Project at the Maui High Performance Computing Center.

REFERENCES

Brown, J, H., R. E. Good, P.M. Bench, and G. Faucher, 1982: Sonde measurement for comparative measurements of optical turbulence. Air Force Geophysics Laboratory Technical Report, AFGL-TR-82-0079. ADA 118740

Businger, S., R. McLaren, R. Ogasawara, D. Simons, and R. J. Wainscoat, 2002: Starcasting. *Bull. Amer. Meteor. Soc*., **83**. 858-871.

Dewan, E. M., R. E. Good, B. Beland, and J. Brown, 1993*: A Model for* C_n^2 *(Optical Turbulence) Profiles using Radiosonde Data.* Phillips Laboratory Technical Report, PL-TR-93-2043. ADA 279399.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev*., **121**, 764-787.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1995: A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note T/N-398 + STR, 122 pp. [Available from NCAR Information Services, P.O. Box 3000, Boulder, CO 80307]

Jumper, G. Y., and R. R. Beland, 2000: Progress in the understanding and modeling of atmospheric optical turbulence. 31st AIAA Plasma Dynamics and Laser Conf., 19-22 June 2000, Denver, Co.

Lefevre, R., F. H. Ruggiero, and K Roe, 2003: Impacts of Numerical Weather Prediction Spatial Resolution on an Atmospheric Decision Aid for Directed Energy Weapon Systems. Preprints, DoD HPCMO Users Group Conference, June 9-13, 2003. Bellevue WA.

Lindzen, R. S., and M. Fox-Rabinovitz, 1989: Consistent vertical and horizontal resolution, *Mon. Wea. Rev*., **117,** 2575-2583.

McQueen, J. T., R. R. Draxler, and G. D. Rolph, 1995: Influence of grid size and terrain resolution on wind field predictions from an operational mesoscale model. J*. Appl. Meteor*., **34**, 2166-2181.

Ola, P., G. Persson, and T. T. Warner, 1991: Model generation of spurious gravity waves due to inconsistency of the vertical and horizontal resolution. *Mon. Wea. Rev*., **119**, 917-935.

Pecnick, M. J., and D. Keyser, 1989: The effect of spatial resolution on the simulation of upper-tropospheric frontogenesis using a sigma-coordinate primitive equation model. *Meteor. Atmos. Phys*., **40**, 137-149.

Ruggiero, F. H., and D. A. DeBenedictis, 2000: Three-dimensional modeling of optical turbulence. Preprints, DoD HPCMO Users Group Conference, June 5-8, 2000. Albuquerque, N.M.

Ruggiero, F. H., and D. A. DeBenedictis, 2002: Forecasting optical turbulence from mesoscale numerical prediction models. Preprints, DoD HPCMO Users Group Conference, June 11-14, 2002. Austin TX.

Tatarski, V. I., 1961: Wave Propagation in a Turbulent Medium, McGraw-Hill.