Comparison of WRF and MM5 for Optical Turbulence Prediction

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Abstract

Above the planetary boundary layer, optical turbulence typically occurs on spatial scales of tens of kilometers in the horizontal and only tens of meters or less in the vertical. These "pancake layers" of optical turbulence can be important to applications that require optical viewing or the use of lasers along long slant paths at high zenith angles. The small vertical scale of these phenomena means they are almost always subgrid-scale for mesoscale models and therefore must be parameterized. Unlike the prognostic subgrid-scale parameterizations that exist in models to account for the energy exchanged between model layers, optical turbulence parameterizations are diagnostic in that they need to quantify a phenomena usually occurring entirely within a model layer without feedback to the adjacent layers. A method to estimate optical turbulence by correlating the turbulence outer scale with vertical wind shear over 300 m intervals has been developed and used extensively by the Air Force Research Laboratory (AFRL) over the past 10 years. While this technique was originally developed for use with high spatial resolution radiosonde data, it has recently been adapted to run with mesoscale model data. Validation studies of the optical turbulence parameterization coupled with the Fifth Generation Penn State/ National Center for Atmospheric Research Mesoscale Model (MM5) have shown that MM5 does not predict the wind fields and associated shears to fine enough resolution to provide accurate optical turbulence predictions. In this presentation, we will present results of comparisons of optical turbulence prediction via the AFRL technique using MM5 and the Weather Research and Forecast (WRF) model (CHSSI code CWO-6) as inputs. WRF has been designed to run at much finer resolutions than MM5 and uses higher-order numerics in its dynamical equations so that there is less filtering of small-scale features. The forecasts will be validated using measured profiles of optical turbulence from two different measurement campaigns in New Mexico.

Introduction

The Airborne Laser (ABL), an element of our nation's Ballistic Missile Defense System (BMDS), will detect and destroy boosting ballistic missiles. The ABL will use lasers on board the aircraft to detect, track, and destroy the missile. The lethality laser can be affected by severe optical turbulence. Optical turbulence is the fluctuation of density in the atmosphere and its acts to defocus the laser beam which reduces its power on target and thus its effective range. In order to provide guidance to mission planners for ABL tests and eventual operations, the ABL Element Office is managing the development of an Atmospheric Decision Aid (ADA) to diagnose and forecast in real time the location and magnitude of optical turbulence in the upper troposphere and lower stratosphere.

Real-time prediction of optical turbulence is a difficult problem. Layers of intense optical turbulence, while possibly stretching hundreds of kilometers in the horizontal, tend to occur on vertical scales from a few centimeters to 100 meters. While direct numerical simulations explicitly resolving the turbulence at these resolutions is possible (i.e. Werne et al 1999) the codes involved take days to run on the most advanced high performance computers. Mesoscale numerical weather prediction models can easily run fast enough to provide forecasts in real time, however they cannot come close to resolving the turbulence at the necessary scales to be of use to the ABL ADA.

To predict optical turbulence the ADA will take mesoscale numerical weather prediction model output of volume-averaged variables of temperature, pressure, and winds from an operational mesoscale NWP model. That data in turn will be used in a parameterization relating the volume-averaged variables to optical turbulence. The parameterization of optical turbulence, defined as the refractive index structure constant (C_n^2), is based on the following equation developed by Tatarski (1961):

$$C_n^2 = 2.8\left(\frac{\left(79x10^{-6}P\right)}{T^2}\right)^2 L_o^{4/3}\left(\frac{\partial T}{\partial z}+\gamma\right)^2, \qquad (1)$$

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. We make the assumption that the value $\partial T/\partial z$ derived from the mesoscale model output is sufficient to solve the equation but in reality we realize it is most likely not resolved at a scale sufficient to fully satisfy the equation. However a bigger problem to solving the problem is to determine a value of $L_o^{4/3}$, which Tatarski (1961) refers to as the outer length or the largest scale of inertial range turbulence although Beland and Brown (1988) have questioned this definition. Dewan et al. (1993) developed a set of parameterizations for $L_0^{4/3}$ based on highly resolved vertical wind shear observations. There are two equations, one for the troposphere and one for the stratosphere:

$$L_o^{4/3} = 0.1^{4/3}x10^{(1.64+42.0xS)} \quad \text{(Troposphere)} \qquad (2)$$

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

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, 2002) first showed results of coupling mesoscale output with the Dewan parameterization of optical turbulence. Lefevre et al. (2003) and Ruggiero et al. (2004) examined the impact of varying mesoscale model resolution on the optical turbulence predictions. One of the important results from these validation tests was that increasing mesoscale model resolution beyond current operational settings did not result in the depiction of smaller scale features by the models. The model that these tests were conducted on was the Fifth Generation Penn State/National Center for Atmospheric Research Mesoscale Model (MM5). This is the current mesoscale model employed for operations by the Air Force Weather Agency (AFWA). AFWA is beginning efforts to transition to a new mesoscale model, the Weather Research and Forecast (WRF) model that was developed in part by the CHSSI program (CWO-6).

In this paper we look at the performance of MM5 and WRF relative to predicting optical turbulence using the Dewan et al (1993) parameterization. We will examine each model using data from an optical turbulence measurement campaign.

2. Mesoscale Models

2.1 MM5

MM5 is the latest version of the mesoscale model originally developed by Anthes and Warner (1978). More recent documentation on the model can be found in Grell et al. (1995) and at http://box.mmm.ucar.edu/mm5/. The model's dynamic core is non-hydrostatic and is based a set of equations for a fully compressible atmosphere in a rotating frame of reference. The prognostic variables are pressure perturbation, momentum, temperature, and five moisture variables. It uses the Arakawa and Lamb (1977) B grid type structure which permits greater efficiency in the computations on the B-grid. It was designed to run at grid spacings as small as 10 km. Advection is handled by a 2^{nd} order centered scheme. Time splitting is used computer separately the fast and slow moving waves. For slower moving waves a long time step is used with the leapfrog approach with the use of the Asselin filter. For the faster moving waves, the implicit Crank-Nicholson approach is used. Initially MM5 was designed as serial code but to take advantage of shared memory multiprocessor computers, a horizontal domain decomposition parallism using MPI was incorporated into the code (Michalakes, 1999).

2.2 WRF

The Weather Research and Forecast (WRF) model is a multi-agency collaborative effort to develop the next generation community mesoscale NWP model. Its development has been funded in part by the HPCMO's CHSSI program. The version used in this project is 1.3. It is being designed to run at horizontal grid spacings of 1-10 km. It uses 3^{rd} order accurate Runge-Kutta integration and fifth order discretization of advection. It uses the Arakawa and Lamb (1977) "C" grid. There is no explicit computational damping. The WRF code was designed to run in either serial or parallel mode with a choice of MPI and/or OpenMP. Extensive documentation on the model can be found at http://wrf-model.org/.

3. Experiment Design

Each model was run for seven different days in September 2002 corresponding to optical turbulence observations (details below). Each model was run with the same 42 vertical sigma levels and used 27 km horizontal grid spacing. The model's horizontal domain contained 118 by 118 grid points centered over Holloman AFB, NM. Each model was initialized using Global Forecast System (GFS) analyses which were at 1.0° horizontal resolution and 24 pressure levels up to 10 mb. The GFS analyses also provided the lateral boundary conditions during the model integrations. Model topography was provided from a 10 minute resolution global database. A 60 second time step was used. Each model run was initialized at 1200 UTC (0600 local).

The output from each of the mesoscale model runs where then used to compute C_n^2 using the Dewan et al. (1993) approach detailed above. To decide which whether to use (2) or (3) to compute C_n^2 the location of the tropopause was objectively computed by the method of Roe and Jasperson (1980). That method estimates the tropopause to be located at that height above 5000 m at which dt/dz exceeds –2.8 K km^{-1} for a depth of at least 1 km.

Validation of the optical turbulence forecasts was conducted using optical turbulence observations from balloon borne thermosonde measurements. Brown et al. (1982) describe the principle of the operation of the thermosonde. The thermosondes make simultaneous precise measurements of temperature at two locations separated by a horizontal distance of 1 m. Jumper and Beland (2000) explain the theory of how C_n^2 is derived from the horizontal temperature difference. The balloons carrying the thermosonde also carry a standard rawinsonde, which provides horizontal wind, temperature, moisture, and pressure measurements. All balloons were launched from Holloman AFB, MN at latitude 32.87°, longitude –106.13°, and at an altitude of 1249 m. For each day of measurements there were three or four launches spread out approximately 90 minutes apart usually beginning about 0100 UTC (1900 local). This gave the model approximately 13 hours of integration prior to the beginning of the observations. For each balloon launch data was collected up to an altitude of up to 30 km. Due to errors with the equipment not all the balloons provided usable data but each of the seven days had at least one good flight.

Using the horizontal wind data from the rawinsonde, a trajectory of the balloon flight was computed. The model data was then spatially and temporally interpolated to the balloon flight path therefore producing a model-generated profile of the thermosonde and rawinsonde data in the same format as the observed data.

4. Results

Since optical turbulence's effect on lasers is along its path, we decided to use the integrated parameter of Rytov variance as the figure of merit for validation. Rytov variance is a measure of scintillation along the beam's path and is important in affecting

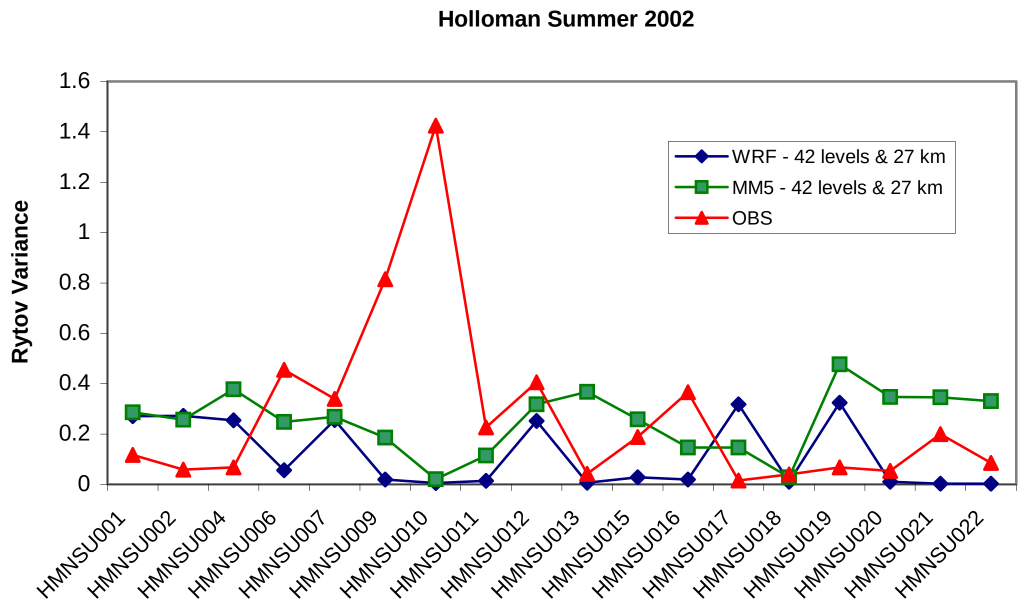

Figure 1. Rytov variance computed from observed and WRF and MM5 derived C_n^2 profiles for sample laser path for each of the balloon flights in the Holloman Summer 2002 Experiment.

ABL's performance (see Beland 1993 for more information on the Rytov variance). For this project a simulated ABL path was used. The path started at 12.5 km (MSL), had a slant range of 168.6 km, and an ending altitude at 17 km. The observed and model forecast profiles of C_n^2 were adapted to the simulated path by assuming that C_n^2 was horizontally homogeneous. While this may be a weak assumption, for the purposes of the comparison of model versus observed it does not effect the results.

Figure 1 show the Rytov variance on a balloon by balloon basis for all the good balloon flights for the observed and MM5 and WRF generated profiles. Table 1 shows the RMS and bias comparison between the two model runs. On the basis of the RMS and bias results, the MM5 generated profiles were better than those from the WRF model. Examining each individual balloon flight, the MM5 did better than WRF by close to a factor of 2 to 1. In eight of the nine cases where the observed Rytov variance exceeded that of the CLEAR1 model, the MM5 results were closer to the observed value than was WRF. It is also obvious that both model runs spectacularly missed the high Rytov variance observed with Balloon 10. This causes the overall RMS values to be quite high.

Table 1. Root-Mean-Square and bias error in Rytov calculations for WRF and MM5 derived C_n^2 profiles of sample laser path.

	WRF	MM5
RMS	0.4307	0.3632
BIAS	-0.1580	-0.0246

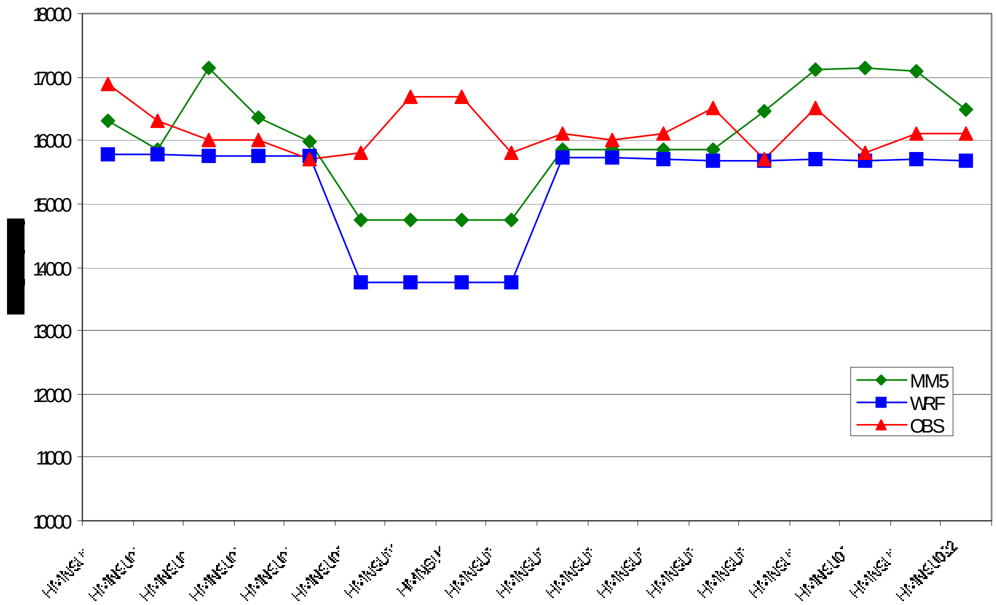

Figure 2. Tropopause heights for each of the balloon profiles for the observed and model produce profiles. The observed tropopause was determined from a subjective examination of the temperature profile. The WRF and MM5 tropopause heights were determined using the procedure of Roe and Jasperson (1980).

From the results in Table 1 it is obvious that Rytov variances computed from the WRF model shows a bias of underestimating the actual Rytov variance, while the use of MM5 data only shows a small bias. One possible source of the WRF underestimation of the Rytov variance is the temperature output, particularly in how it is used to compute the tropopause. From (2) and (3) above, for a given shear the computed C_n^2 will tend to be less in the stratosphere than the troposphere. During the time the balloon flights were carried out, the tropopause was located at an average height of 16.1 km, well within the simulated path. Figure 2 shows the tropopause location based on the observed, MM5, and WRF temperature profiles. Clearly the WRF model systematically tends to under predict the tropopause height as compared to MM5. Figure 3 shows a comparison of the temperature profiles for the observed and model profiles for one of the balloon flights. The pattern of the WRF model producing a kink in the temperature profile below that seen by MM5 and then having a warm bias in the stratospheric temperatures is seen in many of the other individual profiles.

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