Technical Support Document
August 2010

Assessment of 2007 WRF Meteorological Modeling in support of Regional Air Quality Modeling in the Ozone Transport Region (OTR)

Contributors

Gopal Sistla
Michael Ku
Winston Hao
New York State Department of Environmental Conservation
625 Broadway
Albany, NY 12233

Table of Contents

Introduction

One of the critical components in photochemical modeling is the development of meteorological data that are necessary to simulate air pollutant fields. As part of this effort and based upon the prior experience, the Modeling Committee of the Ozone Transport Commission (OTC) decided on the use of the Weather Research Forecast (WRF) model which has superseded MM5, the NCAR-Penn State model that was used in similar efforts in the past.

Since the photochemical modeling effort encompasses continental United States, initial efforts were coordinated with other multi-state organizations in the development of a protocol, bench-mark testing to provide exchange of information and to achieve a degree of consistency between individual efforts in the development of the meteorological fields.

The photochemical modeling effort is aimed at addressing the 24-hr $PM_{2.5}$ and 8-hr ozone NAAQS issues within the Ozone Transport Region (OTR), and based upon the ambient measurements from 2005 to 2008, the modeling committee identified 2007 as the year for which meteorology was found to be conducive both for ozone and $PM_{2.5}$ (Downs 2009). There was concurrence from the other regional planning organizations for the use of 2007 as the meteorological year, thus providing a common basis and exchange of information for use in photochemical modeling. Also, embedded in this process was the concept that the selected year is in agreement with the state periodic inventory cycle to the extent possible.

Based on several years of photochemical modeling, one can say intuitively, that a good meteorological model performance will yield more confidence in predictions of air quality model. While there are no set standards on assessment of simulation of meteorological models, Dolwick (2005), suggested two types of evaluation be performed before the simulated meteorological fields are utilized in air quality work. One is the operational evaluation consisting of comparing the model against observed data on a pair-wise basis for specific meteorological parameters such as wind speed, wind direction, temperature, and mixing ratio. The second evaluation is the phenomenological assessment aimed at examination of the meteorological features such as the nocturnal low level jets (NLLJ) that are conceptually described as being responsible for the regional transport of ozone and its precursors in the northeast corridor of the modeling domain.

Methodology

The approach used in this effort is to establish a framework to exercise WRF, given that several competing options are available. To this end, a series of WRF simulations were performed under different options and compared with observed datum for two 20 day periods, one in summer and one in winter that were associated with high pollutant levels over the eastern United States. Based on comparison of the simulated and observed fields, a final model configuration was developed and utilized to generate the necessary meteorological fields for 2007.

A summary report on the setup and development of the model configuration is available elsewhere (Baker 2010). Briefly, the adopted vertical layer structure included a total of 34 layers with the lowest level at 20 m and extending up to about 18 km with the simulation conducted in a nested-mode at 36 and 12km horizontal grid spacing. The model domain is displayed in Figure 1, and Table 1 lists the vertical heights.

The annual production simulation was a shared exercise --- the input files were prepared by the University of Maryland (UMD) and the simulations were performed both at UMD and NYSDEC-- which enabled to meet the schedule of completing the meteorological data simulation in a timely manner. The data sets are archived and are made available on request. The operational details are described in the benchmark report (Baker 2010) and were adhered to perform the annual simulation as well.

Analysis

Even though the WRF simulation utilizes four dimensional data assimilation (4-DDA) in which measured data are used, it is customary to compare the simulated fields to the measured data. In the current analysis besides this traditional step, comparison is also made to measurements taken at CASTNet sites and to the available wind profiler data, precipitation, cloud cover fraction and estimates of PBL height.

The analysis focused both on the entire domain and on the sub-region of interest- the Mid Atlantic Northeast Visibility Union (MANE-VU) plus Virginia. The statistics are reported for these two geographical regions for surface measurements of temperature, wind speed, direction, and mixing ratio. A modified version of the METSTAT package (Environ 2010) had been adopted to perform the statistical calculations, and was further modified to calculate additional statistics and extended to include monthly statistics.

The domain-wide statistical information provides insight into the model performance on an overall basis, while the assessment of the sub-region provides model's ability at a smaller spatial scale, that it is not masked by improved level of performance in the other areas. The analysis reported here is limited to the 12 km portion of the modeling domain, even though data are available for the continental US at the spatial resolution of 36 km.

Comparison with TDL data

Even though the TDL data had been utilized in the 4-DDA process, Table 2a, 2b and 2c lists the monthly statistics for wind speed, temperature and mixing ratio, respectively, for the 12 km domain, and in Table 3a, 3b and 3c are listed the monthly statistics for wind speed, temperature and mixing ratio, respectively, for the MANE-VU region. Since the observed data had been used in the model 4-DDA process, there is no recommended pass/fail performance standard, and the assessment only provides a general overall confidence in the simulated meteorological data. Appendix A provides the plots showing the hourly simulated and measured data averaged over the TDL sites within the 12 km domain and the MANEVU sub-regions for the mean, and bias estimated as the predicted minus the measured.

Wind Speed

Statistical analysis of the wind speed is presented in Tables 2a and 3a for the domain and MANE-VU region, respectively. In developing these statistics all measured data were included with the observed calm wind conditions that were often measured a value of 3 knots or less for wind speed. This inclusion of the calm winds is intended to provide a better understanding of the WRF simulation as calm conditions are often found to occur during summer months that are prone to yield high pollution levels. Clearly examination of the data listed in Tables 2a and 3a indicate that the summer months of May, June, July and August tend to have higher normalized mean bias than the remainder months in both cases. However no such clear distinction was evident for the other statistical metrics. The fact that this feature is also found with CASTNet data, even though these data were not part of the 4DDA suggests that there is a need to for further examination.

Examining the hourly data of the measured and simulated wind speed averaged over the domain and over the MANE-VU region along with the corresponding bias (see Appendix A), it can be stated that WRF tends to underpredict the daytime peak and overpredict the night time low wind speed with bias in the ±1 m/s range for the non-summer months. The differences are more pronounced for the summer months, with the bias reaching -2 m s^{-1} or more for the TDL data over the domain, indicating the need for further detailed assessment of the WRF system for this time period.

Temperature

Overall monthly statistical estimates are listed in Tables 2b and 3b for the domain and MANE-VU region, respectively. Three statistical parameters, mean bias, normalized mean bias and mean fractional bias are found to be generally higher for the months of May, June, July, and August both for the domain and for the MANE-VU region, even though such a trend was not evident from the listed monthly correlation coefficients. This feature is similar to that of wind speed for the summer months, indicating the need for further assessment of the WRF system. Appendix A displays the plots for the modeling domain and the MANE-VU region the averaged hourly temperature and mean bias.

Mixing Ratio

Overall monthly statistical estimates are listed in Tables 2c and 3c for the domain and MANE-VU region, respectively. In general the model-based estimates are higher than measured for the months of May through October over the domain as well as the MANE-VU region. However the magnitude of the monthly differences are found to be much higher in the MANE-VU region than over the entire modeling domain, suggesting regional differences in the model performance for this variable. This is much more evident from the listed monthly correlation coefficients for the domain and the MANE-VU region. While the magnitude of the correlation coefficient is in the range of 0.68 to 0.91 for the domain the range exhibited for the MANE-VU region are in the range of 0.30 to 0.65. In particular the correlation listed for the MANE-VU region for the summer months of June, July and August is in the range of 0.29 to 0.30 compared to 0.66 to 0.68 for the overall domain. Appendix A displays the plots for the modeling domain and the MANE-VU region the averaged hourly mixing ratio and mean bias.

Wind Direction

While no statistical estimates were developed for this variable, Appendix A displays the averaged hourly comparison of the reported wind direction to that simulated by WRF for the domain and for the MANE-VU region along with the mean bias. Visual examination of the bias plots indicates an average bias of ±5º and ±10º over the modeling domain and MANE-VU region, respectively, with tendency to be slightly higher during the summer months of June and July.

Correlation Coefficient

In Appendix A, the hourly correlation coefficient is displayed for the domain and the MANE-VU region for the three meteorological parameters – wind speed, temperature, and mixing ratio – for the months of April through October, which is identified as the ozone season. This is intended to provide the temporal variation of the correlation coefficient on a daily basis over the region based upon the TDL data. In April, often the day to day correlation for mixing ratio shows significant variation, while the range appears to be more tempered for temperature and the wind speed falling in between them. However, this is in contrast to the display in June where the wind speed appears to have a lower level of correlation compared to the mixing ratio or temperature for both domains.

Comparison with CASTNet Data

As noted before the CASTNet measurements were not part of the 4-DDA, and as such a comparison between these data and simulation would provide for an independent assessment of the WRF simulation. Spatially the CASTNet monitoring network is not as widespread as TDL and therefore no geographic delineation was made in these comparisons. The analysis is for temperature and wind speed only as there is no mixing ratio data available for the CASTNet and the statistical results are listed in Tables 4a and 4b. In Appendix A are the comparisons between these data on an hourly basis displayed by monthly blocks. Also included in the display is the comparison between simulated and measured wind direction by day of the month.

Wind Speed

Examination of the statistical parameters listed by month in Table 4a indicates that correlation coefficient is comparatively low for June, July and August, a result similar to the TDL data. This is also evident from the normalized mean bias and mean fractional bias estimates.

Temperature

Table 4b lists the statistical estimates for the comparison of temperature on a monthly basis. In general, the model estimates of mean bias on a monthly basis are below a degree or so, which are in line with the estimates of correlation coefficient.

These results suggest that the WRF simulation can be considered a fair representation of the meteorological conditions, with the need for assessment of the wind speed particularly during the summer months which are often associated with a large number of hours with calm conditions.

Other Comparisons

In addition to the above, we also examined the model simulations for selected locations where wind profiler data was available. In addition we also made comparisons of cloud fraction and precipitation in this assessment.

Wind profilers

Hourly wind profiler data was acquired for 5 selected sites – Charlotte, NC; Raleigh, NC; Baltimore, MD; Rutgers, NJ; and Stowe, MA. Figure 2 displays the approximate locations of these 5 sites. The intent of this analysis is to assess the ability of the WRF simulation in capturing the nocturnal low level jet (NLLJ), which has been suggested as the means by which air pollutants are transported downwind and provide for potential increases in ozone levels the next day through mixing processes associated with the rise of the morning boundary layer.

Based on the ambient measurements, an example day August 3, 2007 was selected since it has recorded some of the high ozone levels over the region of interest. Figures 3 through 8 display the observed and simulated hourly wind speeds as a function of elevation at these 5 locations. In general the WRF captured the pattern of the wind field as measured by the profiler. An example is the location and the time of the occurrence of the NLLJ as well as the shift in the wind field from a more structure into more convective condition around 15Z. However, the WRF showed much weaker NLLJ strength than observed, especially at the Rutgers, NJ site (Figure 5). No quantitative comparisons are made due to differences in the grid resolution between WRF and wind profiler observed data, but on a qualitative basis there seems to be fair agreement between the WRF fields and the measurements based on the wind profiler network.

To get a better appreciation of these qualitative comparisons, the wind profiler data are displayed every 3 hours for August 3, 2007 at these 5 locations in Figures 9 to 13, respectively. For example at the Baltimore, MD the measured and the simulated WRF profiles show good agreement as the day progresses from 00Z to 15Z, and starts to deviate for the remainder hours (see Figure 8). Similar inferences can be drawn for other stations, suggesting that the WRF meteorological fields simulated are in fair agreement with the measured data.

Cloud Fraction

Another assessment that was performed is a comparison of the cloud fraction estimated by MCIP 3.5 beta version based on WRF simulation against the cloud fraction derived from the GOES-12 satellite images. This satellite image derived product, surface radiation budget (SRB), is available from the Department of Atmospheric and Oceanic Science (http://metosrv2.umd.edu/~srb/gcip/webgcip.htm) at a horizontal grid spacing of 0.5º latitude and longitude on hourly basis for an area bounded by 70 º -125 º W longitude and 25 º -50 º N latitude. The satellite based cloud data were processed through interpolation and map projection conversion to match the MCIP output at 12 km. The WRF data are processed through MCIP (meteorology and chemistry interface processor) that adapts the WRF data to the photochemical grid model. Figures 14 to16 display the SRB cloud and MCIP cloud for 17Z for August 1 to 3, respectively. Visual examination of these Figures suggests that the WRF and SRB estimates of cloud fraction shown fair to reasonable agreement in spatial distribution or pattern, although the intensity of the SRB cloud fraction may be a reflection of the coarse grid used in obtaining those data compared to that based on WRF.

Precipitation

We also examined the precipitation estimates based on WRF with stage 4 precipitation data (http://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/stage4), in terms of monthly accumulation. As an example the precipitation estimates from the model and measured for the months of February and August are displayed in Figures 17 and 18, respectively. Other monthly plots of precipitation are shown in Appendix A. Qualitative examination of these plots indicates that on an overall basis there is good spatial agreement between the model and measured data in terms of the pattern, although there is considerable structure in the measured data. It should be noted that in 2007 there were a total of 15 named tropical storms starting in early May through mid December with many of the storm tracks (see Figure 19) over Central America and glancing off of the US mainland (Weather Underground 2010). Table 5 lists the named storms along with their intensity scale. There were only two category 5 storms with one of the Dean occurring in August with higher degree of precipitation not seen from the model simulation. The other Category 5 storm is Felix, with a trajectory path towards Central America and well outside the modeling domain.

PBL Height

One of the variables that is not directly measured is the planetary boundary layer (PBL) height which is a critical parameter in air quality simulations. However, there are indirect methods to provide estimates of the PBL height, which can then be compared to those estimated by WRF. To this end we utilized lidar-based observations made at City College of New York (CCNY) in New York City (Gross, 2010). For the lidar-based observation the PBL height is defined as the height where the peak lidar refraction occurs. Due to measurement limitations, only daytime PBL heights from lidar-based measurements are available for comparison. Since the WRF data are gridded in the horizontal at 12 km, the cell in which CCNY located is selected for comparison with the lidar PBL height data. Figures 20 a, b, and c show the scatter plot comparison of all available data as well as only the cold months and warm months, respectively. For the overall data (Figure 20a), the correlation coefficient is 0.64, which can be considered to be a fair agreement between these estimates of PBL height. However, WRF is found to be underpredicting mainly in the cold season (see Figure 20b) but with a higher correlation coefficient of 0.70 compared to the summer season (see Figure 20c) with a correlation coefficient of 0.59 and more scatter in the data. Clearly, a more systematic assessment needs to be undertaken to get a better understanding of these comparisons and also no major conclusions can be drawn as this is only one location in a large modeling domain.

Conclusions

An assessment of the 2007 WRF-based simulation of meteorological data with measured data that is either used in the 4-DDA or independent data indicates that the simulated fields are in fair agreement with the measured data. Also, examination of the simulated cloud cover, precipitation and PBL heights with other independent data shows fair to good agreement, suggesting the credibility of the simulation for its use in air quality applications.

Reference

Baker, D. (2010) Sensitivity Testing of WRF Physics Parameterizations for Meteorological Modeling in Support of Regional SIP Air Quality Modeling in the OTR. Available at www.otc.org/

Dolwick, P. (2005) Meteorological Modeling: Model Performance Evaluation, presented at the 3rd PM/RH/O3 Modeling Workshop May 20, 2005

Downs, T. (2009) See at http://www.maine.gov/dep/ftp/OTC_MOD_COM/

Gross, B. (2010) LIDAR data collected at CCNY location (Personal communication)

METSTAT (2010) Available at www.camx.com

Weather Underground (2010) http://www.wunderground.com/hurricane/at2007.asp