Developments in Environmental Science, Volume 6
C. Borrego and E. Renner (Editors)

ISSN: 1474-8177/DOI:10.1016/S1474-8177(07)06214-6

Chapter 2.14

Forecasting ozone and $PM_{2.5}$ in southeastern U.S.

M. Talat Odman, Yongtao Hu, Michael E. Chang and Armistead G. Russell

1. Introduction

QA :1

There is an increasing interest in day-to-day variation of air quality. As the public is becoming more health conscious, air pollution is being perceived as a serious problem. In response, local authorities are looking for short-term management strategies to avoid bad pollution episodes. The press and the media are beginning to carry air quality forecasts as routine extensions of weather forecasts. These air quality forecasts are produced using various techniques. Persistence, climatology, statistical regression, close neighbor, and decision tree models are among the most popular methods. More recently, three-dimensional (3-D) air quality models made their entrance into the forecasting world.

Air quality forecasting in Atlanta, Georgia started with the 1996 Olympic Games and continues ever since (Cardelino et al., 2001). A panel of experts gets together every day and issues an ozone forecast for the next day. One of the outcomes of this forecast is “ozone alerts” that are displayed as electronic signs on the highways. These signs urge the drivers to telecommute or to refuel after sunset whenever an “ozone day” is imminent.

3-D modeling has been one of the methods used in Atlanta forecasts ever since the beginning (Chang and Cardelino, 2000). The Urban Airshed Model (UAM) is run daily using diagnostic meteorology. However, the emissions data used in this operation have not been updated in recent years, and the models and methods used do not reflect the current state-of-the-science. Among the other 3-D forecasting operations, the only one that covers the southeastern U.S. is the NOAA/EPA national forecast (Eder et al., 2006). The models used in this operation consist of the Eta-

CMAQ modeling system with 12-km resolution (Otte et al., 2005) over the eastern U.S.

Last year, $PM_{2.5}$ forecasting started in Atlanta in addition to ozone. Also, the forecasts are being expanded to other cities in Georgia (e.g., to Macon which is 135 km south-southeast of Atlanta). We have been asked to develop a state-of-the-science 3-D modeling system that can forecast ozone and $PM_{2.5}$ over most of Georgia. This paper describes the initial version of the forecasting system we developed and gives an overview of our operation which started on May 1, 2006.

2. Forecasting system and its operation

Our goal is to provide accurate, "fine-scale," local air quality forecasts sufficiently in advance that the public and local authorities can take necessary actions. NOAA/EPA's target is to issue nationwide 2-day forecasts with 2.5-km resolution in 10 years (Davidson et al., 2005). On a local scale, we want to get there, and go beyond, much faster. In particular, our objective is to forecast longer periods with finer resolution (~1 km). Also, in addition to air quality, we want to be able to forecast the effectiveness of local control strategies in order to avoid pollution episodes.

We use the Weather Research and Forecasting (WRF) model for the forecasting of meteorology (http://wrf-model.org/). We initialize WRF with 84-h forecasts from the North American Mesoscale (NAM; formerly known as Eta) model (http://nomads.ncdc.noaa.gov/). We utilize the Sparse Matrix Operator Kernel Emissions (SMOKE) model for emissions (CEMPD, 2004). Finally, we use the Community Multiscale Air Quality (CMAQ) model for chemistry and transport (Byun and Ching, 1999). We are currently using the standard version 4.5 of CMAQ but to achieve our objectives we will soon incorporate the following model extensions we developed in recent years: (1) the time-saving variable step algorithm (Odman and Hu, 2007), (2) the direct decoupled method that allows calculation of emission sensitivities along with pollutant concentrations (Hakami et al., 2003), and (3) the adaptive grid algorithm that allows very high (~100 m) resolution (Odman et al., 2002).

The modeling domain is covered with three nested grids of different resolutions: (1) a 36-km grid (72 × 72) over the eastern U.S., (2) a 12-km grid (72 × 72) over most of the southeast, and (3) a 4-km grid (99 × 78) over Georgia and portions of neighboring states. The horizontal domains for WRF are slightly larger than those used in CMAQ. Also, while 34 vertical layers are used in WRF, there are only 13 unequally spaced vertical layers in CMAQ.

In order to issue tomorrow's forecast by 10 a.m. today, the operation must start $2\frac{1}{2}$ days in advance (e.g., Wednesday's forecast by Sunday night). We first simulate a 3-day period over the 36-km grid using 00Z NAM data, initial conditions from the previous cycle (i.e., warm start), and "clean" boundary conditions. Then we simulate $2\frac{1}{2}$ days over the 12-km grid using 12Z NAM data and initial/boundary conditions from the 36-km grid. Finally, we simulate 24 h over the 4-km grid using 12Z NAM data and initial/boundary conditions from the 12-km grid. The operation is mostly automated but it still requires about 1 h of human interaction per day. A total of 6 CPUs are employed.

Emission inputs must be up-to-date for accurate forecasts. We projected the National Emissions Inventory (NEI) for the year 2002–2006 using growth and control factors. For example, we used the Economic Growth Analysis System (EGAS) model to project the major power plant emissions and applied controls from NO_x State Implementation Plans. We use monthly averaged data for major point sources and wild-land fires. We forecast mobile emissions by using emission factors based on forecasted daily average temperatures. Finally, we forecast biogenic emissions using summertime leaf indexes.

3. Forecasting products

The current products are the 24-h ozone and $PM_{2.5}$ forecasts issued once per day. They are posted to a web site (http://www.ce.gatech.edu/research/forecast/) as soon as they become available. The forecast for Atlanta is summarized in terms of the peak 1-h ozone and $PM_{2.5}$ values, their location, and time of occurrence. For example, "Peak 1-h ozone tomorrow will be 65 ppb at Gwinnett at 2 p.m." In addition to tomorrow's forecast, today's forecast remains posted until tomorrow. Finally, there is an evaluation for yesterday's forecast. It compares the value, location, and time of the forecasted peak ozone and $PM_{2.5}$ to the value, location, and time of the observed peaks. For example, "Peak 1-h ozone was predicted to be 72 ppb at Conyers at 4 p.m. The observed peak value was 66 ppb at Conyers at 4 p.m." In this example, while the location and time of the peak was forecasted accurately the value was overestimated by 9%.

Graphical products include charts showing time series of 1-h ozone and $PM_{2.5}$ values at 11 monitoring locations in metropolitan Atlanta and several other cities in Georgia. These charts display the forecasts from the 4- and 12-km grids. For evaluation purposes, the observations are also plotted on the same charts as soon as they become available. Also, every day, the correlation between the predictions and observations is evaluated by means of scatter plots of all 1-h values at all sites. Finally, ozone maps are also available to compare our forecast on the 12-km grid visually to the NOAA/EPA forecast posted on the NOAA website (http://www.nws.noaa.gov/aq/).

4. Operational evaluation

Atlanta's ozone forecasting record from 2000 to 2004 is quite impressive. 577 days were forecasted correctly as non-events and 94 days as ozone days. There were 63 false alarms and 31 misses. Since our 3-D forecasting operation has a very short history (only 10 days at the time of this presentation) and no bad air quality days occurred up to this point, we will not attempt to calculate similar statistics. Instead, we will present more detailed evaluations.

The forecasted 1-h average ozone and $PM_{2.5}$ concentrations are compared with the observations published the next day by the Ambient Monitoring Program of the Georgia Department of Natural Resources (http://www.air.dnr.state.ga.us/amp/). Figure 1 shows such a comparison at all the monitoring locations in Metro Atlanta for all the hours on May 12, 2006. The bias in ozone is in the form of overestimations for ozone concentrations below 20 ppb. Most of these are nighttime values at some specific stations. These locations are probably under the influence of NO_x titration that the model cannot simulate due to insufficient resolution and/or uncertainties in land use and emissions data. $PM_{2.5}$ concentrations are mostly overestimated below $5\,\mu g\,m^{-3}$ and generally underestimated above that value.

The forecasts are generally accurate but occasionally they fail to capture the temporal variation of pollution levels. For example, the forecasted ozone for Conyers on May 6, 2006 was in near perfect agreement with observations (Fig. 2). The fact that the 4-km forecast is more accurate than the 12-km forecast is encouraging for the pursuit of higher resolution. While May 6 had perfect conditions for ozone forecasting (clear and sunny), May 4 presented many challenges: there were scattered afternoon thundershowers throughout Atlanta. This led to the suppression of peaking afternoon ozone concentrations. Two such events can be seen at Douglasville's ozone observations in Fig. 2: one at 16 EDT and another at 18 EDT. Thundershowers are very difficult to forecast and they were completely missed in this case. The forecasted ozone remained flat due to cloud cover but no scavenging was predicted.

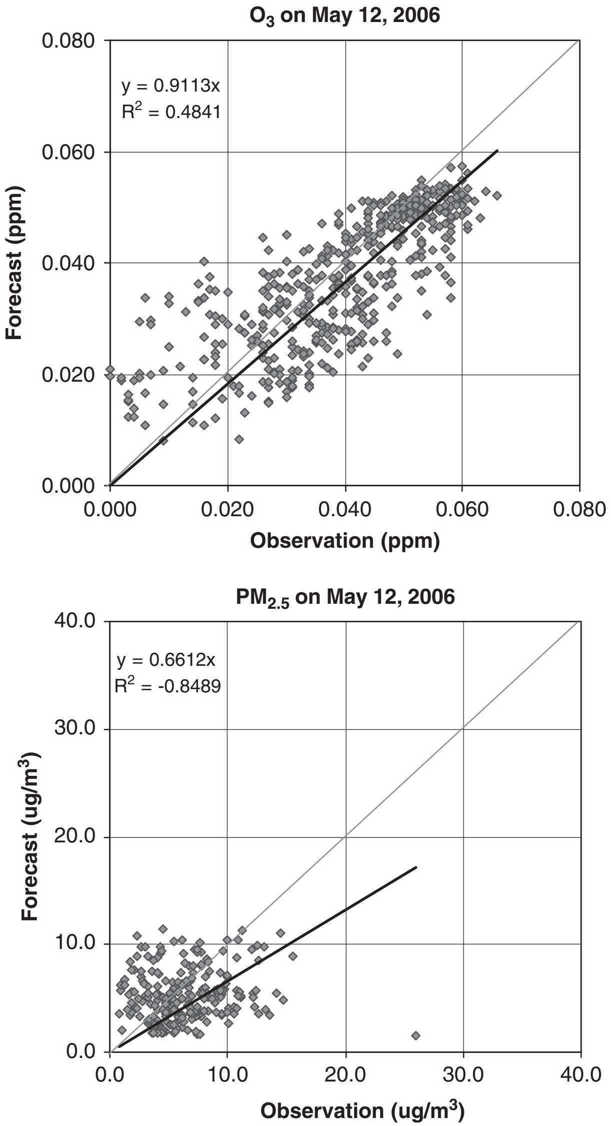

Figure 1. Comparison of forecasted concentrations to observations on May 12, 2006: ozone (top) and $PM_{2.5}$ (bottom).

Figure 3 shows good agreement between the temporal variations of observed and predicted $PM_{2.5}$ at South Dekalb on May 5. The peaks during morning rush hours, early afternoon, and late evening are all

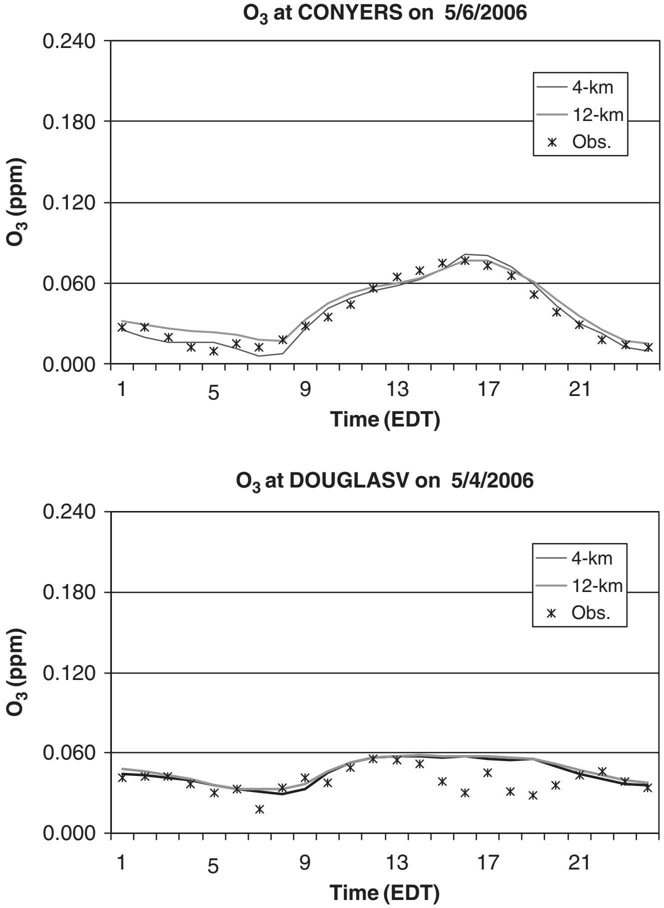

Figure 2. Good and poor ozone forecasts. May 6, 2006 was a sunny day and ozone was predicted almost perfectly at Conyers, with slightly better accuracy over the 4-km grid (top). Scattered thundershowers throughout the afternoon on May 4, 2006 were hard to predict leading to poor ozone predictions at Douglasville (bottom).

forecasted though their levels are slightly off. In this case, there is no clear indication that the 4-km grid is leading to a better forecast than the 12-km grid. However, predicting $PM_{2.5}$ at Newnan on May 4 was very challenging for the models. There were very strong variations in $PM_{2.5}$ throughout the day. Once again, the sudden drops in the afternoon are due to thundershowers that were not predicted. But the level of early afternoon and evening peaks are severely underestimated. This suggests

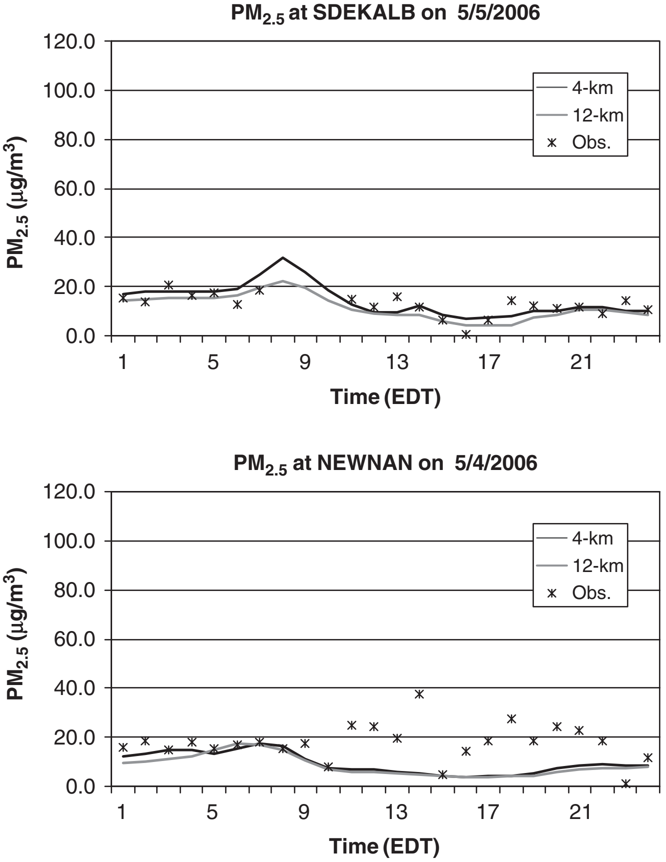

Figure 3. Good and poor $PM_{2.5}$ forecasts. May 5, 2006 was a sunny day and $PM_{2.5}$ was predicted almost perfectly at South Dekalb (top). Scattered thundershowers throughout the afternoon on May 4, 2006 as well as some local emission events led to a poor $PM_{2.5}$ forecast at Newnan (bottom).

that there might be some local emission events leading to these peaks but the models are unable to capture these events.

5. Conclusions and future work

A "fine-scale" forecasting operation using 3-D models started in Georgia on May 1, 2006. Forecasts were issued on time every day since May 3; there were no bad air quality days so far (as of May 12, 2006). Ozone forecasts are generally accurate. The only bias seems to be the nighttime overestimations at some stations. The peak error is 10–20%. The correlation between predictions and observations is fairly good: R^2 is around 0.6 but lower on some days. The diurnal variations of ozone are captured at many sites.

$PM_{2.5}$ is harder to forecast than ozone and it is generally underestimated. The peak error is 20–40%. The correlation between predictions and observations is not very strong: R^2 is less than 0.4 on many days. The morning peaks are generally predicted at the right level and time but afternoon and evening peaks are generally underestimated and some are completely missed.

We will continue the operation until September 30, 2006 and then conduct a thorough evaluation of the summertime forecasts. We will improve the modeling system based on identified weaknesses. Our goals for next year are to extend the domain of coverage, increase the resolution, elongate the forecasting period, issue daily updates, and improve the accuracy. Our longer-term goals are to link the forecast to health-effect studies such as investigating the impacts on asthmatic children (i.e., whether the forecasts improve the quality of their life) and conducting long-term exposure studies for which we are archiving our data. Another goal is to simultaneously forecast the impacts of predetermined short-term local control strategies in order to avoid imminent pollution episodes.

Discussion

E. Genikhovich:	In Russia, we have a long-lasting practice of issuing the air pollution forecasts and applying them to short-term emission control programs. If such a program has started, the measured concentrations of atmospheric pollutants influenced by reduction of corresponding emissions are not used for evaluation of the forecast score. There are other ways to do it, in particular related to upper percentiles of annual PDF of concentrations.
M.T. Odman:	Our operation is fairly new and we can certainly benefit from your experience. One of our goals is to forecast the sensitivities to emission reductions simultaneously with ozone and $PM_{2.5}$ concentrations. The high-order direct decoupled method that we

developed (Hakami et al., 2003) allows us to compute these sensitivities very accurately. If our sensitivity forecast is used by the local authorities and some local short-term control programs are activated on time to avoid pollution episodes, we would have achieved our objective (notwithstanding the implications of issuing a false alarm). Afterwards, when the forecast is being evaluated, we can use the forecasted sensitivity information along with the actual emission controls that took place to modify our original air quality forecast. This would be the best correction for the feedback, which alters the original forecast. In an ideal world, if the authorities inform us of their action plan on time, we can apply the necessary correction to our forecast before broadcasting it to the public (and hopefully avoid false alarms).

J.W. Kaminski: How long is a meteorological forecast? Would you consider a 3-day meteorological forecast to be too long?

M.T. Odman: The current length of the meteorological forecast is 3 days (plus 5 h, which is the local time difference from UTC). This, of course, is a fairly long forecast to be accurate under rapidly changing meteorological conditions. We are planning several new measures for next year, which will reduce the operation time such that a 2-day meteorological forecast can be used instead. This is expected to improve the accuracy of our air quality forecasts significantly.

ACKNOWLEDGMENT

This work is supported by the Georgia Department of Natural Resources.

REFERENCES

Byun, D., Ching, J. (Eds.), 1999. Science algorithms of the EPA Models-3 community multiscale air quality system. U.S. Environmental Protection Agency.

Cardelino, C., Chang, M., St John, J., Murphey, B., Cordle, J., Ballagas, R., Patterson, L., Powell, K., Stogner, J., Zimmer-Dauphinee, S., 2001. Ozone predictions in Atlanta, Georgia: Analysis of the 1999 ozone season. J. Air Waste Manage. Assoc. 51, 1227–1236.

CEMPD: SMOKE V2.1 User's Manual. [Available online from http://cf.unc.edu/cep/empd/products/smoke/version2.1/manual.pdf].

Chang, M., Cardelino, C., 2000. Application of the urban airshed model to forecasting next-day peak ozone concentrations in Atlanta, Georgia. J. Air Waste Manage. Assoc. 50, 2010–2024.

Davidson, P., Seaman, N., McQueen, J., Mathur, R., Wayland, R., 2005. National air quality forecasting capability: Initial operational capability. NOAA presentation.

Eder, B., Kang, D., Mathur, R., Yu, S., Schere, K., 2006. An operational evaluation of the Eta-CMAQ air quality forecast model. Atmos. Environ. 40, 4894–4905.

Hakami, A., Odman, M.T., Russell, A.G., 2003. High-order, direct sensitivity analysis of multidimensional air quality models. Environ. Sci. Technol. 37, 2442–2452.

Odman, M.T., Hu, Y., 2007. A variable time-step algorithm for air quality models. J. Geophys. Res. Atmos. (in press).

QA :2

Odman, M.T., Khan, M.N., Srivastava, R.K., McRae, D.S., 2002. Initial application of the adaptive grid air pollution model. In: Borrego, C., Schayes, G. (Eds.), Air Pollution Modeling and its Application XV: Proceedings of the 25th NATO/CCMS International Technical Meeting on Air Pollution Modelling and Its Application held in Louvain-la-Neuve, Belgium, October 15–19, 2001. Kluwer Academic/Plenum Publishers, New York, pp. 319–328.

Otte, T., Pouliot, G., Pleim, J., Young, J., Schere, K., Wong, D., Lee, P., Tsidulko, M., McQueen, J., Davidson, P., Mathur, R., Chuang, H., DiMego, G., Seaman, N., 2005. Linking the Eta model with the community multiscale air quality (CMAQ) modeling system to build a national air quality forecasting system. Weather Forecast. 20, 367–384.

AUTHOR QUERY FORM

ELSEVIER	**Book: DENS-V006** **Chapter: 6214**	**Please eail or fax your responses and any corrections to:** **Eail:** **Fax:**

Dear Author,

During the preparation of your manuscript for typesetting, some questions may have arisen. These are listed below. Please check your typeset proof carefully and mark any corrections in the margin of the proof or compile them as a separate list*.

Disk use
Sometimes we are unable to process the electronic file of your article and/or artwork. If this is the case, we have proceeded by:
☐ Scanning (parts of) your article ☐ Rekeying (parts of) your article
☐ Scanning the artwork

Bibliography
If discrepancies were noted between the literature list and the text references, the following may apply:

☐ The references listed below were noted in the text but appear to be missing from your literature list. Please complete the list or remove the references from the text.
☐ *Uncited references:* This section comprises references that occur in the reference list but not in the body of the text. Please position each reference in the text or delete it. Any reference not dealt with will be retained inthis section

Queries and/or remarks

Location in Article	Query / remark	Response
AU:1	Please provide an abstract for the chapter.	
AU:2	Please provide complete details of the reference (Odman and Hu, 2007).	