3.4 APPLICATIONS OF COLUMN MODELS FOR TERMINAL WEATHER NOWCASTS

John Keller, Chris Smith, and F. Wesley Wilson

MIT/Lincoln Laboratory
Lexington, Massachusetts

1. INTRODUCTION

The Planetary Boundary Layer (PBL) is that part of the atmosphere, which is directly influenced by the presence of the earth's surface, and which responds to surface forcing with a time–scale of an hour or less. The Residual Layer (RL) is the portion of the lower atmosphere, which was part of the PBL within the past several hours, and which has become separated from the influence of short–term surface forcing, usually by the formation of a cooler layer at the surface. In the mid–latitudes, the height of the combined PBL and RL is usually 1–2 kilometers. A column model is a one–dimensional prognostic model for the state of a single column of the atmosphere, with special attention to the processes in the lowest few kilometers. It is designed to diagnose and nowcast the vertical structure of the PBL.

Important information for ITWS[1] nowcast products are the vertical profiles of horizontal wind velocity, temperature, humidity, and turbulent kinetic energy (TKE) in the lowest few kilometers (Sankey, 1994). Traditionally, operational meteorologists have obtained estimates of these quantities by balloon soundings, a measurement process that is not well–suited for continuous updates. We are investigating the possibility of developing an operational column model to obtain this vertical structure information for use in the ITWS. Our approach involves using a combination of sensing technology and analysis techniques that have proven successful in several research programs.

Column models are designed to mimic the processes by which the surface forces the processes in the low atmosphere at times when local radiation is a dominant factor. Fluxes are measures of the net rates of these transport processes. The widely–used Oregon State University column model (OSU1DPBL) parameterizes the fluxes by gradient transfer techniques (Troen and Mahrt, 1986). This model has provided dependable service in several field experiments, providing information with a vertical resolution of tens of meters. It is not designed to provide a fine–scale description of the stable nocturnal PBL. The French model COBEL has been developed to forecast the occurrence of radiation fog, and therefore concentrates on modeling the stable nocturnal PBL (Bergot and Guedalia, 1994). It uses a prognostic equation to estimate TKE in the stable boundary layer and parameterizes the fluxes in terms of the TKE (Duynkerke, 1991).

A discussion of the potential uses of the column model in the ITWS is followed by the considerations that motivate the design of an operational column model. The prototype design is described. We conclude with the results of a preliminary evaluation using STORMFEST data (STORM Project Office, 1992) and a discussion of plans for a more comprehensive evaluation.

2. COLUMN MODEL APPLICATIONS IN ITWS

There are several ITWS products that could benefit from column model profiles. These include ceiling and visibility nowcasts, Wake Vortex Advisory System (WVAS) meteorological support, terminal–area in–flight icing diagnosis and nowcasts, microburst prediction, and convective storm growth and decay.

Two areas of initial emphasis are nowcasting the times of the onset and dissipation of low ceilings and reduced visibility events and nowcasting the boundary layer structure associated with wake vortex dissipation. Reduced airport capacity due to low ceiling and restricted visibility is a major cause of air traffic delay (Wilson, et al, 1993). The rate of wake vortex dissipation is a key factor in runway capacity (Evans and Welch, 1991).

The times of onset and dissipation of low ceilings and reduced visibility are very sensitive to the structure of the atmospheric profile in the lowest few hundred meters. Column models can provide information essential for nowcasting these times, when these events are strongly influenced by radiative processes. An example of a COBEL nowcast of the lifting and burnoff of radiation fog is shown in Figure 1.

The vertical structure of the boundary layer has a strong influence on the rate of dissipation of wake vortices: observations indicate that wake vortices dissipate quickly when there is a strong negative lapse rate and when there is a high level of TKE (Greene, 1986). NASA, in collaboration with ITWS, is conducting an extensive data collection exercise at Memphis to quantify the magnitudes of these effects (Campbell et al, 1995). An accurate column model could be used to nowcast the dissipation rate.

[1] The Integrated Terminal Weather System (ITWS) is a development program initiated by the Federal Aviation Administration (FAA) to produce a fully–automated, integrated weather information system to improve the safety, efficiency, and capacity of terminal area aviation operations. The ITWS will acquire data from FAA and National Weather Service sensors as well as from aircraft in flight in the terminal area. The ITWS will provide products to Air Traffic personnel that are immediately usable without further meteorological interpretation. These products include current terminal area weather and short–term (0–30 minute) predictions of significant weather phenomena.

---

*The work described here was sponsored by the Federal Aviation Administration.

Corresponding author address: John Keller,
MIT/Lincoln Laboratory, 244 Wood st., Lexington, MA 02173

3. DESIGN REQUIREMENTS

The initial objective of the ITWS operational column model is to provide an accurate 0–1 hour nowcast of the vertical profile of horizontal wind, temperature, humidity, and TKE. The model must be initialized automatically, providing information of consistent accuracy without the need for human intervention or tuning. Its data will come from sensors that perform reliably with minimum maintenance.

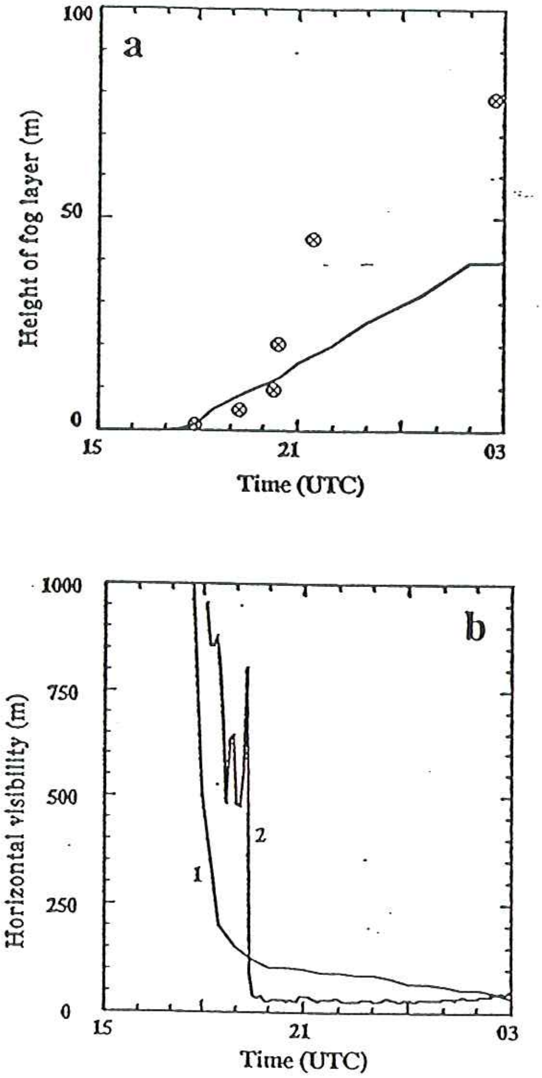

Figure 1. COBEL forecast of fog height and horizontal visibility: (a) simulated (line) and observed fog layer height, and (b) simulated (curve 1) and observed (curve 2), from (Guedalia and Bergot, 1994).

The relationship of the column model to the operational mesoscale models is especially important. During times of strong horizontal advection or deep convection, mesoscale modeling is better–suited to estimate the structure of the vertical profile. At times when radiative processes provide significant local forcing, the column model, supported by special localized sensing, is well–suited to provide a fine–scale analysis of the vertical structure of the PBL. In this sense, the benefits of the column model and the mesoscale model are complementary. The column model analysis routinely uses regional information from a mesoscale model for initialization and to monitor large scale forcing.

The operational column model will need improved local surface data. One–minute updates of the surface winds, temperature, and humidity could be provided from the airport ASOS (Powell, 1993). In addition, soil surface temperature and moisture are used by most of the current column models. Our investigations involve the use of measured surface fluxes. The sensors to provide this additional information could be incorporated as additions to the airport ASOS.

The OSU1DPBL model currently provides profiles of temperature, moisture, and horizontal winds with a 10m resolution updated every 5 minutes. At this time, we are unaware of any ITWS product which needs finer resolution, with the possible exception of fog. In the fog studies with COBEL, there appears to be a need for very fine resolution in the lowest few tens of meters. A finer resolution near the surface may be required for accurately modeling the nocturnal stable layer. As the developers of ITWS products are able to quantify their needs, the column model development will adjust to meet the specific requirements.

Products from an operational model must be available at all hours and at all seasons. This requirement imposes a need for comprehensive capability that has not been established for the research models. COBEL uses have been restricted to nocturnal studies; its performance during the day has not been studied. The skill of OSU1DPBL for modeling the nocturnal stable layer remains to be established. The following questions need special attention:

1. Can the model maintain an accurate profile of the nocturnal stable layer?
2. Can the model maintain an accurate profile during deep convection?
3. Can the model maintain an accurate profile during the evening transition of the PBL?
4. Can the model maintain an accurate profile with a multiply stratified RL?
5. Are there seasonal situations that present special challenges to the model?

The answers to these questions can be obtained only by running the model for an extended periods, at multiple sites, and with ample validation data. To do this solely for the development of the column model technology would be prohibitively expensive. Our intention is to treat each ITWS demonstration site as an opportunity for data collection to support model development (Sankey, 1994).

4. PROTOTYPE OPERATIONAL COLUMN MODEL

We have begun development of an operational column model by modifying OSU1DPBL. Regional information to support the column model analysis will come from the operational

Rapid Update Cycle (RUC) of the National Center for Environmental Prediction (NCEP) (Benjamin et al, 1994). This provides an immediate operational capability and an ability to have improved regional information as the planned upgrades to the RUC come into service. RUC currently has a 60 Km horizontal grid, and there are discussions of reducing this to 10 Km by early next decade. A third modification is directed towards the problem of having the model be representative of the airport region. The need is for sensing information that supports the computation of regionally representative fluxes. Our approach is to modify the OSU1DPBL to ingest measured fluxes directly. We designate this flux forced model by FFOSU.

Most field studies with column models have been conducted at regionally homogeneous locales, such as large plowed fields or over the sea. In these regions, in situ soil temperature and moisture sensors are believed to provide representative values for the surface conditions. While airports are generally open and flat around the runways, there are surface inhomogeneities: grass, runways, taxiways, and usually some nearby structures. The approach regions offer additional diversity: low structures, water, shrubbery, rolling terrain, etc. Obtaining representative information of the soil and canopy by in situ sensing would be a significant challenge in these complex environments.

Direct assimilation of measured fluxes provides a possible mechanism for obtaining regionally representative flux estimates for the column model. The concept is to use 10 hz sampling of wind, temperature, and moisture to support the direct computation of the correlations that provide flux estimates and to ingest averaged fluxes directly into the model. Field experiments indicate the region of influence on the measured fluxes can be controlled by the selection of the height of the flux measurement system (Horst and Weil, 1992) Thus, the height of the instrument package becomes a control mechanism for representativeness. An obvious problem with this approach is that it cannot provide a nowcast, until a way is found to nowcast the fluxes. Even without a flux nowcast, this approach provides a continually updated diagnosis of the current sounding.

Decisions about the temporal averaging of fluxes are an important part of designing the data assimilation process. What is important to the accurate modeling of the transport processes is accurately estimating the net rates of transport. Correct estimation of these net rates requires averaging the covariances over periods from 5 to 20 minutes, depending on the meteorological situation (Kaimal and Finnagin, 1994).

Physical atmospheric processes and the analogous numerical processes in the column model provide substantial smoothing of the input data. This property of the model is not exploited in the OSU implementation, since the fluxes, which are generated by its soil model, are already quite smooth. Our current approach is to insert five–minute covariances and depend on the model physics to provide the remaining smoothing. This strategy will be reexamined when there is enough data to conduct a thorough analysis.

In order to support fog dissipation studies and wake vortex decay, it is important that this model provide a TKE profile. We have decided to use the Musson–Genon TKE parameterization (Musson–Genon, 1987), which is based on TKE production by vertical wind shear and buoyancy. The TKE is computed by a post–analysis diagnosis after each time step.

In summary, FFOSU was created by modifying OSU1DPBL as follows:

1. Automatic initialization using a RUC column,
2. Ingest of geostrophic winds and regional subsidence from the RUC,
3. Direct assimilation of measured fluxes, and
4. Musson–Genon TKE diagnosis.

Additional enhancements are under consideration:

5. COBEL flux analysis for the nocturnal stable layer,
6. Indirect assimilation of measured fluxes, and
7. Air mass transformation analysis for advective forcing.

The additional enhancements are directed towards providing a robust, regionally representative nowcast in a wide variety of situations. COBEL techniques would sharpen the nocturnal analysis. Indirect assimilation would use OSU1DPBL flux parameterizations as constraints in a Kalman Filter assimilation of fluxes. This approach could provide both smoother fluxes and a flux nowcast. Properly adjusting to advective forcing is essential for an all purpose model. No priorities have been established for these improvements.

5. EVALUATION WITH STORMFEST DATA

Data collected from the Memphis WVAS experiment will provide an opportunity for the evaluation of the performance of OSU1DPBL and FFOSU over an extended period of time. In preparation for this extensive evaluation, we have conducted a preliminary evaluation using archived data. The purpose of this exercise is to demonstrate that the FFOSU concept is a sound extension of OSU1DPBL.

Data from the STORMFEST experiment provide one of the few publicly available archives that contain both surface fluxes and soundings. By the nature of the experiment, most data collection occurred during events with significant synoptic forcing. Neither OSU1DPBL or FFOSU are designed to incorporate forcing by horizontal advection; so we selected an evaluation period when horizontal advection is not a dominant factor, the Intensive Operation Period IOP–20 (12 March '92).

Weather during the IOP–20 is typical of that seen after passage of a weak cold front. Temperatures ranged from just below freezing early in the day to just above freezing by mid afternoon. There was light scattered snow in the morning, but the associated clouds had cleared by 1300 CST. Winds were light and northerly throughout the period. The PBL was well mixed until just before sunset. It also appeared to be a dynamically and advectively weak situation.

The STORMFEST data of interest are from two sources. Surface soil and atmospheric observations including 4m fluxes were recorded by the NCAR Atmosphere–Surface Turbulent Exchange Research (ASTER) field array located near Sabetha, KS (Businger et al, 1990). Cross–chain LORAN Atmospheric Sounding System (CLASS) soundings were conducted hourly some 25 km to the east (Rust et al, 1990). The column models were initialized with the sounding and forced with the measured soil surface moisture and temperature (OSU1DPBL) or the 4m momentum, heat, and moisture fluxes (FFOSU). The model outputs are compared with the 10m temperature and moisture every 5 minutes and with the subsequent hourly soundings.

Two deficiencies in the data have the potential to degrade this preliminary evaluation: (1) no mesoscale model data sets are available, and (2) the 25 km offset between the ASTER site and the CLASS site. Mesoscale model data are used to estimate of the strength of the regional vertical motion, an important factor in model performance; due to the weak dynamics, regional vertical motion was set to be zero. The sounding was adjusted to estimate the effective sounding at the ASTER site (Figure 2). Using the difference between the surface observations from these sites, the temperature was adjusted in the vertical assuming a well–mixed condition between the surface and the top of the PBL. The structure in the free atmosphere was not changed.

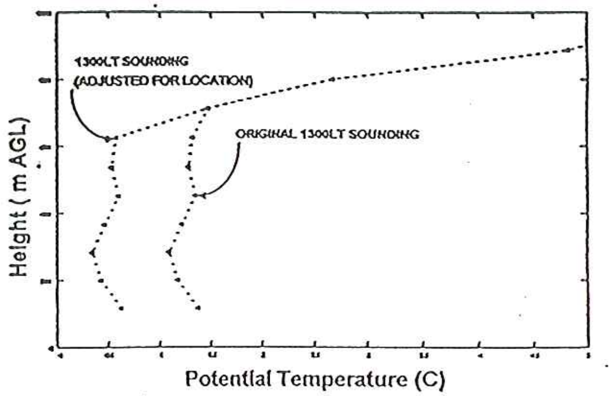

Figure 2. Potential temperature sounding, before and after offset adjustment.

Since both models performed very well, we do not believe that these deficiencies are cause for concern. There is evidence of a minor initial adjustment in the 10m temperature, which may be due to sounding errors, and there is a slight raising of the height of the inversion layer by both models, which may be due to an error in the vertical motion.

Two runs of the models were made:

1. Initialize at 1300 CST and run from 1300 to 1800, and
2. Initialize at 1400 CST and run from 1400 to 1800.

Three comparisons with observation data are presented in figures 3–6.

The observed and modeled fluxes compare rather well. The modeled fluxes are consistent between the two runs and match the trends of the observed 5–minute covariances, except for the brief surge in the heat flux at 1400 which is not reflected in the modeled fluxes. There is a significant difference in smoothness, which may indicate that FFOSU will have difficulty on a warmer day.

Close inspection of Figure 3 reveals that there is a slight high bias in the temperature flux in the late afternoon and in the moisture flux throughout the afternoon. These flux biases are consistent with the deviations from the observed data that can be observed in Figures 4–6.

The time series of temperatures and mixing ratios at 10 m are shown in Figures 4 and 5. Both models show an initial spin–up, reflected by a .5 degree C temperature surge and an initial drying. We cannot determine if this is due to an error in the initialization sounding or to a bit of spin–up instability. After this, both models track the 10m temperature quite accurately. FFOSU provides an accurate, but slightly dry, estimate of the mixing ratio. OSU1DPBL drifts to overly moist through the afternoon.

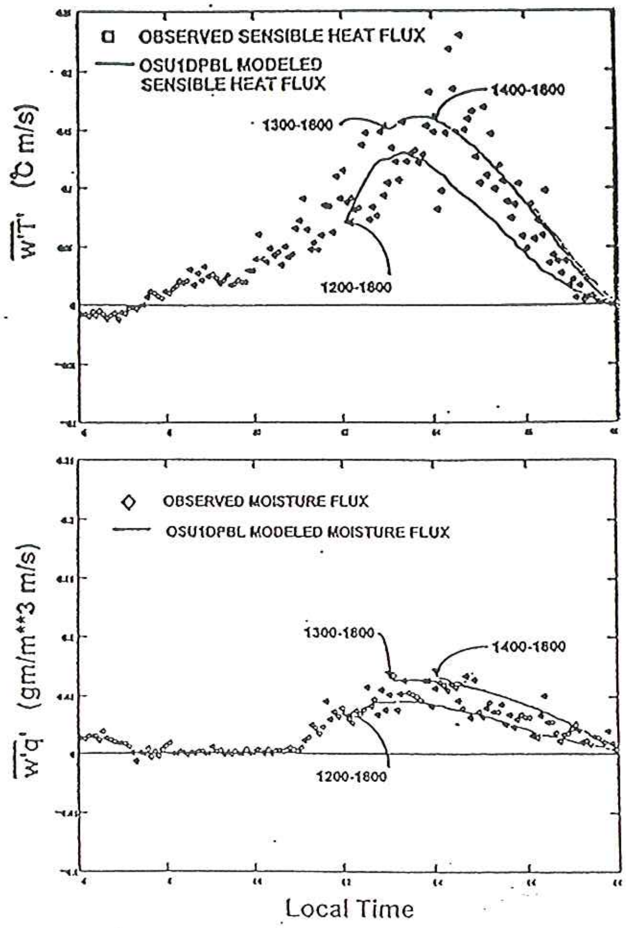

Figure 3. Comparison of observed and OSU1DPBL modeled sensible heat and moisture fluxes.

The modeled vertical profiles of potential temperature and moisture compare well the hourly soundings. The temperature differences are within a few tenths of a degree Celsius, which is close to the 0.5 C mean sensor error typical for rawinsondes (Martner et al, 1993). At 1400, the results are virtually indistinguishable from the observations. In the second hour, neither model result warms the PBL as fast as is observed. The fact that FFOSU does show better warming may be due to the brief surge in the heat flux from 1400 to 1430. There is a bit more error in the modeled moisture profiles. Both models continued to moisten as the PBL began to dry from 1400 to 1500.

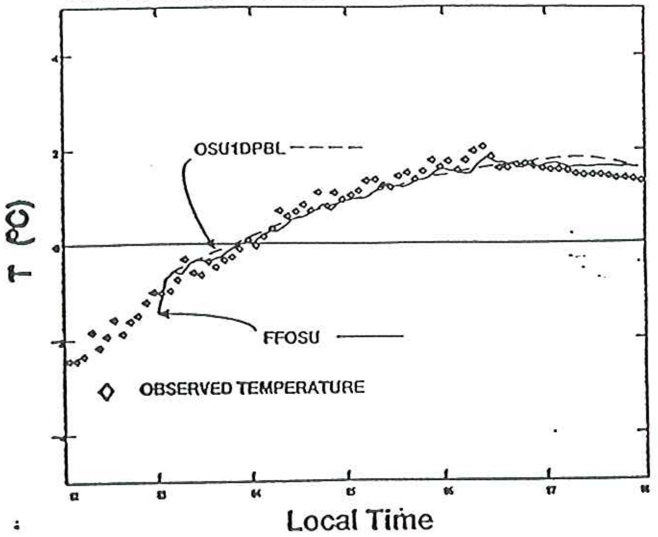

Figure 4. Comparison of the observed and modeled 10 meter temperature.

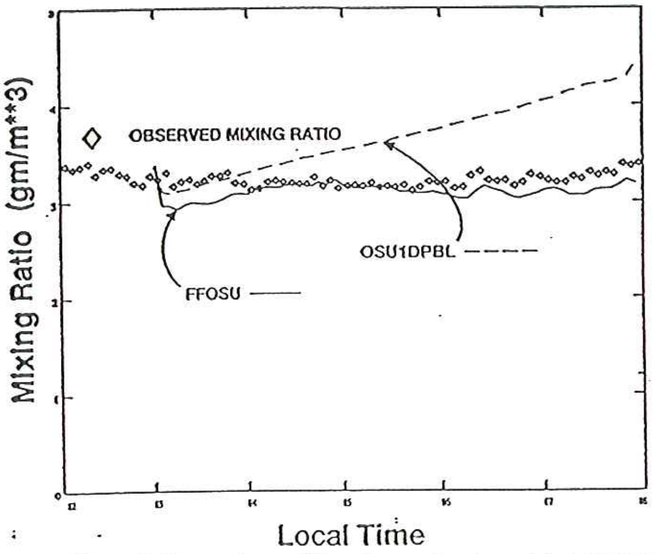

Figure 5. Comparison of the observed and modeled 10 meter mixing ratio.

6. MEMPHIS COLUMN MODEL EVALUATION

In addition to the ITWS data collection, a special data collection effort will be conducted at Memphis to support the wake vortex studies (Campbell et al, 1995). Special atmospheric data will be collected from the fall of 1994 through the summer of 1995. This data collection exercise provides an exemplary opportunity for prolonged evaluation of column models.

The heart of the system is a 45m tower on the airport that will collect 1 hz winds, temperature, and moisture at 10m increments and heat, moisture, and momentum fluxes at 5m and 45m. Soil surface temperature and moisture and net radiation will be measured near the base of the tower. In addition, there will be hourly CLASS soundings during wake vortex data collection activities, approximately 10 soundings a day for 4 weeks in the fall of 1994 and again in the summer of 1995. Automated soundings from a SODAR and PROFILER/RASS are also planned.

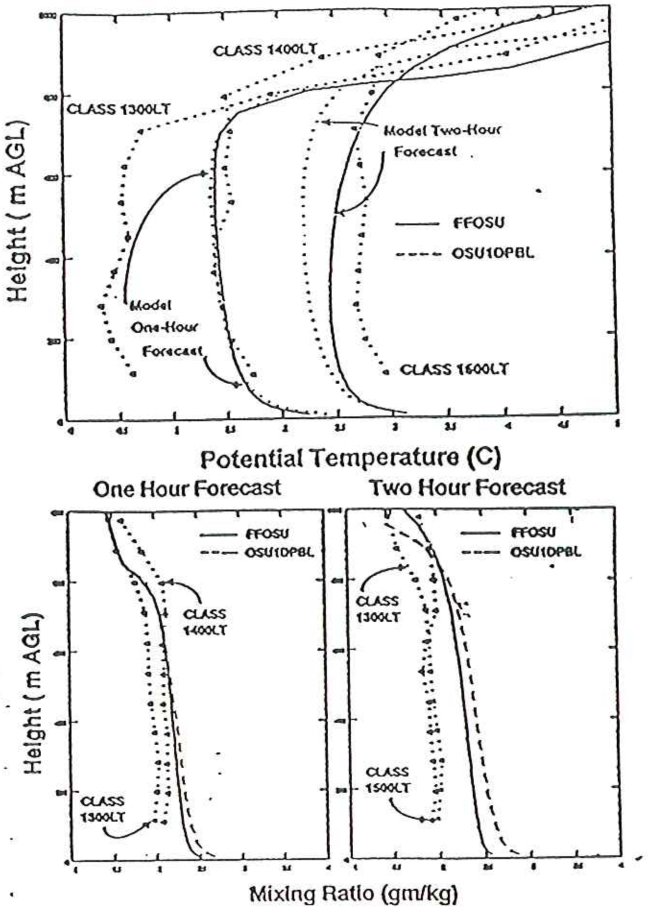

Figure 6. Comparison of the CLASS soundings at 1300 and 1400 CST (local time) with the profiles from the OSU1DPBL and FFOSU models.

Our plan is to use these data in an extensive column model evaluation exercise. The initial effort will be on a statistical evaluation of model performance. This exercise will produce bulk measures of operational model performance and a catalogue of types of substandard performance.

These evaluations will be based on comparisons similar to the previously described comparisons with the STORMFEST data. Time series of the model output will be compared with the tower data at 10m, 20m, 30m, and 40m. Full profiles will be compared with the hourly CLASS soundings when they are available. The SODAR will be used to evaluate the accuracy of the tracking of the inversion cap by the model. An important new capability is the comparison of the time series of observed TKE and 5m and at 40m with the diagnosed TKE. Because of the continuity of the data, it will be possible to study the skill of the model during repetitive situations such as transitions from stable to mixed and from mixed to stable.

7. SUMMARY

With the recent advances in boundary layer sensing and column modeling, it is reasonable to consider the development of an operational column model. Several ITWS products would benefit from the information that this model could provide. An important issue is the development of sensing techniques to support the operational column model is that of providing regionally representative information in complex environments. An attractive possibility is the of use measured fluxes instead of fluxes modeled from soil surface measurements. Initial investigations using archived STORMFEST flux data are encouraging. The Memphis data set will provide an opportunity to conduct a more complete evaluation of the potential of this technology.

REFERENCES

Benjamin, S.G., K.J. Brundage, P.A. Miller, T.L. Smith, G.A. Grell. D. Kim, J.M. Brown, T.W. Schlatter and L.L. Morone, 1994: The rapid update cycle at NMC. Preprints, *Tenth Conference on Numerical Weather Prediction*, Portland, OR, Amer. Meteor. Soc.

Bergot, T. and D. Guedalia, 1994: Numerical forecasting of radiation fog. Part I: numerical model and sensitivity tests. *Mon. Wea. Rev.* 122, 1218–1230.

Bleck, R. and S.G. Benjamin, 1993: Regional weather prediction with a model combining terrain–following and isentropic coordinates. Par I: model description. *Mon. Wea. Rev.*, 121, 1770–1785.

Businger, J.A., W.F. Dabberdt, A.C. Delany, T.W. Horst, C.L. Martin, S.P. Oncley and S.R. Semmer, 1990: The NCAR Atmospheric–Surface Turbulent Exchange Research (ASTER) Facility. *Bulletin of the Amer. Meteor. Soc.*, 71, 1006–1011.

Campbell, S.D., Dasey, T., Heinrichs, R., Matthews,M.P., 1995: Overview of 1994 Memphis wake vortex testing program. 6th Conference on Aviation Weather Systems, Dallas, *Amer. Meteor. Soc.*

Duynkerke, P.G., 1991: Radiation fog: a comparison of model simulation with detailed observations. *Mon. Wea. Rev.*, 119, 324–341.

Evans, J.E. and J.D. Welch, 1991: Role of FAA/NWS terminal weather sensors and terminal air traffic automation in providing a vortex advisory service. *Proceedings of the Aircraft Wake Vortices Conference*, Vol.2 (24–1) Washington D.C. NTIS.

Greene, G.C., 1986: An approximate model of vortex decay in the atmosphere. *J. Aircraft,* 23, 1986.

Guedalia, D. and T. Bergot, 1994: Numerical forecasting of radiation fog. Part II: a comparison of model simulation with several observed fog events. *Mon. Wea. Rev.* 122, 1231–1246.

Horst, T.W. and J.C. Weil, 1992: Footprint estimation for scalar flux measurements in the atmospheric surface layer. *Bound.–Layer Meteor.*, 59, 279–296.

Kaimal, J.C. and J.J. Finnigan, 1994: Atmospheric Boundary Layer Flows, *Oxford University Press*, Oxford.

Martner, B.E., D.B. Wuertz, B.B. Stankov, R.G. Strauch, E.R. Westwater, K.S. Gage, W.L. Ecklund, C.L. Martin and W.F. Dabberdt, 1993: An evaluation of wind profiler, RASS and microwave radiometer performance. *Bull. Amer. Meteor. Soc.*, 74, 599–2577.

Menon–Genon, L., 1987: Numerical simulation of a fog event with a One–dimensional boundary layer model. *Mon. Wea. Rev.*, 115, 592–607.

Powell, M.D., 1993: Wind measurement and archival under the Automated Surface Observing System (ASOS): user concerns and opportunity for improvement. *Bull. Amer. Meteor. Soc.*, 74, 615–623.

Rust, W.D., D.W. Burgess, R.A. Maddox, L.C. Showell, T.C. Marshall and D.K. Lauritsen, 1990: Testing a mobile version of a Cross–Chain LORAN Atmospheric (M–CLASS) Sounding System. *Bull. Amer. Meteor. Soc.*, 71, 173–180.

Sankey,D.A.,1994: An overview of FAA–sponsored aviation weather research and development. *5th Conference on Aviation Weather Systems, Vienna, VA, Amer. Meteor. Soc.*

STORM Project Office, NCAR, 1992: STORM Fronts Experiment Systems Test (STORM–FEST) Operations Plan.

Troen, I. and L. Mahrt, 1986: A simple model of the atmospheric boundary layer: sensitivity to surface evaporation. *Bound.–Layer Meteor.*, 37, 129–148.

Wilson, F.W., J.Keller, R.G. Rassmussen, and P.Zwack, 1993: ITWS ceiling and visibility products. 5th International *Conference on Aviation Weather Syst4ems, Vienna, VA, Amer. Meteor. Soc.*