2009 AMAD Peer Review: Session 1
Model Development and Diagnostic Testing

Planetary Boundary Layer Modeling for Meteorology and Air Quality

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Environmental Issue

Air quality assessment and mitigation requires the use of credible air quality modeling tools. An air quality modeling system includes emissions modeling, meteorology modeling, and chemistry and transport modeling. Sub-grid-scale turbulent vertical transport models, which are commonly called planetary boundary layer (PBL) models, are required components of regional and mesoscale Eulerian Grid models that are unable to resolve turbulent scales of motion. Mischaracterization of the depth and evolution of the PBL and intensity of turbulent transport leads to severe errors in both meteorological and chemical simulations. PBL processes strongly affect temperature, humidity, clouds, and wind profiles. Similarly, PBL processes greatly influence chemical concentrations and reactions within the lowest few kilometers of the atmosphere. Therefore, accurate representation of the diurnal evolution of PBL depth and turbulent transport within the PBL are critically important in both the meteorological and chemical parts of the modeling system. **Since the bulk of air pollution is emitted into the lowest atmospheric layers, air quality model predictions and model response to emission reductions are very sensitive to the model's characterization of PBL processes.**

Research Objectives

The objective of this research is to develop and test a model of the PBL for use in both meteorology and air quality models. The requirements of this PBL model are that it produce realistic fluxes and profiles in the PBL, produce accurate PBL height simulations, be equally applicable to meteorological and chemical species, be appropriate for all stability conditions without discontinuities, and be computationally efficient.

Background

Turbulent transport in the convective boundary layer (CBL), as commonly exists over land during daytime, is particularly difficult to model because the turbulence is sub-grid-scale in the horizontal (when Dx > 1 km) while the vertical scale of convective eddies is typically larger than the vertical grid spacing. Thus, the assumption of flux-gradient proportionality, as for eddy diffusion models, is not appropriate for CBLs. A simple solution to this problem is to add a gradient adjustment term to the eddy diffusion equation as is often done for heat fluxes in meteorology models. However, this is not a general solution to all modeled parameters. Another solution is to consider direct transport across non-adjacent vertical grid cells to simulate the effects of large convective eddies that span multiple layers. This type of model is often called "transilient" or "non-local closure" (e.g. Stull 1984). The Asymmetric Convective Model (ACM) is a very simple and efficient transilient model designed for vertical transport in the CBL (Pleim and Chang 1992). Version 2 of the ACM (ACM2) combines the simple non-local closure scheme with eddy diffusion (Pleim 2007a&b) (Figure 1).

Modeling Approach

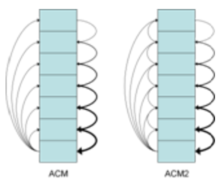

Figure 1. Schematic of transport among model layers for ACM and ACM2

The ACM2 model was recently developed for use in both meteorology and chemical transport models to realistically simulate vertical transport of any quantity both within and above the PBL in all stability conditions. The non-local component is used only within the CBL and increases in strength with increasing convective instability up to a maximum of about 50% of the total heat flux at the lowest model interface.

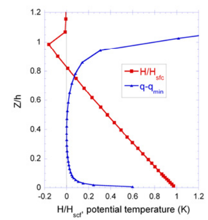

Figure 2. Vertical profile of potential temperature and heat flux simulated by ACM2 for convectively unstable conditions.

An important demonstration that the ACM2 appropriately partitions local and non-local fluxes is shown in Figure 2. Note that the heat flux is positive (upward) for the lower 80% of the CBL while the potential temperature gradient is decreasing with height only in the lowest 25% of the CBL. Such counter gradient flux is not possible using simple eddy diffusion models. These results agree quite closely with LES results as shown by Stevens (2000).

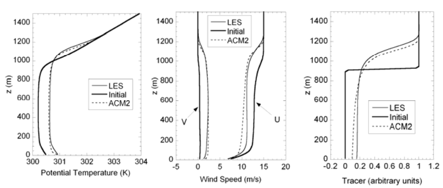

Figure 3 shows the ACM2 model compared to LES for an experiment with constant surface heat flux (Ayotte et al 1996). After about 10τ, where τ is the convective turn-over time ($\tau = z_i/w_*$), after initialization the ACM2 potential temperature profile compares almost exactly with the LES result. The *u* and *v* wind components also compare well although the ACM2 *u* profile shows a bit more gradient in the lower half of the PBL. The ACM2 tracer profile similarly shows slightly too much gradient in the lower layers. These deficiencies probably result from the simplified structure of the transilient matrix that neglects mid-sized eddies that are not attached to the surface layer. Such small discrepancies, however, should not be relevant for application in mesoscale models

Results and Discussion

The ACM2 has been incorporated in the Weather Research and Forecasting (WRFv3) mesoscale meteorology model and the Community Multiscale Air Quality (CMAQ) model. The Pleim-Xiu land surface model (Xiu and Pleim 2001 and Pleim and Xiu 2003) and the Pleim surface layer scheme (Pleim 2006) have also been added to WRFv3. The WRF and CMAQ models were run with 12 km grid resolution for August – October 2006 to compare with measurement data from the TexAQS II field experiment. We are particularly interested in verification of PBL heights at various times of day and vertical profiles of both meteorological and chemical parameters.

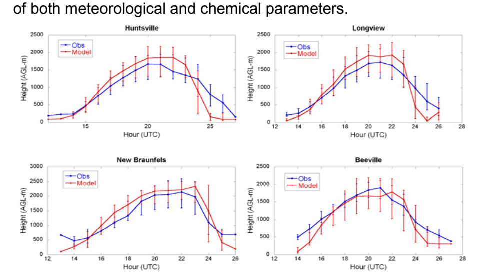

Figure 4 shows comparisons of PBL heights between the WRF model, using ACM2, and estimates derived from radar wind profilers in Texas provided by Jim Wilczak and Laura Bianco (NOAA/ESRL). The lines are the median values at each hour from all data during the 2.5 month period. The bars indicate the 25th and 75th percentiles. The observed and modeled distributions overlap for each hour, although the model often overpredicts in the midday and afternoon.

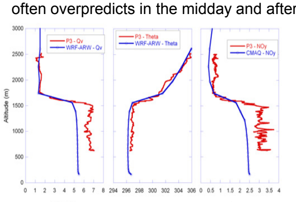

Figure 5. Vertical profiles of WRF-CMAQ results and NOAA P3 aircraft spiral measurements about 120 km SE of Dallas at 19 UTC on 9/25/2006

The most direct measure of success for a PBL model for both meteorology and air quality is its ability to accurately simulate the vertical structure of both meteorological and chemical species. Figures 5 and 6 show examples of WRF and CMAQ results, both using the ACM2, compared to aircraft measurements where the top of the PBL mixed layer is well defined and well modeled for meteorology variables (θ and q_v) and chemical variables (NOy). While such simultaneous measurements of vertical profiles of meteorology and chemistry are very rare, these results are encouraging.

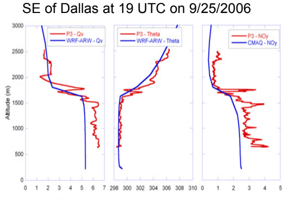

Figure 6. Vertical profiles of WRF-CMAQ results and NOAA P3 aircraft spiral measurements about 170 km SW of Dallas at 20 UTC on 9/25/2006

Conclusions

The ACM2 has been developed to provide accurate and consistent PBL modeling for meteorology and air quality models. Consistency is very important for accurate representation of boundary layer mixing (chemical concentrations in the mixed layer), advective transport (wind shear at PBL top), and chemical reactions (dependencies on temperature and humidity). In addition to the results shown here, a comprehensive meteorological evaluation of WRF runs that used the ACM2 shows very good performance for surface parameters such as T-2m, q_v-2m, and WS-10m as well as vertical profiles compared to commercial aircraft measurements (Gilliam and Pleim, 2009) (see Poster 1.5). Similarly, evaluation of many gas and aerosol species concentrations simulated by CMAQ using the ACM2 compared to several monitoring networks show generally good performance, as shown in Poster 1.1.

Future Directions

•More comprehensive evaluation of vertical profile information from the TexAQS II field study with 12km and 4km grid cell sizes.

•Testing and refinement of stable boundary layer modeling through continued involvement in international model intercomparison experiments, as well as a modeling project for winter conditions in Fairbanks AK.

Impact

For the first time, a PBL model with non-local closure attributes for modeling convective conditions, is applied successfully to both meteorology and air quality modeling. Thus, consistency of sub-grid-scale vertical transport of meteorological and chemical species is assured. The ACM2 has been included in the most recent public releases of NCAR's WRF and EPA's CMAQ models, as a consistent PBL treatment in *both* meteorology and air quality models

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