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Initial Evaluation of Terminal Area Atmospheric Vertical Structure Prediction Algorithms Using Fall 1994 ITWS/Wake Vortex Programs' Meteorological Data

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16. Abstract

A Dynamic Atmospheric Vertical Structure Nowcast System (DAVS-NS) is being developed that will add value to the Integrated Terminal Weather System (ITWS) by providing current and short-term forecasts of the vertical atmospheric structure focused at specific sites within the terminal domain. Operational applications of these estimates of the atmospheric vertical structure include predicting changes in airport operation rates due to ceiling and visibility (C&V) changes and in predicting wake vortex behavior. The core of this system would be a one-dimensional boundary layer column model. This report summarizes the evaluation of a modified Oregon State University (OSU) column model using data collected during the fall 1994 combined National Aeronautics and Space Administration (NASA) wake vortex project and the ITWS site operations at Memphis International Airport (MEM).

Further efforts are necessary to develop and test an operational DAVS-NS prototype. The accuracy typically seen in column model predictions of the vertical temperature structure will limit errors in wake vortex dissipation rates to within a factor of two. Given the current working hypothesis for the San Francisco stratus burn-off phenomenon that rests largely on warming of the marine boundary layer by surface heat flux, the OSU model will also appear to be well suited for addressing this particular problem.

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ABSTRACT

A Dynamic Atmospheric Vertical Structure Nowcast System (DAVS-NS) is being developed that will add value to the Integrated Terminal Weather System (ITWS) by providing current and short-term forecasts of the vertical atmospheric structure focused at specific sites within the terminal domain. Operational applications of these estimates of the atmospheric vertical structure include predicting changes in airport operation rates due to ceiling and visibility (C&V) changes and in predicting wake vortex behavior. The core of this system would be a one-dimensional boundary layer column model. This report summarizes the evaluation of a modified Oregon State University (OSU) column model using data collected during the fall 1994 combined National Aeronautics and Space Administration (NASA) wake vortex project and the ITWS site operations at Memphis International Airport (MEM).

We have concluded that further efforts necessary to develop and test an operational DAVS-NS prototype appear to be worthwhile. The accuracy typically seen in column model predictions of the vertical temperature structure would limit errors in wake vortex dissipation rates to within a factor of two. As well, given the current working hypothesis for the San Francisco stratus burn-off phenomenon that rests largely on warming of the marine boundary layer by surface heat flux, the OSU model would also appear to be well suited for addressing this particular problem.

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1. INTRODUCTION

To determine whether the atmospheric environment can support phenomena responsible for Ceiling and Visibility (C&V) changes and/or long-lived wake vortices, it is important to know the vertical temperature structure of the atmosphere in the lower one or two kilometers of the atmosphere. In theory, sensors could be installed at airports to collect data to resolve the vertical temperature structure. Unfortunately, the implementation and real time operation of these sensors, including frequent balloon soundings and perhaps even raising a 40 or 50 m sensor tower on airport grounds, would be prohibitively expensive. In this report, we assess the potential of the Oregon State University (OSU) one-dimensional column model for providing a cost-effective means of monitoring and providing short-term predictions of the atmospheric vertical temperature structure.

In a previous study (Keller, et al., 1995), the feasibility of using a one-dimensional atmospheric boundary layer (ABL) column model as part of a Dynamic Atmospheric Vertical Structure (DAVS) Nowcast System was evaluated for two cases during the winter 1992 STORM-Fronts Experiment Systems Test (STORM-FEST). Two different implementations of the OSU model were examined: one that used the original OSU implementation (Troen and Mahrt, 1986; Ek and Mahrt, 1993) where estimates of surface fluxes come from its Soil-Vegetation Atmosphere Transfer (SVAT) model and one whereby observed surface fluxes were substituted. We found that the OSU model had some potential for providing accurate short-term forecasts (up to 90 minutes) of the temperature and humidity in the ABL that comprises the lowest several kilometers of the atmosphere; however, a number of important issues could not be adequately addressed. These issues include:

1. Performance over complex, nonhomogeneous airport surfaces,
2. Importance of collocating vertical atmospheric sounding and surface sensors, and
3. Performance for a more diverse range of weather conditions.

It was decided, therefore, that before a prototype real-time DAVS-NS is designed and assembled using the OSU column model, it should be subjected to further tests. Ideally, the sensors would be similar to those used in STORM-FEST, but the experiment design would more directly address these technical issues. The 1994-95 combined National Aeronautics and Space Administration (NASA) wake vortex project and ITWS site at Memphis International Airport (MEM) provides an opportunity for parallel DAVS-NS development that benefits both wake vortex and C&V efforts.

Since the STORM-FEST site was over a homogeneous surface (Kansas farmland), whether surface fluxes measured over a complex airport environment would be similarly useful remained somewhat uncertain. This was perhaps the most critical unresolved issue; addressing it the principal objective in this study. Although no two airports are exactly alike, the surfaces associated with MEM and environs are far less homogeneous than those of Kansas farmland, and the results seen for the particular MEM case should more closely reflect the performance that could be expected at other airports.

In addition, some possible ambiguity resulted because in the STORM-FEST field experiment the sites of surface flux sensors and Cross-chain Loran Atmospheric Sounding System (CLASS) soundings that provided the data for model initialization and validation were separated by a distance of about 25 km. In the MEM data sets the CLASS release site, tower and surface sensors are collocated.

It was also of interest to determine how the OSU model would perform under a wider range of conditions than were available from the STORM-FEST data sets, particularly for stable boundary layers. It may be necessary to adopt the French column model, COuche Brouillard Eau Liquide (COBEL), (Bergot and Guedalia, 1994) that was specifically developed for stable boundary layers. Before we can determine the importance of COBEL to a future DAVS-NS, however, it is necessary to know the OSU model's limitations for these conditions. This study defines two fundamental classes of experiments: cases where the ABL was likely to have been well mixed and those for which the situation is ambiguous. A specific example will be examined in somewhat more detail before the general results for a class of model runs are discussed.

2. EVALUATION USING MEMPHIS DATA SETS

Two different versions of the OSU one-dimensional column model are evaluated using the MEM data sets: the original version, that relies on its own SVAT model to provide estimates of surface fluxes, and a modified version using vertical fluxes directly from the 5 m flux sensor. Of fundamental interest is to see how these two implementations of the OSU model can predict the evolution of the thermal structure in the lower atmosphere. Accurate predictions of the thermal structure - or "vertical stratification" - in the lower one to two km of the atmosphere are important for short-term predictions of C&V phenomena and wake vortices that are important to terminal operations. In this report, the vertical gradient of potential temperature[1] is used to represent the atmosphere's vertical stratification. The relevance of using potential temperature is discussed further in Keller, et al. (1995).

There is some similarity between the NASA / ITWS Memphis experiments reported here and the previous study that used STORM-FEST data (Keller, et al., 1995). Specifically, no estimates of large-scale vertical motion were available due to the absence of concurrent mesoscale model data. As for the STORM-FEST case studies, the large-scale vertical motion was set equal to zero. As before, it is expected that this assumption will make little difference given the region of the atmosphere and the general weather for the period examined. Finally, the data used for both the earlier experiments and those to be discussed in this report were not gathered during strong storms. There were, however, some periods of light brief rain showers during several of the days. A summary of the prevailing weather for each of the days during this study is shown in Table 1.

Table 1.
Dominant Weather at the Time Data Was Gathered for this Study.

Date	Weather Conditions
29 NOV 94	Clear, cool; cold advection
30 NOV 94	Clear, cool; weak cold advection
01 DEC 94	Clear, warmer; weak warm advection
02 DEC 94	Increasing clouds, cloudy by noon; weak warm advection
03 DEC 94	Cloudy, few rain showers; weak warm advection
04 DEC 94	Cloudy, rainy. (Operations suspended)
05 DEC 94	Cloudy (fog and stratus); weak cold advection
06 DEC 94	Similar to 05 DEC
07 DEC 94	Fog in AM, becoming cloudy; frontal passage about 1740Z; little advection
10 DEC 94	Cloudy, some rain; cold advection

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[1] Potential temperature accounts for the normal tendency of temperature to decrease adiabatically with height as pressure decreases. Potential temperature increasing with height defines stable stratification; decreasing, unstable stratification.

There are several significant differences between the Memphis and STORM-FEST data sets. Unlike for the STORM-FEST data sets, the tower sensors were collocated with the release point of the CLASS balloons. The 45 m Memphis meteorological tower was also much higher than the 10 m Atmosphere-Surface Turbulent Exchange Research facility (ASTER) tower used during STORM-FEST. Probably the most significant difference, however, was the complexity of the surface. The ASTER data sets were obtained over open farmland that provided much less complex surface conditions than the surrounding airport environment where the Memphis tower was centered. A sense of this complexity can be gained from Figure 1, which shows the Memphis airport and vicinity.

2.1 Description of Data Sets Relevant to Column Model Evaluation

The most comprehensive source of data were from the sensors mounted on a 45 m tower. State of the atmosphere variables (SAVs) of temperature, relative humidity, wind speed and direction were measured at 5, 10, 20, 30 and 44 m at a 1-Hz sampling rate. Vertical fluxes of temperature and momentum were estimated by the eddy correlation technique (Dabberdt, et al., 1993) from data sampled at 10 Hz. Vertical fluxes of moisture mixing ratio were estimated using the same technique from 20 Hz data. The flux sensors were located on the tower at 5 and 40 m. For SAV and surface flux data sets, one-minute averages interpolated to 15-second increments were used for this study.

Soil, radiation and atmospheric pressure data at the surface were also obtained. The soil data comprised temperature and moisture content 10 cm below the surface. Atmospheric pressure data were adjusted to sea level. Surface radiation was measured as total downward and total upward components. Pressure values corresponding to the sensor levels above the surface were calculated assuming hydrostatic balance.

Other data were available besides that obtained from the tower sensors. Above the tower, SAV profiles were obtained from CLASS balloon soundings. Other parameters related to the surface such as roughness, soil type, vegetation canopy height and type were estimated by an on-site inspection.

2.2 Method of Evaluation

Consideration of the physical processes occurring in the lower ABL has led to the hypothesis that the version of the OSU model that uses measured fluxes will be more accurate in some atmospheric conditions than others. Specifically, it would be expected to perform better when the ABL is well mixed than when it is stably stratified. The former conditions are most likely during sunny, breezy weather while the latter are often seen during calm, clear nights. This report discusses the results from two fundamental classes of experiments: cases where the ABL was likely to have been well mixed and those for which the situation is ambiguous. A specific example is examined in somewhat more detail before the general results for a class of model runs are discussed.

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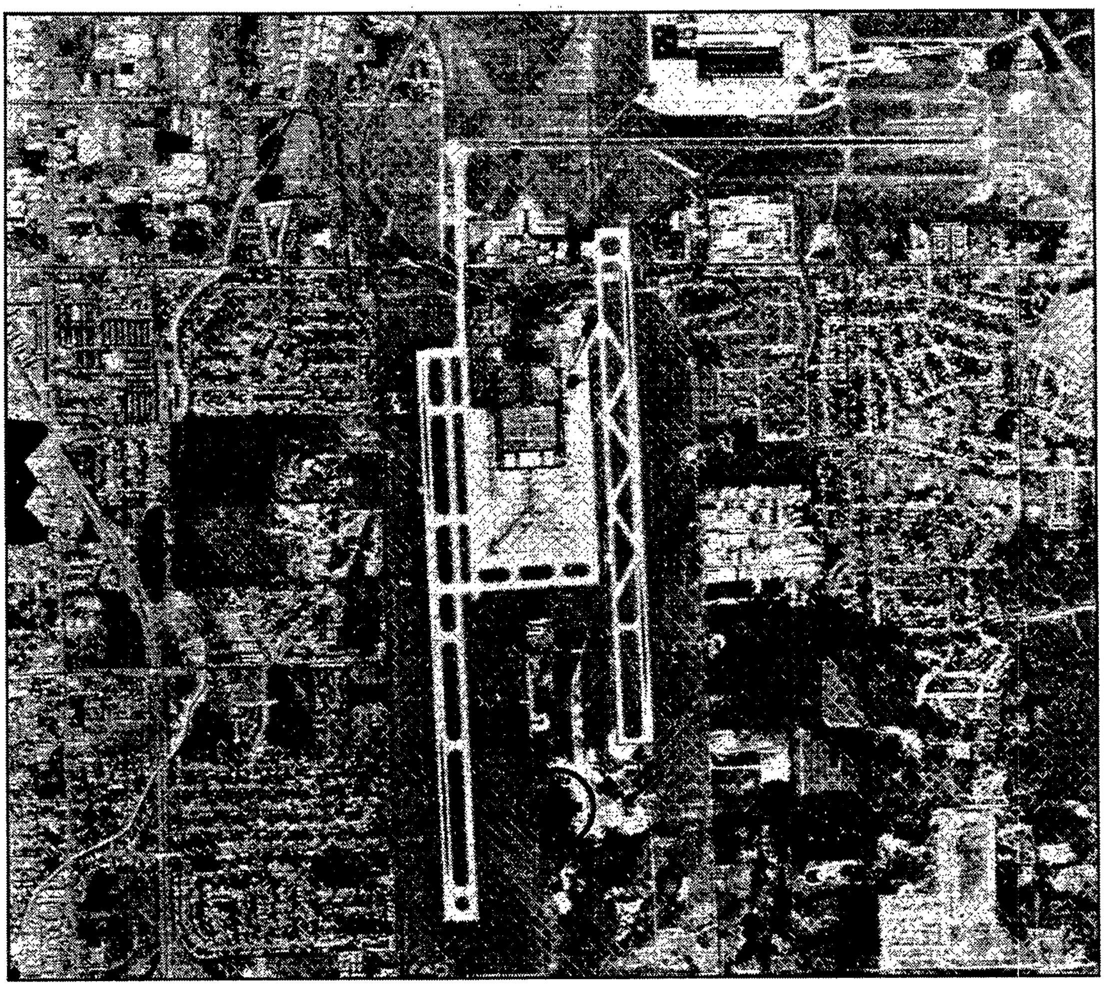


Figure 1. Aerial photograph showing the MEM ITWS and wake vortex test beds, and vicinity. The sensor tower location is indicated by the cross.

OSU column model data requirements, discussed in detail in Keller et al. (1995), include an initial SAV profile. Within the model, this profile then evolves as the various forces included in the model algorithm act on it. For the MEM cases to be examined in this report, profiles include SAV data from both the tower and CLASS soundings. A specific example (1700Z 01 DEC 94) is shown in Figure 2. For the version of the OSU model that uses the observed fluxes directly (often referred to in this report as the "flux-forced" version), these input data include the 5 m flux data. In this study, using the same model configuration parameters and varying only the initial composite CLASS plus tower SAV input profile, a series of model simulations have been performed to produce two-hour forecasts of the profile evolution.

One way of assessing the accuracy of a particular model simulation graphically is to compare a predicted SAV profile to the measured one corresponding to the model prediction time. Most graphical comparisons in this report, however, are between model and

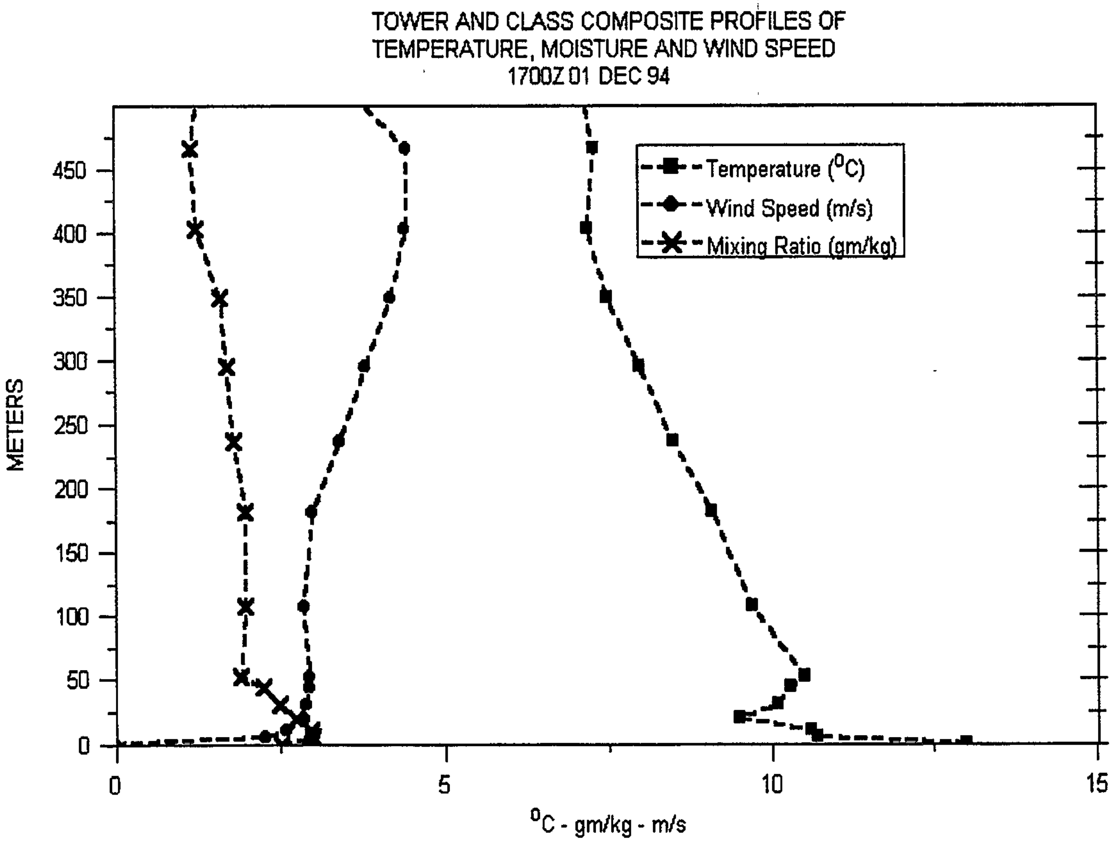


Figure 2. Example of CLASS sounding / sensor-tower composite profile.

observed time series data plots of potential temperature error ($\theta_{Model} - \theta_{Observed}$) at tower sensor heights. However, for the two particular cases examined, temperature is shown. The heights used are 10, 20 and 30 m for temperature and potential temperature and 5 m for the surface heat flux.

A number of potential sources of error for this study have been identified. These potential sources of error include:

1. Biased sensor data,
2. Inaccurate cloud cover (OSU model SVAT flux version only),
3. Ignoring horizontal advection and other forcing due to the atmosphere's circulation,
4. Setting mean vertical motion to zero and
5. Model spin-up.

While techniques to ameliorate most of these sources of error could be used in future studies (for example, by including additional data sources or using alternative model implementations), it was not considered appropriate for this report where the primary concern is to establish a benchmark. In the cases discussed in this report, only the effect of inaccurate cloud cover is considered to be a significant problem.

The most fundamental source of error is in the temperature sensors themselves. Despite serious attempts to remove biases in the temperature sensors, significant biases in the temperature data have been revealed. One way to estimate these biases is to examine the potential temperature structure revealed by the data when neutral conditions are likely ($d\theta/dz = 0$). Neutral conditions are most likely during the daytime under unbroken cloud cover. Figure 3 shows profiles of the departure of potential temperature from its layer-mean value calculated over the lowest 250 m for several days during cloudy daytime conditions. Under strictly neutral conditions, the departures of potential temperature from the

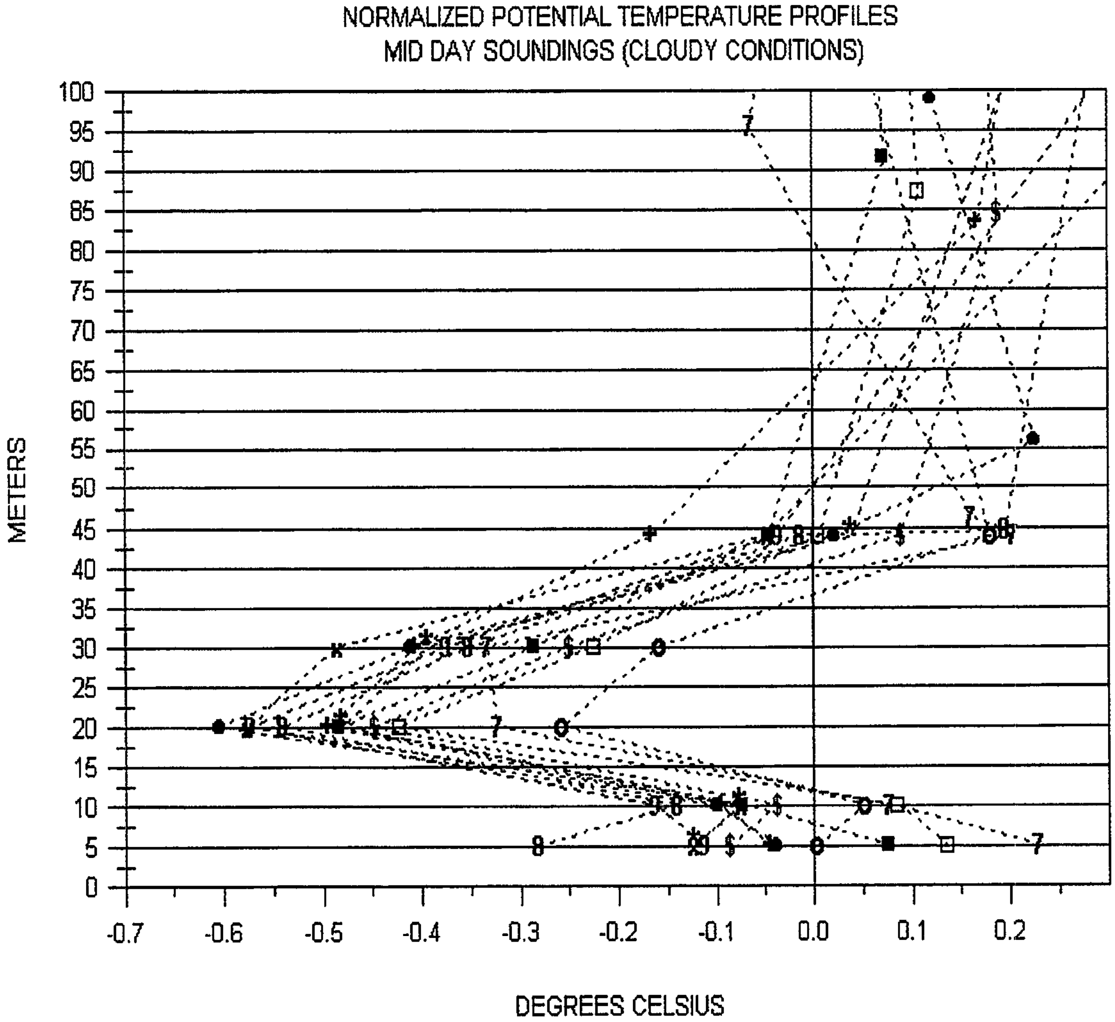


Figure 3. Normalized potential temperature profiles calculated for several days with neutral stability.

mean at a given time should be randomly distributed around the zero line (due to random sensor error and real, local temperature fluctuations). Evidence of systematic error can be seen at the 20 and 30 m levels, while little evidence of significant error can be seen at the other levels. While theoretically errors of this type can be removed, no quantitative accounting for sensor biases is made in the results shown in this report. Rather, the focus is on comparing modeled and observed tendencies.

Inaccurate cloud cover should only be a potential problem for the SVAT version of the OSU model. Cloud above the ABL is particularly a problem. The OSU model is able to generate its own ABL cloud but is unaware of cloud that may exist at higher altitudes. Existence of daytime cloud cover reduces the magnitude of the heat flux below that expected during clear skies. This would be captured in the 5 m flux data but not by the SVAT OSU model unless it generates significant cloud at the top of the ABL that would reduce the solar radiation and, effectively, "give the right answer for the wrong reasons."

A 24-hour model simulation of observed and OSU model cloud cover is shown in Figure 4 for 07 DEC 94. In this case the total cloud cover, largely composed of cloud above the ABL, is underestimated compared to that observed (SAOs). How the SVAT model estimated surface fluxes can be affected if the OSU model does not account for cloud cover is shown by Figure 5. It can be seen that surface heat fluxes are estimated by the OSU model to be much larger during the mid morning than observed.

Horizontal temperature advection, resulting when the wind flows with a component normal to isotherms, is usually not important for short-term forecasts out to less than several hours. It can, however, be important during frontal passages if horizontal gradients are especially large. The early period for which data were gathered at MEM was characterized by clear skies, light winds and without any fronts in the area (Table 1). Later, a weak quasi-stationary front meandered back and forth across the region. The surface analysis for 12Z 06 DEC 94, showing surface observations and the location of a quasi-stationary front (Figure 6), exemplifies the synoptic situation for this later period. Despite its proximity to the frontal zone, forcing by horizontal temperature advection during this period in the Memphis region was usually rather small. Horizontal temperature gradients, estimated using surface grid data from the 50 km horizontal resolution Canadian operational mesoscale model (Figure 7), were less than 1 °C per 100 km. Horizontal wind speeds observed were less than 10 km/hr so that temperature changes forced by horizontal advection were less than 0.1 °C/hr.

Surface fluxes can increase near frontal zones for other reasons. Enhanced vertical gradients in the horizontal wind field in the immediate vicinity of even weak fronts can lead to increased shear turbulence and vertical fluxes. As well, replacing a warm, moist air mass with a cooler and drier one will increase the surface heat fluxes. Evidence of this effect occurring following a late morning frontal passage on 07 DEC 94 (Table 1) can be seen in Figure 5 in the 5-m observed fluxes after 1730Z.

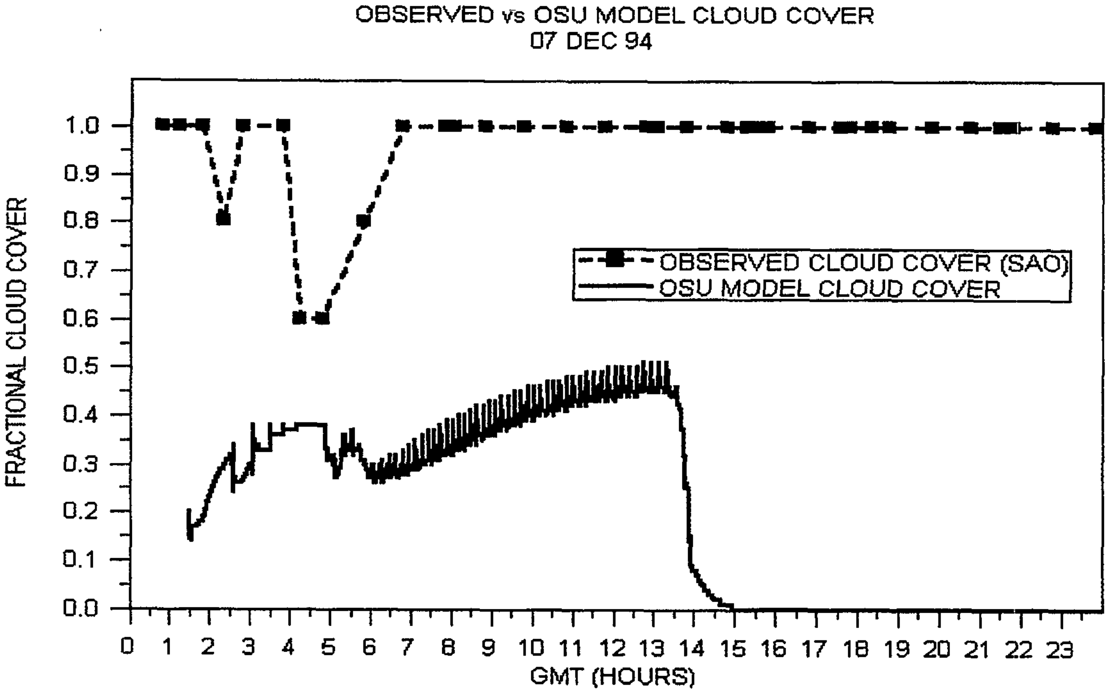


Figure 4. Observed and OSU model cloud cover for 07 DEC 94.

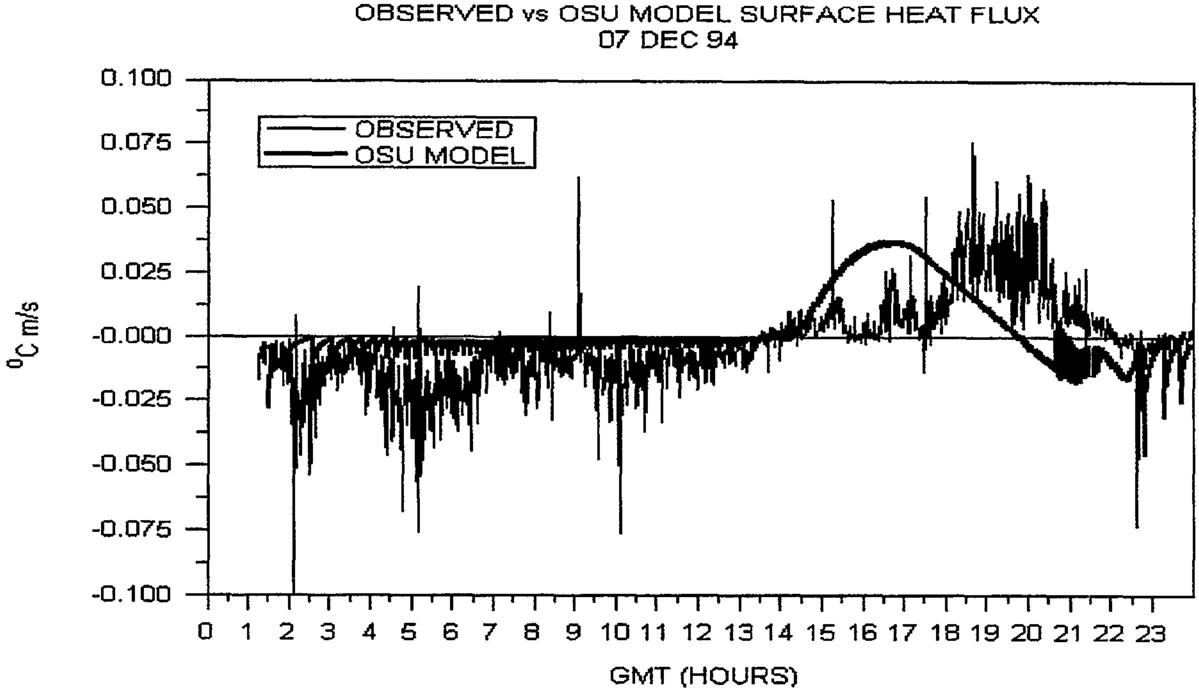


Figure 5. Observed and OSU model heat flux for 07 DEC 94.

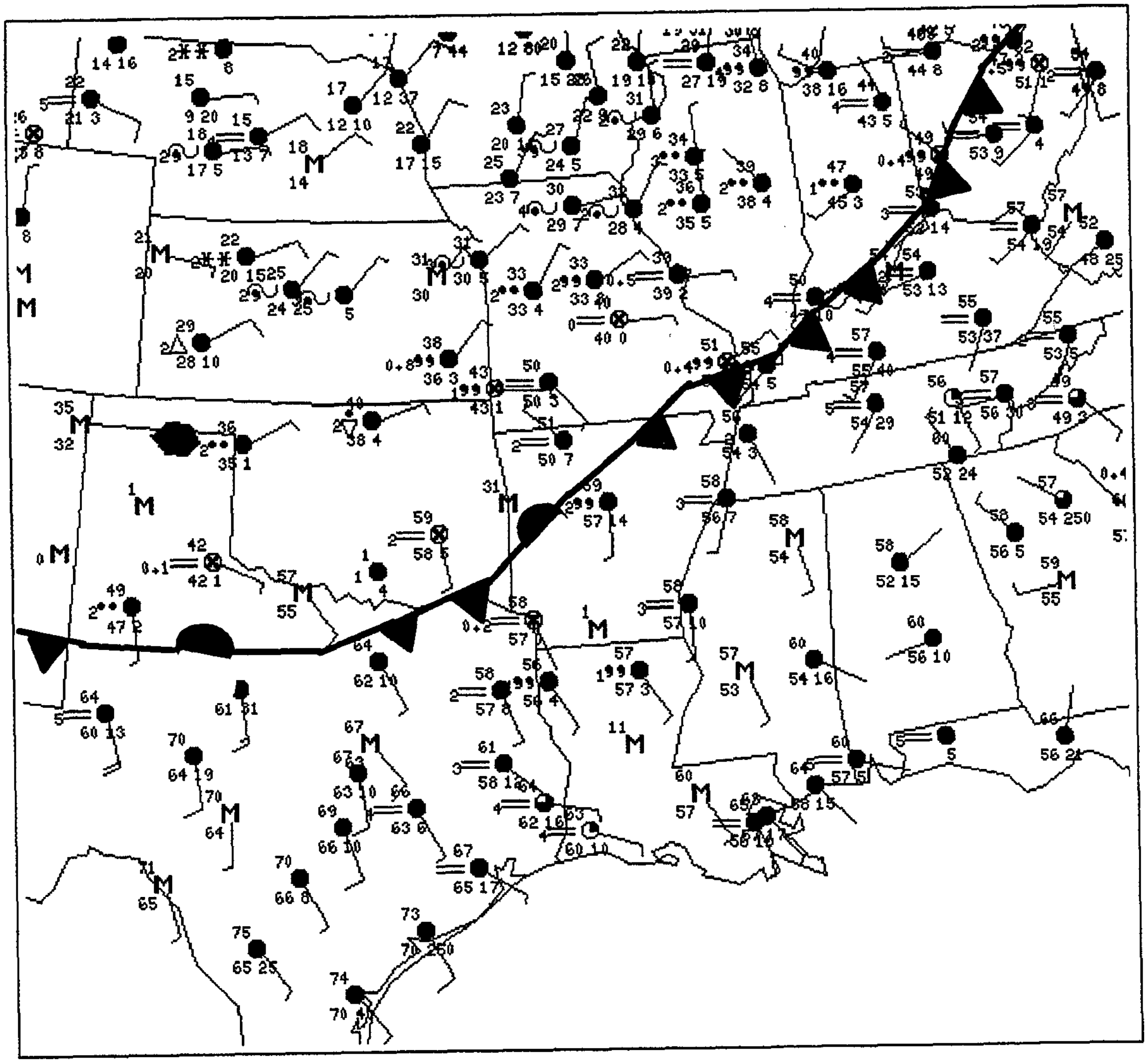


Figure 6. Surface analysis valid 11Z 06 DEC 94.

As for the STORM-FEST case studies, the large-scale vertical motion ($w = dz/dt$) is set equal to zero in the OSU model for the experiments discussed in this report. As in the case for horizontal temperature advection, this contribution to temperature evolution is most important during dynamically active weather. Another source of dynamic temperature forcing due to the atmosphere's circulation is adiabatic heating or cooling. This forcing is proportional to the pressure change following the air motion, or

$$\partial T/\partial t \propto \omega$$

where $$\omega \equiv \partial p/\partial t + \mathbf{v} \bullet \nabla p + w \bullet \partial p/\partial z$$

is the p-velocity, or omega. This effect is not considered for the cases in this report.

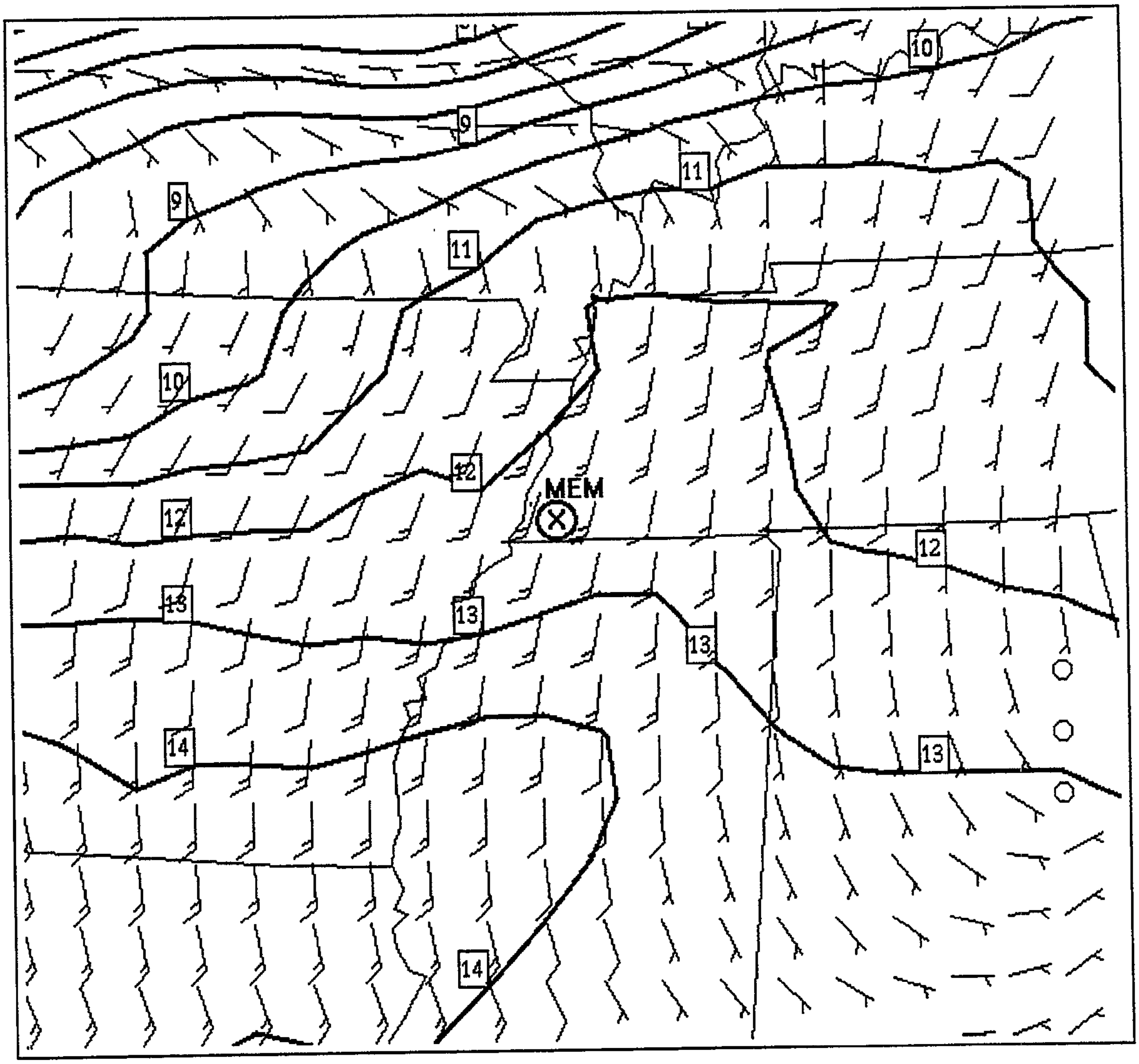


Figure 7. Canadian operational mesoscale model surface wind and temperature field for 12Z 06 DEC 94.

3. PERFORMANCE FOR OPTIMAL CONDITIONS

Our first concern was to determine the performance of the two OSU model implementations in estimating the current atmospheric vertical structure and forecast its evolution over the next two hours during the well-mixed ABL conditions that are expected to be optimal for the version that uses measured fluxes directly. The first series of two-hour model simulations using initialization times, based on the CLASS balloon release time stamp, were no earlier than about 1628Z (10:28 AM) local time (Table 2). This maximized the chance that sufficient surface heating had occurred to produce a well-mixed ABL.

Table 2.
Start Times of Experiments During Conditions Judged as Optimal for OSU Model Performance Using Observed Fluxes. All Runs Were for Two Hours.

Date	Initialization Time
29 NOV 94	1758Z (1158LT)
01 DEC 94	1701Z (1101LT)
02 DEC 94	1628Z (1028LT)
03 DEC 94	1804Z (1204LT)
05 DEC 94	1758Z (1158LT)
06 DEC 94	1759Z (1159LT)
07 DEC 94	1815Z (1215LT)
10 DEC 94	1814Z (1214LT)

3.1 Measured and Modeled Tower (10, 20 and 30 m) Temperatures

Model performance for one representative example for well-mixed conditions is discussed here. A case was chosen at random from those listed in Table 1. For this case the simulations were started using a composite CLASS and tower profile constructed for 1701Z 01 DEC 94. The weather was generally clear with light winds and weak warm advection.

OSU model surface fluxes for this case, estimated by its SVAT module, and 5 m measured heat fluxes shown in Figure 8a are reasonably close. In Figure 8a, the observed one-minute average 5 m fluxes are indicated by the broken line while the model fluxes are indicated by the solid line. The much greater variance in the observed fluxes compared to the model fluxes is to be expected since the observed fluxes are point values while the model fluxes are averages over a vertical "surface layer". The depth of this vertical surface layer is set within the OSU model as one tenth of the mixed layer depth.

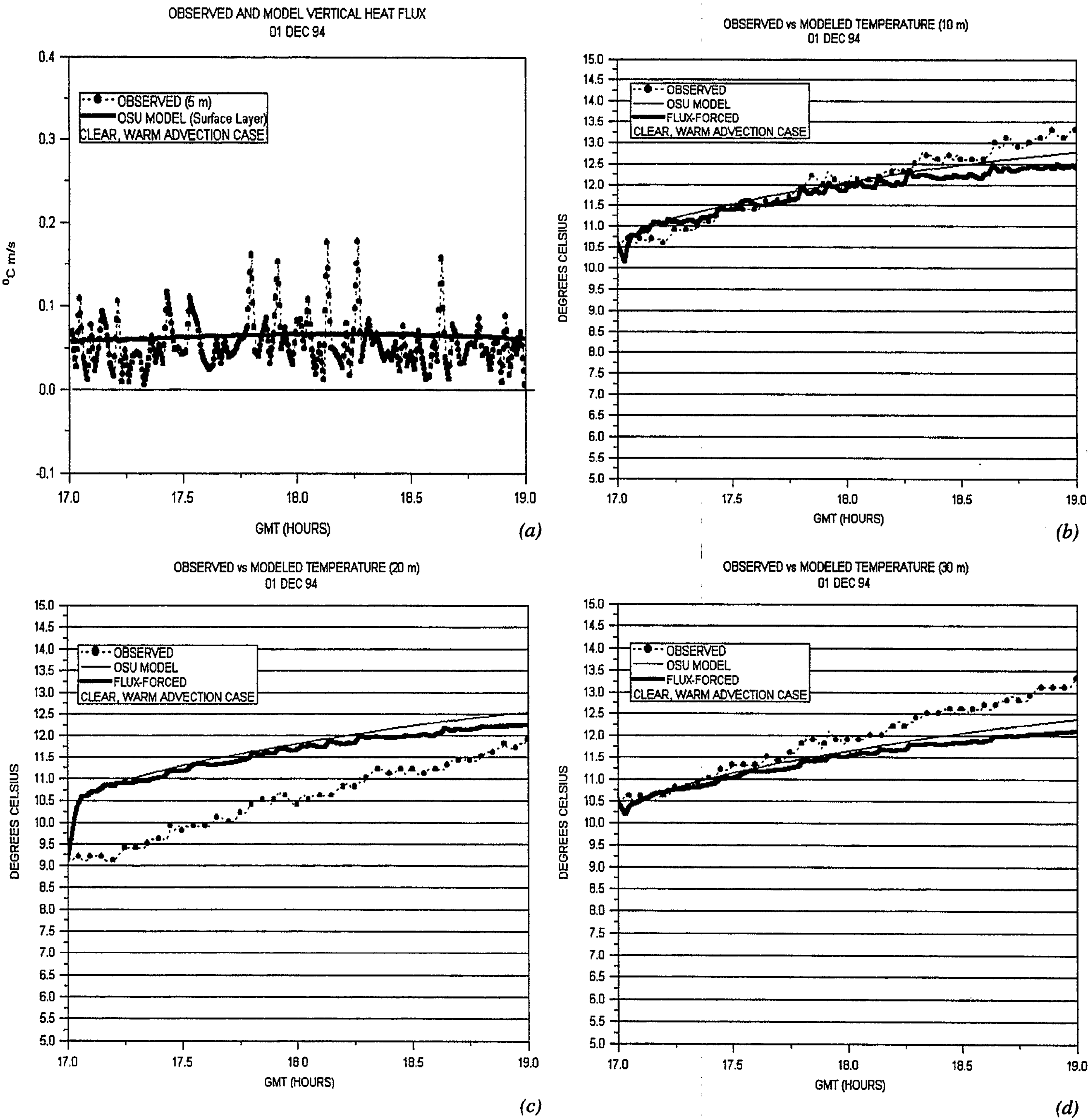


Figure 8. Observed and modeled time series of surface (5 m) heat flux (a) and temperature at 10 m (b), 20 m (c) and 30 m (d) for 1700 - 1900Z 01 DEC 94.

Consistent with the tower observations, both implementations of the OSU model indicate generally increasing temperature over the two-hour simulation period. The temperature time series for 10, 20 and 30 m are shown in Figures 8b, 8c and 8d, respectively. A slightly larger increase is seen in the observed temperature, which probably reflects the effect of warm advection. Evidence of model spin up can also be seen for this case as indicated by the slight jump in the temperature early in the simulation. The magnitude of this jump is roughly the same as the perturbations seen in both the observed and flux-forced OSU version temperature perturbations.

For this case, the performance of the column model in maintaining a realistic vertical potential temperature structure was good, with the flux-forced OSU model version showing somewhat more accurate results. Figure 9 shows the observed potential temperature profile measured at 1700Z and 1900Z. The 1700Z profile was used to initialize both

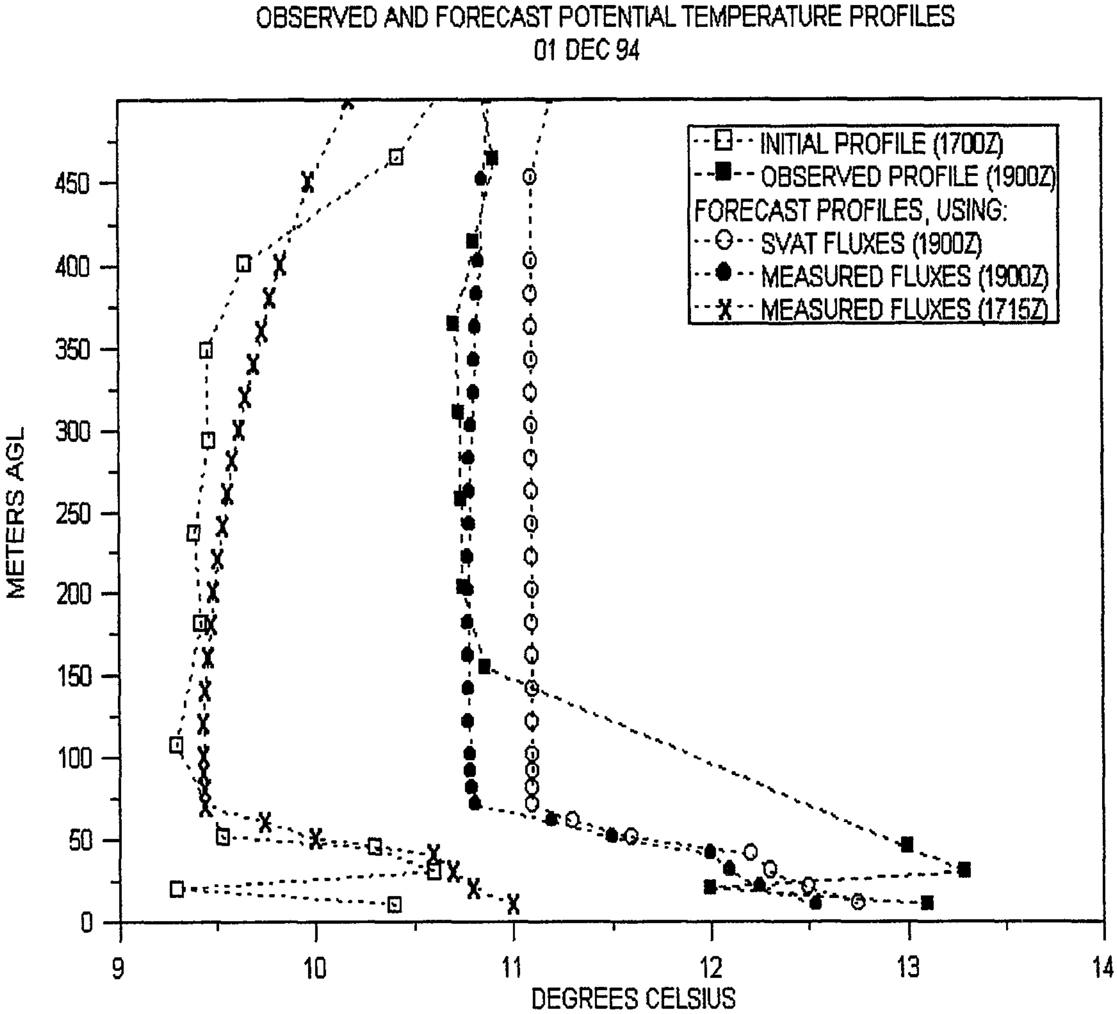


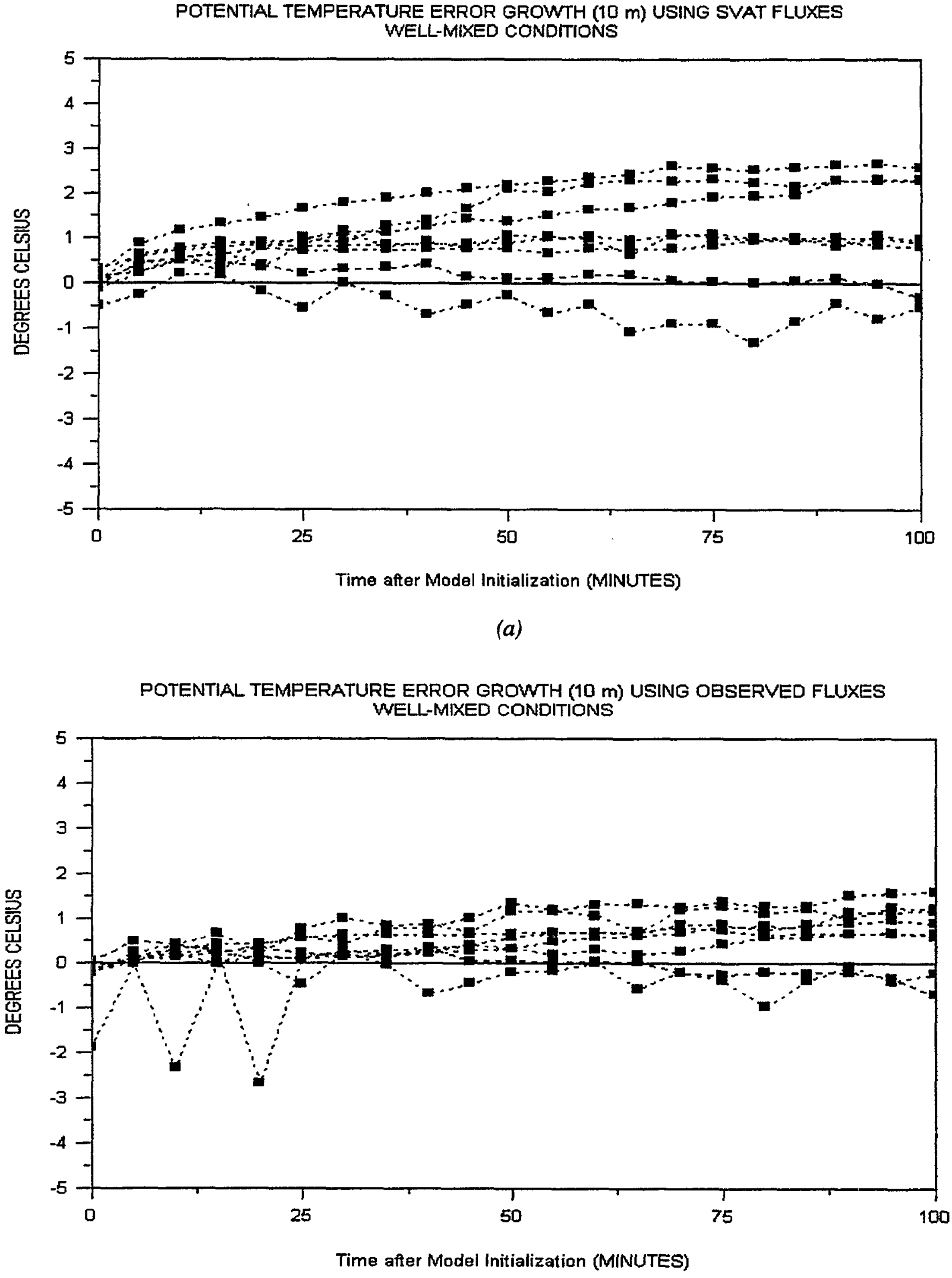
Figure 9. Observed and forecast potential temperature profiles at initial and forecast times using SVAT model and observed surface (5 m) fluxes for 01 DEC 94.

versions of the OSU model. Inspection of Figure 9 reveals considerable noise in the variance of the temperature profile through the tower height. Presumably this is partly due to the effect of the sensor biases discussed earlier. Perhaps a more representative vertical structure profile is that generated by the flux-forced version OSU model after 15 minutes, indicated by the line with the 'X' symbol. Until a firm determination of the temperature biases is available, the precise vertical structure at the tower level is uncertain. Further inspection of Figure 9 reveals that both OSU model versions capture the change in the vertical thermal structure (stratification) above the tower reasonably well. The performance for this particular case is typical of the general performance of the column model for predicting the vertical thermal structure that was observed for other cases in this study.

3.2 General Model Performance for Potential Temperature

Model performance for all optimal-condition experiments is now addressed. In general, the performance of the column models under these conditions is quite good. The flux-forced column model performed better, probably because the effect of cloud above the ABL on the surface fluxes was captured in the observed fluxes. Figure 10 shows the potential temperature error growth at the 10 m level as a function of time after model initialization for the SVAT flux version OSU model (a) and the flux-forced version (b). The corresponding results at the 20 and 30 m levels are shown in Figures 11 and 12, respectively. An idea of the relative skill for these simulations can be seen by the tendency for the lines and symbols to diverge with time. At all three levels shown, these diverge more rapidly for the SVAT OSU model version. Little evidence of significant model spin-up is seen, but there is clear evidence of temperature sensor bias. Several apparently extreme potential temperature errors, seen early in the results using observed fluxes (flux-forced) for 10 m, are a reflection of flux sensor data drop-out that occurred during this period.

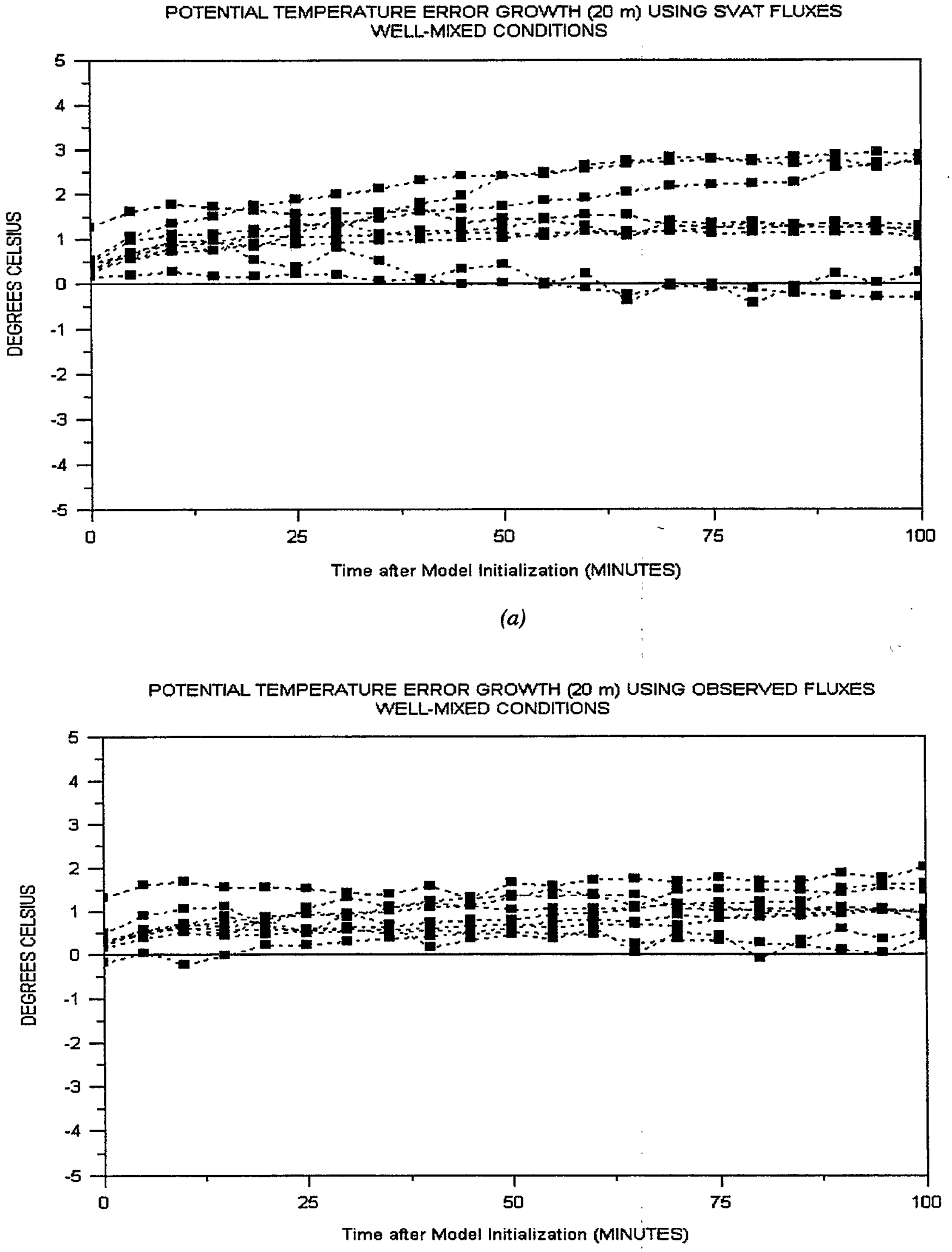
Inspection of the results for the flux-forced version, since they tend to be largely parallel to the abscissa (little error growth) after the first few minutes, may provide a way of deducing the temperature sensor biases. At 10 m the temperature sensor is too cold, perhaps by a few tenths of a degree. The sensors at both 20 and 30 m appear to have an even larger cold bias, perhaps averaging half a degree Celsius for 20 m and only slightly better at 30 m. If nothing else, the column model should force a vertical profile that is physically self-consistent. In general, the error growth rate for the flux-forced simulations remains virtually constant, so that even if one insisted on using the sensor temperature as truth its temporal variance could be reproduced by using the model tendencies. The close agreement shown above the sensor-tower level (CLASS data) in the case discussed in detail earlier (Figure 10) seems to further support this hypothesis.



(a)

(b)

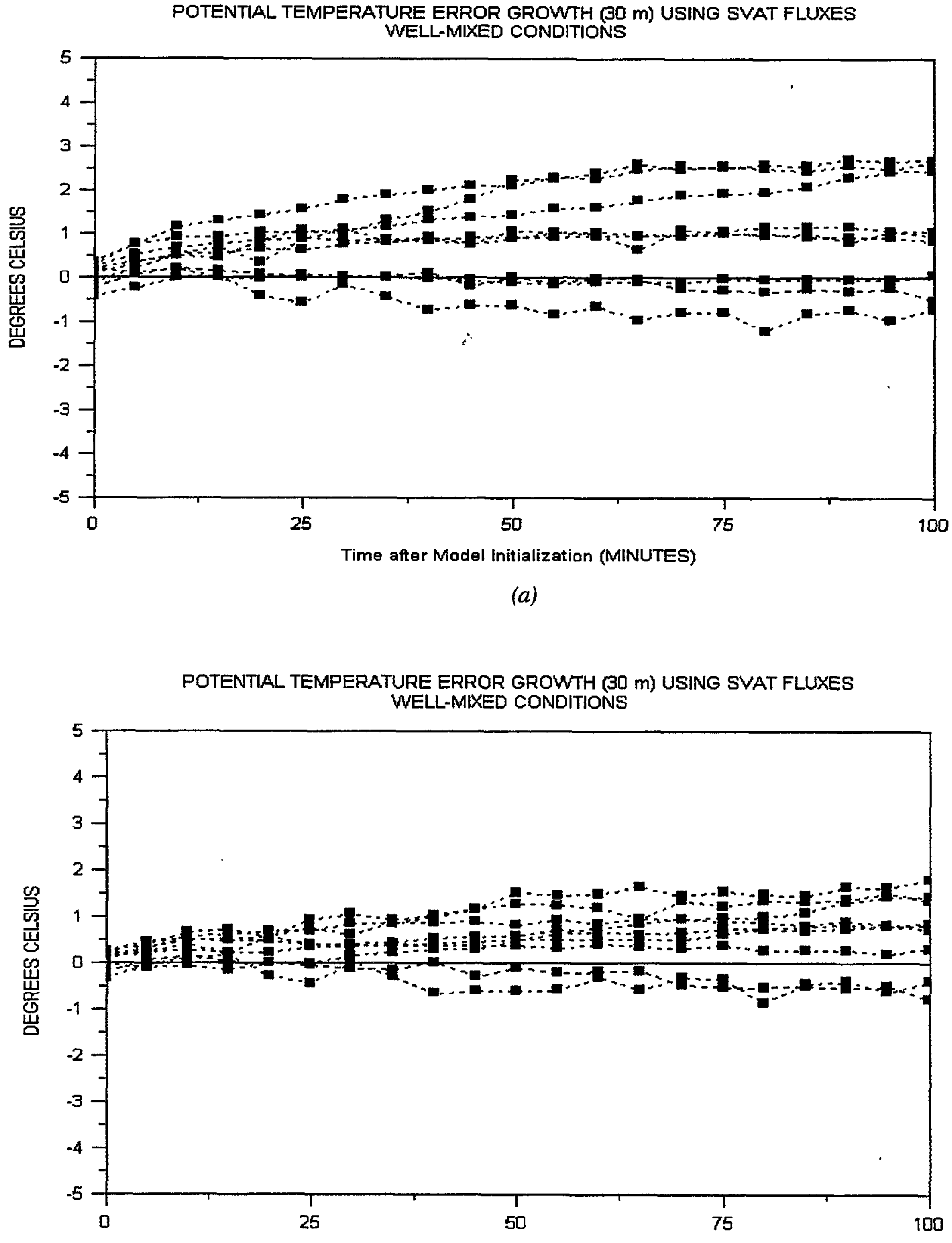
Figure 10. Modeled potential temperature error growth rate as compared with 10 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for eight apparently well mixed cases.



(a)

(b)

Figure 11. Modeled potential temperature error growth rate as compared with 20 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for eight apparently well mixed cases.



(a)

(b)

Figure 12. Modeled potential temperature error growth rate as compared with 30 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for eight apparently well mixed cases.

4. PERFORMANCE FOR NON-OPTIMAL CONDITIONS

Once column model performance under well-mixed ABL conditions apparently optimal for flux-forced model performance were examined, it was of interest to determine its performance at other times. These cases, representing the balance for which data are available, are summarized in Table 3.

Table 3.
Start Times for Experiments Performed During Non-Optimal ABL Conditions.

Date	Start Times	Meteorological (Non-Optimal) Condition
30 NOV 94	2058Z (1458LT)	Stable surface layer; ABL de-coupling
01 DEC 94	1426Z (0826LT)	Stable layer before sunrise
03 DEC 94	1256Z (0656LT)	Stable layer before sunrise
	1428Z (0828LT)	Cloudy, with precipitation
05 DEC 94	1454Z (0854LT)	Cloudy, with precipitation
	1926Z (1326LT)	Cloudy, with precipitation
	2113Z (1513LT)	Cloudy., with precipitation
06 DEC 94	1602Z (1002LT)	Cloudy, with precipitation
07 DEC 94	0130Z (1931LT)	Stable surface layer; ground fog
	1521Z (0921LT)	Cloudy
	1930Z (1330LT)	Cloudy
10 DEC 94	1930Z (1330LT)	Cloudy, with precipitation

4.1 Measured and Modeled Tower (10, 20 and 30 m) Temperatures

A case was chosen where the performance of the flux-forced OSU model was judged to have been particularly unimpressive. A representative example of model performance for non-optimal conditions is 0130Z 07 DEC 94. The start time for this simulation was well after sunset. Some cloud was observed (mainly above the ABL), along with light winds and little advection. Fog formed later in the night, suggesting that conditions favored the formation of a stable layer near the surface.

Both SVAT module and 5 m measured heat fluxes are quite small as shown in Figure 13a, but not dramatically different. Observed one-minute average 5 m fluxes are indicated in Figure 13a by the solid line and modeled fluxes are indicated by the dots.

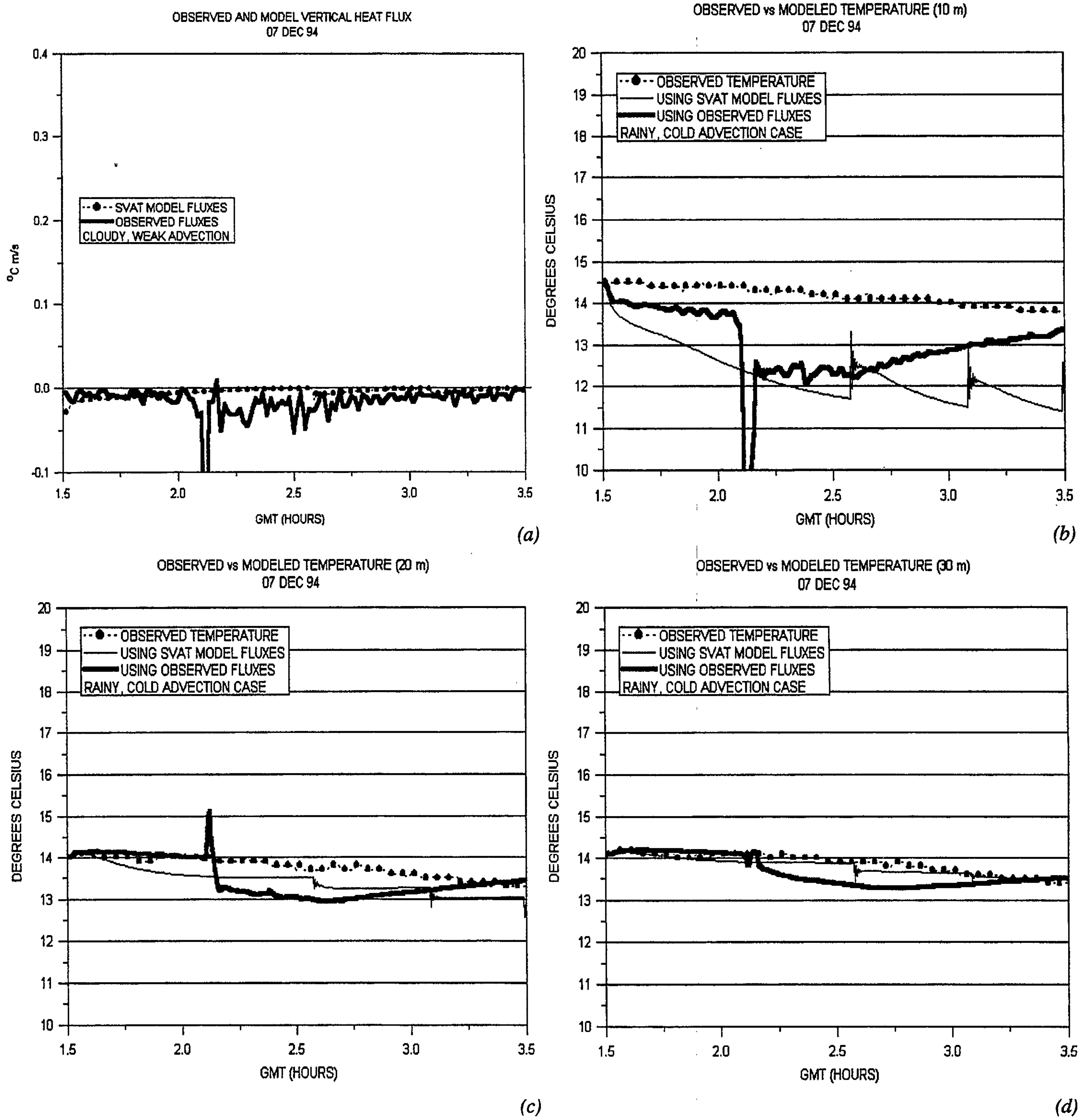


Figure 13. Observed and modeled time series of surface (5 m) heat flux (a) and temperature at 10 m (b), 20 m (c) and 30 m (d) for 0130 - 0330Z 07 DEC 94.

As in the case for a mixed ABL discussed in the last section, the observed fluxes are expected to show more variance than the model fluxes. However, the sharp drop seen in the observed 5 m flux just after 0200Z is probably due to sensor error. The most frequent cause of this data "drop out" is precipitation, though none was reported at this time.

Consistent with the tower observations, both implementations of the OSU model indicate a generally decreasing temperature over the two-hour simulation period. The temperature time series for 10, 20 and 30 m are shown in Figures 13b, 13c and 13d, respectively. Interestingly, the performance for both versions of the OSU model becomes better at the levels farther from the surface. The impact of the sharp drop in the observed 5 m flux, mentioned above, is clearly seen in the flux-forced OSU model temperature variance for the 10 m level. As well, sharp spikes in the SVAT model temperature time series are evident at just after 2.5 and 3.0 hours GMT, especially at the 10 m tower level. These are artifacts of "turbulent bursts" generated by the OSU model's parameterization of the stable boundary layer. While not evident in the temperature series predicted using measured fluxes, vertical mixing by turbulent bursts is commonly observed in stable atmospheric boundary layers. Both the impact of the sharp drop in the observed 5 m flux and the SVAT model turbulent bursts decrease as a function of height.

The cooling in the potential temperature profile as forecast by the flux forced OSU model is shown in Figure 14. Profiles for each 15 minutes of model simulation are shown. For this case, unfortunately, it is not possible to compare the performance of the column model against a measured profile of potential temperature. This is because no observed SAV profile is available after 0131Z until 1521Z.

4.2 General Model Performance for Potential Temperature

In general, the performance of the flux-forced OSU column model under these non-optimal conditions is better than expected. Figure 15 shows the potential temperature error growth as a function of time after model initialization for the SVAT flux version OSU model (a) and the flux-forced version (b). The corresponding results for 20 and 30 m are shown in Figures 16 and 17, respectively. As for the previous set of experiments for well-mixed ABL conditions, an idea of the relative skill for these simulations can be seen by the tendency for the lines and symbols to diverge with time. At all three levels shown, these diverge more rapidly for the SVAT OSU model version. Several occurrences of flux sensor data drop-out, caused when rain showers passed over the field site, are evident. As for the earlier cases examined, little evidence of significant model spin-up is seen and there is clear evidence of temperature sensor bias.

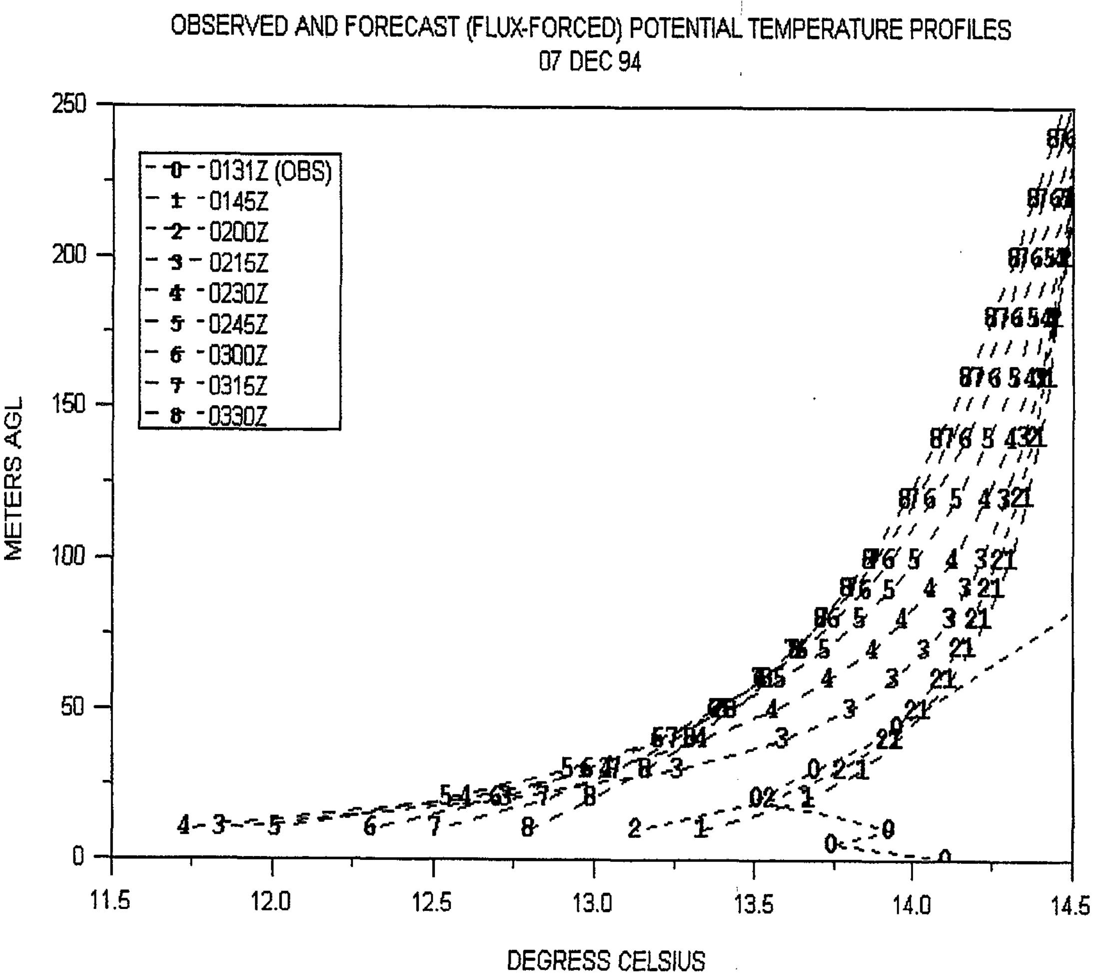
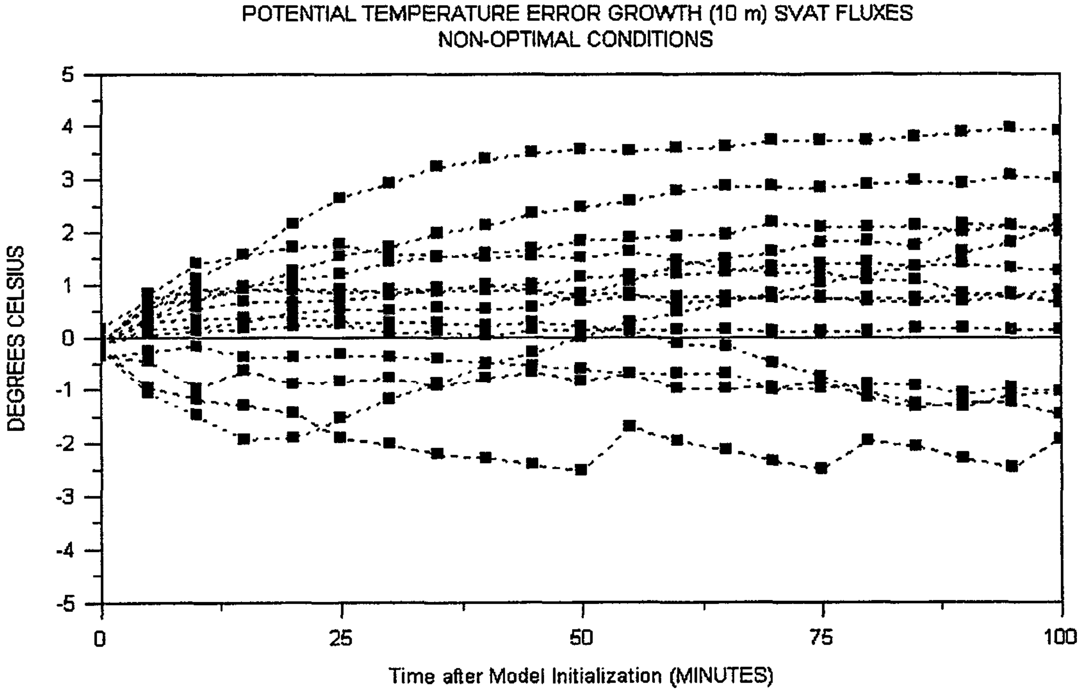
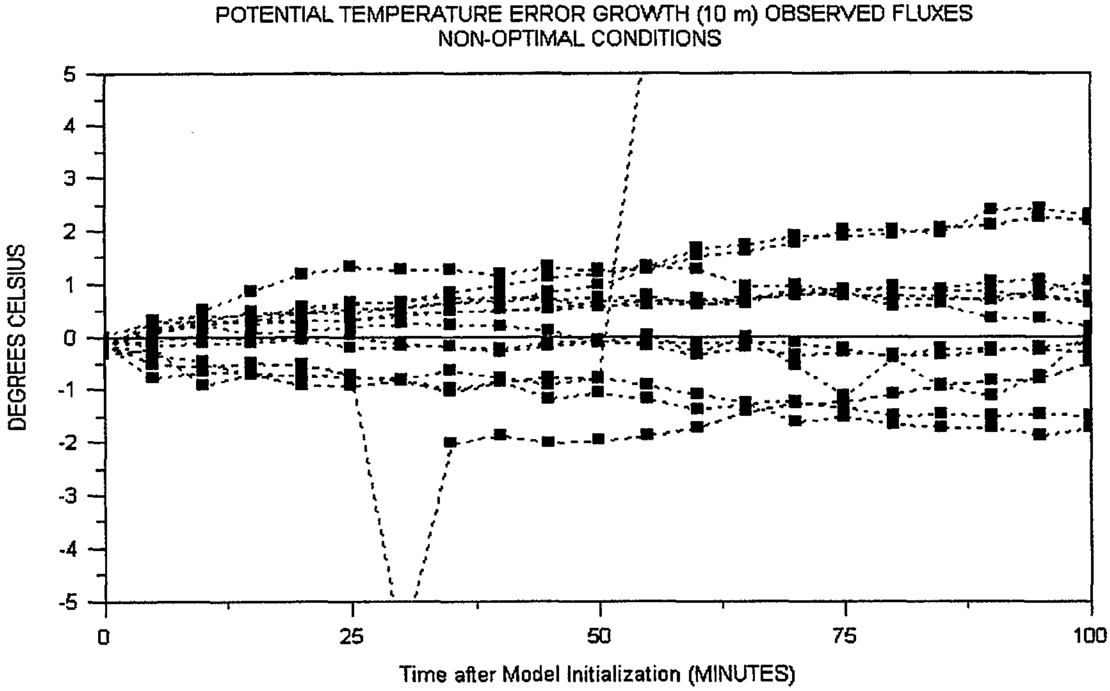


Figure 14. Evolution of the potential temperature profile between 0130Z and 0330Z 07 DEC 94, shown at 15-minute intervals, as forecast by the flux-forced OSU model.

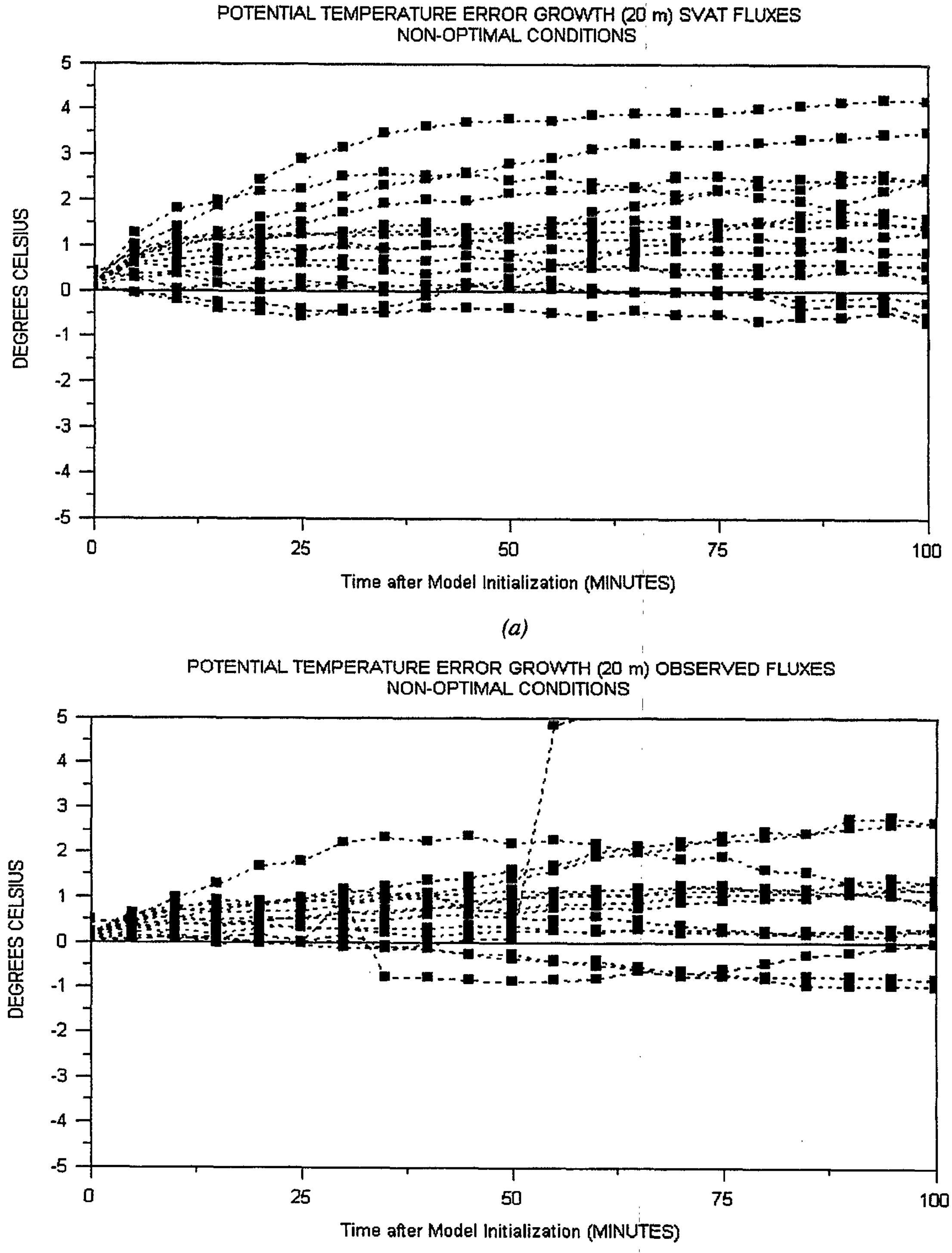


(a)



(b)

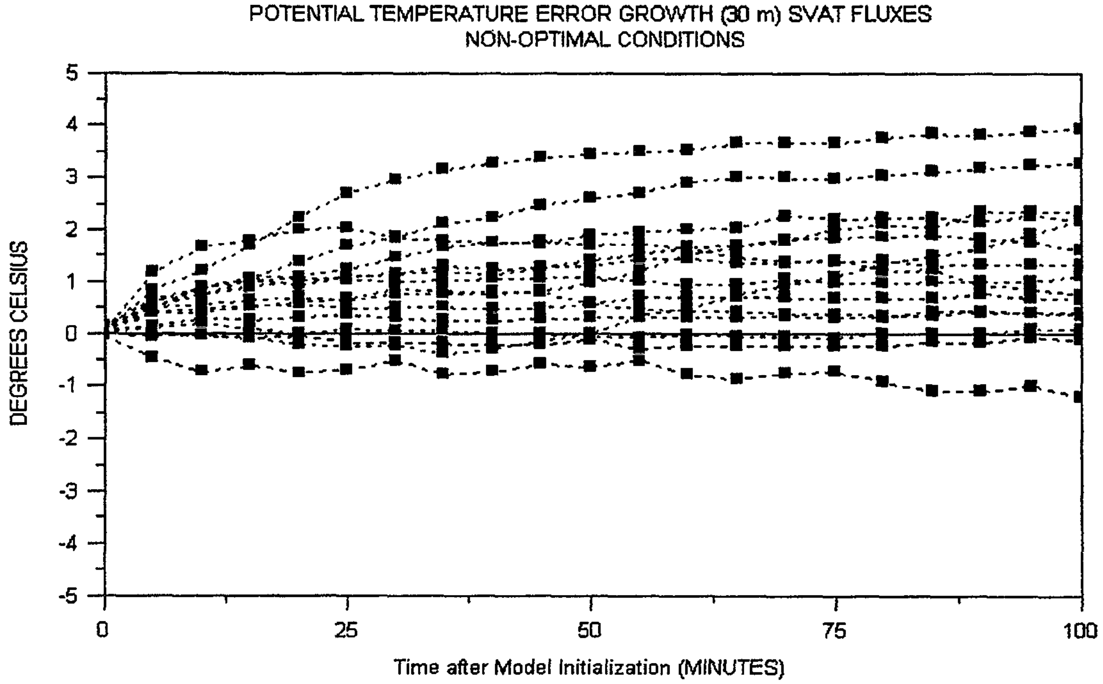
Figure 15. Modeled potential temperature error growth rate as compared with 10 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for 14 apparently non-optimal cases.



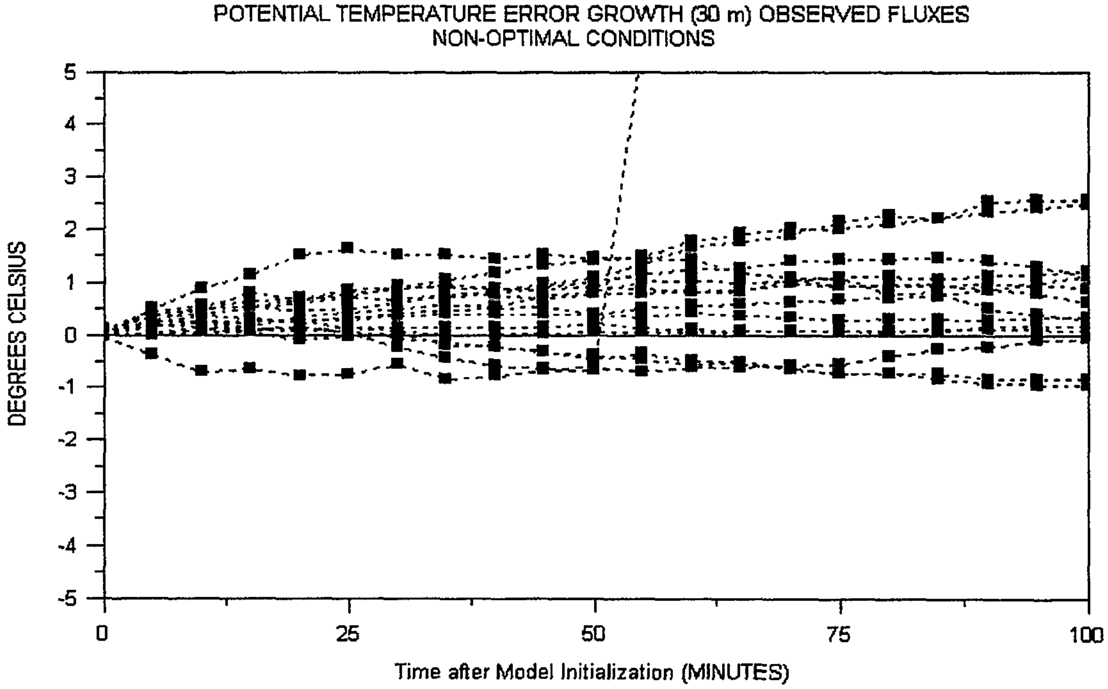
(a)

(b)

Figure 16. Modeled potential temperature error growth rate as compared with 20 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for 14 apparently non-optimal cases.



(a)



(b)

Figure 17. Modeled potential temperature error growth rate as compared with 30 m sensor during first 100 minutes using SVAT (a) and observed fluxes (b) for 14 apparently non-optimal cases.

5. CONCLUSIONS

In general, the flux-forced OSU model appears to be able to maintain an accurate thermal structure - or vertical stratification - of the lower atmosphere. What is particularly impressive is the small rate of error growth in the flux-forced OSU model's potential temperature after the first 30 minutes. This implies that these temperature tendencies should provide an opportunity for generating accurate current temperature profiles. As well, the original OSU model, if provided accurate surface parameters and information about cloud amount above the ABL, should be able to provide lower atmospheric temperature forecasts that are more accurate than persistence out to a few hours. Currently, forecasts of less than six hours only rarely perform better than persistence.

It may be fair to ask whether the OSU column model, while better than persistence or compared to what is currently available operationally, can meet the needs of the ITWS C&V prediction and/or wake vortex dissipation prediction algorithms. Unfortunately, previous studies of these particular phenomena either lacked data defining general meteorological conditions, as for wake vortices, or was concerned with forecast horizons well beyond the one hour that is the current goal of ITWS C&V products. Concurrent measurements that focus on the combination of high precision, short lead time are only beginning now. Current efforts at NASA to analyze the data gathered at Memphis last fall should provide the first direct comparison of measured wake vortex dissipation rates and the lower atmospheric environment, including thermal structure. The first opportunity for data sets related to C&V phenomena in a terminal area is planned to begin during summer '95 in the San Francisco International Airport (SFO) terminal area. However, heuristic analyses can provide some insight to the sensitivity of these phenomena to lower atmospheric conditions in general, and the thermal structure in particular.

An approximate analysis of atmospheric effects on wake vortices has been performed by Greene (1986). The vertical stratification of the atmosphere was among a number of factors, including vertical wind shear and turbulence, that were examined. Greene found that the lifetime of a wake vortex produced by a jumbo jet (DC-10, B747, etc.) doubles from 2 to 4 minutes when the vertical temperature gradient decreases by only 1 °C per 100 m. The example of observed and forecast potential temperature profiles shown in Figure 9 (a typical result) shows for this case that errors in the vertical temperature gradient at levels above the tower are just a few tenths of a °C per 100 m. For a given pressure profile, vertical gradients of temperature and potential temperature are the same. Unfortunately, the degree of error in the vertical temperature structure nearer the surface (Figures 10-12 and 15-17) is unclear due to the ambiguity resulting from sensor bias.

Initial studies in support of the SFO stratus burn-off project have suggested that it may be necessary to forecast the potential temperature to within 1 to 2 °C to provide precise short-term predictions of the stratus burn-off time. Figure 18 shows the relationship between the cloud cover and surface temperature observed at SFO as stratus burned off

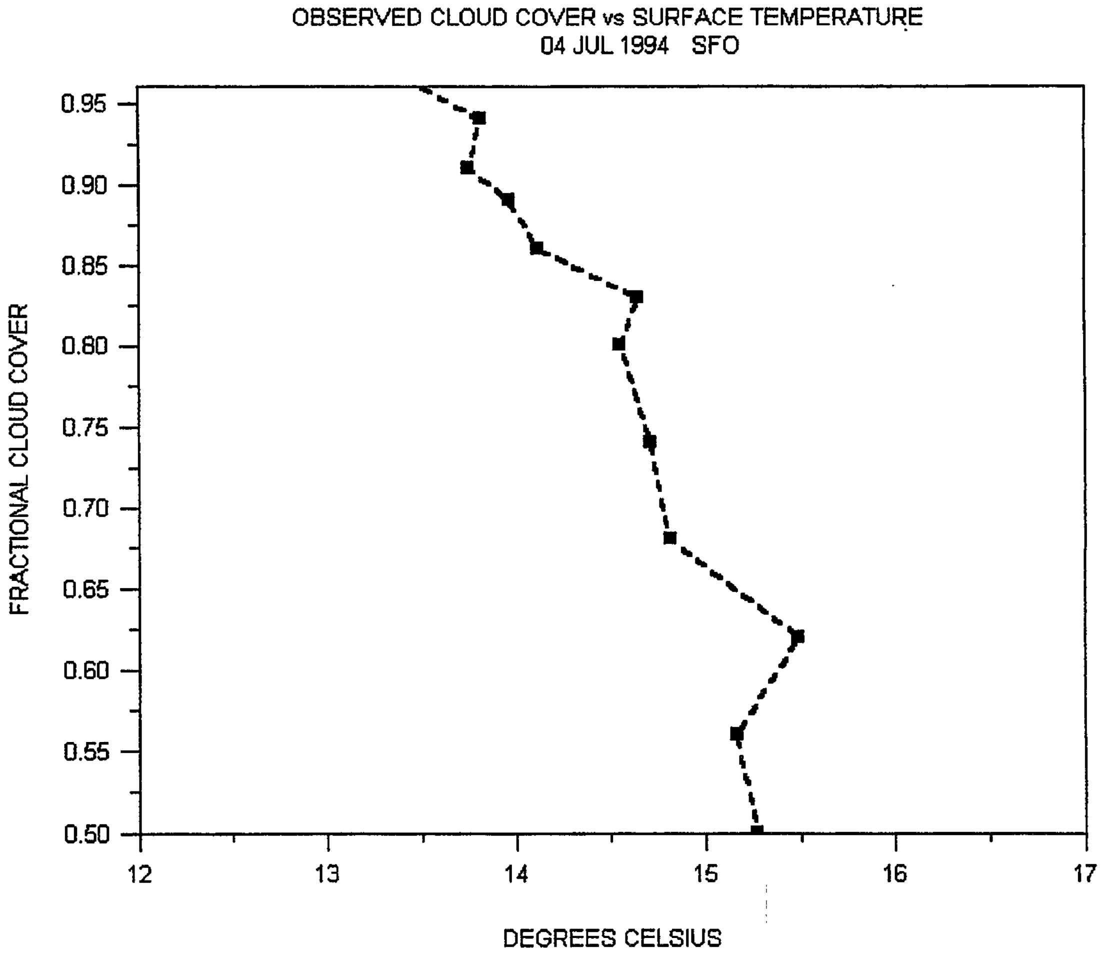


Figure 18. Cloud cover and surface temperature observed during stratus burn-off on 04 JUL 94 at SFO.

on the morning of 04 JUL 94. As the stratus changed from greater than 95 percent (Broken) to 50 precent (Scattered) coverage, the surface temperature warmed approximately 1.5 °C. This transition occurred over a period of only about one hour. In the San Francisco Bay area, relative humidity at the stratus cloud level is mostly a function of temperature at that level, rather than a function of changes in water vapor. For the case of a well-mixed boundary layer with a constant potential temperature (a reasonable assumption for most SFO stratus burn-off events), changes in the surface temperature are the same as changes in the cloud-level temperature. While the column model performance seen using the MEM data sets suggests that it would do well in supporting burn-off forecasts, a final conclusion will rest upon further evaluation using SFO field site data planned for summer '95 and beyond. This is partly because of the intimate connection between the amount of cloud cover (stratus) and the rate of heating of the boundary layer that can lead to a rapid acceleration in the rate of stratus burn-off. To resolve this issue effectively, much better cloud cover data will be required than what is currently available operationally.

6. SUMMARY

Evaluation of two column-model implementations for the first experiment set provided some encouraging results. When viewed in terms of potential temperature error growth at the tower level, the general performance of both versions was quite good. The flux-forced column model performed better, however, particularly during periods of high level cloud (above the ABL). For optimal atmospheric boundary conditions, performance of the flux-forced OSU model was significantly better than that of the original OSU model version using surface fluxes estimated from its own SVAT module. For non-optimal atmospheric ABL conditions, performance of the flux-forced OSU model is still significantly better than the original OSU model. Furthermore, performance of the flux-forced OSU model under non-optimal atmospheric conditions is comparable to that of the original OSU model during optimal ABL conditions.

A number of potential sources of error for this study have been identified. These potential sources of error include:

1. Biased sensor data,
2. Inaccurate cloud cover (OSU model SVAT flux version only),
3. Ignoring horizontal advection and other forcing due to the atmosphere's circulation,
4. Setting mean vertical motion to zero and
5. Model spin-up.

In the cases discussed in this report, only the effect of inaccurate cloud cover is considered to be a significant problem. Since the effect of cloud cover is captured in the measured surface fluxes used by the flux-forced OSU model, this source of error only affects the original version of the OSU model. Model spin-up is evident, but does not appear to be a significant problem.

Further efforts necessary to investigate the OSU column model's applicability to supporting wake vortex and ITWS C&V products would appear to be worthwhile. The vertical structure - or vertical stratification - of the lower atmosphere was among a number of factors, including turbulence and vertical wind shear, that were examined. Greene's (1986) analysis of the lower atmospheric environment's influence on the dissipation rate of wake vortices shows that errors in the vertical temperature gradient °C per 100 m can result in errors in vortex lifetime estimates of about a factor of two. Based on Greene's conclusion, the accuracy typically seen in column model vertical potential temperature structure predictions would limit errors in wake vortex dissipation rates to within a factor of two.

Given the current working hypothesis for the San Francisco stratus burn-off phenomenon that rests largely on warming of the marine boundary layer by surface heat flux, the OSU model would also appear to be well suited for addressing this particular problem. Due to the strong dependency of boundary layer warming on the amount of solar radiation, however, one particularly critical factor necessary for a successful application of the OSU column model as part of a stratus burn-off forecast system would seem to be the timely availability of significantly more precise observations of cloud cover than what is now provided operationally.

ACRONYMS, SYMBOLS AND ABBREVIATIONS

ABL	Atmospheric Boundary Layer
AGL	Above Ground Level
ASTER	Atmosphere-Surface Turbulent Exchange Research facility
CLASS	Cross-chain Loran Atmospheric Sounding System
COBEL	COuche Brouillard Eau Liquide (fog layer liquid water)
°C	Degrees Celsius
C&V	Ceiling and Visibility
DAVS-NS	Dynamic Atmospheric Vertical Structure Nowcast System
Hz	Hertz (cycles per second)
ITWS	Integrated Terminal Weather System
gm	grams
GMT	Greenwich Mean Time
kg	kilograms
km	kilometers
LT	Local Time
m	meters
mb	millibars
MEM	Memphis International Airport
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
OSU model	Oregon State University column model
p	atmospheric pressure
SAO	Surface Aviation Observation
SFO	San Francisco International Airport
SAV	State-of-the-atmosphere Variable
STORM-FEST	Storm-Fronts Experiment Systems Test
SVAT	Soil-Vegetation Atmospheric Transfer
t	time
T	atmospheric temperature
v	horizontal wind vector
w	vertical motion in height (z) coordinates
z	height above Earth 's surface
Z	Zulu (Greenwich Mean Time)
θ	atmospheric potential temperature ($\theta = T(1000/p)^{0.286}$)
ω	vertical motion in pressure (p) coordinates
∇	horizontal gradient vector operator

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