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The Relative Contributions of Data Sources and Forcing Components to the Large-Scale Forecast Accuracy of an Operational Model

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Abstract

In many fluid flows, the majority of the kinetic energy lies in the low wave number part of the energy spectrum. Recently, Browning and Kreiss showed that because this is the case for atmospheric flows, the solution of the diabatic three dimensional equations can be decomposed into a large-scale and residual component. Browning and Kreiss pointed out that this scale separation can be the mathematical justification for initially forecasting only the evolution of large-scale motions and then using those results as boundary conditions for limited area forecasts of developing smaller scale features. In this study, the relative contributions of some of the forcing components in an operational global weather prediction model are quantified in order to determine which are the major contributors to the large-scale forecast accuracy over time. This allows the complexity of the large-scale forcing to be chosen according to a preselected level of accuracy in the large-scale forecast. In a similar manner, the relative contributions of various observational data sources are quantified so that appropriate observational data sources can be chosen to satisfy the preselected level of accuracy.

1 Introduction

Recently, Browning and Kreiss (2002) pointed out that because the majority of the kinetic energy in the atmosphere is contained in the low wave number part of the energy spectrum (e.g. Daley 1991) , balanced large-scale flow should satisfy a particular hyperbolic system of equations forced by the large-scale part of the atmospheric heating for a certain period of time. In general, the various sources of atmospheric heating, e.g. latent heating and solar radiation, are not measured by the observational network, but are included in climate and weather prediction models using approximations of the heating processes called physical parameterizations. To ascertain the appropriate physical parameterization that should be included in the forcing of the hyperbolic system, it is reasonable to determine the relative contributions of the individual parameterizations to the forecast accuracy of a typical global weather prediction model. Then the dominant parameterizations can be added back sequentially to determine the ones that are essential in maintaining the accuracy of the large-scale forecast over time. Earlier, Browning and Kreiss (1996) also analyzed the rate of convergence to the slowly evolving solution when periodically in time inserting various types of data into a time dependent system with multiple timescales. The dependency of the accuracy of the large-scale forecast on the periodic insertion in time of various sources of observational data into the data assimilation scheme is also investigated.

The outline of this paper is as follows. In section 2, a brief overview of the Canadian Meteorological Centre (CMC) global operational model used in this study is given. In section 3, quantitative results on the change of the large-scale forecast accuracy when the physical parameterizations are added sequentially according to their importance are presented. Section 4 contains a discussion on the large-scale forecast accuracy when observational sources are added incrementally to the operational assimilation (periodic updating) precess according to their contribution to the forecast accuracy. The conclusions are contained in section 5.

2 Operational Model Overview

The separation of the solution of the diabatic equations that describe the evolution of the earth's atmosphere into two components based on the decay of the kinetic energy spectrum (Browning and Kreiss, 2002) suggests that the balanced, large-scale component of the solution can be computed using only the large-scale part of the initial conditions and forcing for some period of time. A series of experiments will be be made to determine the relative contribution of various observational data sources and physical parameterizations to the accuracy of the large-scale forecast. The operational model used in this study is the global Environmental Multiscale (GEM) model of the Canadian Meteorological Centre (CMC). Documentation of the numerical approximations and physical parameterizations used in the model at one stage in its continuing evolution are described in Côté et al. (1998) , and Mailhot et al. (1997) respectively. The operational assimilation system is an updated version of the three dimensional variational system described in Gauthier et al. (1999) . The most recent modifications to both the model and the assimilation system are described on the CMC web site (www.msc-smc.ec.gc.ca/cmc/index_e.html). For the purposes of this study, the operational forecasts were run using the configuration in use operationally at the time of the experiments (Spring 2002). The main characteristics of the model are the following:

- semi-Lagrangian, semi-implicit time discretization with a time step of 45 minutes;
- finite-element spatial discretization on a spherical grid with 0.9 degree resolution in latitude and longitude;
- complete physical parameterization, including:
  - Solar and infrared interactive radiation schemes;
  - Land-surface force-restore scheme;
  - Turbulent kinetic energy boundary layer scheme;
  - Surface layer;
  - Kuo-type deep convection scheme;
  - Non-precipitating shallow convection scheme;
  - Sundqvist stratiform condensation scheme;
  - McFarlane gravity wave drag scheme.

Although the results to be presented are only for this version of the CMC assimilation system and operational model, they should generalize to other comparable operational models. The behaviour of the GEM model was extensively tested against that of the previous operational model at CMC, a global spectral model (Ritchie and Beaudoin 1994) and was shown to have essentially the same error statistics for extended forecast periods in different seasons. The CMC web site plot of the time series for the root mean square errors (RMSE) in the forecast winds compared with radiosonde observations at 500 hPa at 48 and 120 hours for a suite of operational models is reproduced in Fig. 1. The GEM model's performance compares to that of other models. As can also be seen from this figure, the maximum large-scale errors occur in the winter months. An interesting atmospheric evolution period from February 05 to February 15, 2001 used to verify recent changes in the operational assimilation and model is also used in this study. (See Fig. 2)

3 Relative Contributions of Physical Parameterizations

As a first step in ascertaining the appropriate forcing to include in the hyperbolic system derived by Browning and Kreiss (2002) , it is reasonable to determine the relative contributions of the physical parameterizations included in the global operational model to the accuracy of the large-scale forecast over time. Then the dominant physical parameterizations can be added sequentially according to their order of contribution to the accuracy of the forecast. This process determines the complexity of the large-scale forcing that is required to match the operational level of large-scale forecast accuracy for a given period of time. In the experiments described in this section, all of the initial conditions were produced by the operational three dimensional variational data assimilation scheme (Gauthier et al. 1999) .

The easiest modifications of the CMC operational model can be accomplished through flags in a configuration (input) file. Thus the initial experiment consisted of comparing the accuracy of the operational model with a no physics (dynamics and topography, but no mountain drag) version of the operational model. The results for this experiment (and the ones that follow) were produces by a standard CMC graphics package that computes the errors in a forecast of the longitudinal velocity component (UU), the speed (UV), the geopotential height (GZ), and the temperature (TT) relative to radiosonde observations as a function of height (hPa) over a given subdomain of the earth. The original package has been modified slightly to show the relative l_2 errors

$$l_2 = \sqrt{\frac{\Sigma\left[(F-O)-\mu_{(F-O)}\right]^2}{\Sigma\,(O-\mu_O)^2}} \tag{1}$$

where F is the forecast, and O the observations, of each of these fields as a function of height for a control (thick line) and comparison (thin line) forecast. Figures 3, 4, and 5 show the average errors for the 21 forecasts initialized at 0 and 12Z during the period mentioned in section 2 of the operational (control) and no physics (comparison) version of the GEM model over North America at 0, 24 and 48 hours, respectively. Note that typically the velocities near the surface are small so that large relative errors there would not be as significant in an l_2 norm over the entire subdomain.

The boundary layer parameterization appears to play an important role in maintaining the quality of the forecast. The turbulent vertical diffusion scheme in the operational model was originally developed by Mailhot and Benoit (1982) and described in Benoit et al. (1989) {Benoi:89. The treatment of eddy vertical diffusion rests on a time-dependent equation for the turbulent kinetic energy (TKE). Vertical transfers due to turbulent air motion are parameterized in the form of vertical diffusion, with the tendencies calculated as follows:

$$\frac{\partial\psi}{\partial t} = \frac{1}{\rho}\frac{\partial}{\partial z}\left[\rho K_\psi\left(\frac{\partial\psi}{\partial z}-\gamma_\psi\right)\right] \tag{2}$$

where ψ is u, v, the relative humidity q, or the potential temperature θ, while ρ is the density. The vertical diffusion coefficients K_ψ are variable and reflect the intensity of the turbulent exchanges. The symbol γ_ψ represents a counter-gradient term. When this parameterization was reintroduced in the otherwise adiabatic model, the large-scale forecast accuracy of the simplified model was very close to that of the operational model especially for the first day, as can be seen in Figs. 6 and 7. The use of a simpler boundary layer parameterization, where the cross-gradient term γ_ψ is dropped, and where the diffusion coefficients K_ψ are constant in time and vary in the vertical following a prescribed cubic profile, produced similar results to the more complex TKE scheme. Figs. 8 and 9 show the average errors of the operational (control) and simple boundary layer (comparison) version of the GEM model over North America.

A simple parameterization of planetary boundary layer appears therefore to be sufficient to maintain forecast accuracy comparable to the operational model for a 24 hour, large-scale forecast. Figure 10 and 11 compares the 24 hour forecast of the absolute vorticity fields obtained from the operational model, and model with only a simple PBL parameterization. The comparable accuracy of the two forecasts translates into very similar large-scale fields.

4 Relative Contributions of Observational Sources

There are a number of sources of observational data of varying quality (for a review of these sources see Daley 1991) . There has been considerable debate as to the scientific value of the various sources, especially relative to their cost. Earlier, Browning and Kreiss (1996) analyzed the most efficient method to periodically insert data in time into a multiple timescale system to reproduce the slowly evolving component. The CMC three dimensional assimilation system (Gauthier et al. 1999) combines different observational data sources with a previous model forecast (background) to produce an analysis (initial conditions) on the model grid every 6 hours. This approach is similar to periodic updating. The main characteristics of the CMC system are the following:

- Incremental method based on a spectral T119 model;
- 28 model levels from the surface to 10 hPa for the vertical resolution;
- Analysis variables are:
    - Streamfunction;
    - velocity potential;
    - temperature;
    - surface pressure;
    - specific humidity.

and it uses the following data sources:

- Radiosondes;
- Dropsondes;
- Aircraft Meteorological DAta Report (AMDAR) and Aircraft Addressing and Reporting System (ACARS);
- Advanced TIROS Operational Vertical Sounder (ATOVS) radiances;
- Satellite winds (SATWINDS) from GOES-8 and 10.

The relative contribution of a number of the observational data sources to the large-scale forecast accuracy was determined and then the data sources added back according to their importance to the accuracy of the forecast for the North American continent. A series of 15 day data assimilation cycles were performed, starting on Feb. 01 2001. From the last 10 days of each cycle, 21 analyses valid at 0 and 12Z were used to initialized the forecasts.

Figure 12 shows the average errors over North America for the 21 analyses for the period mentioned in section 2 done with the complete operational data set (control) and with only the radiosonde observations (comparison) . The error profiles are very similar, with only a slight advantage for the series with the full data set. Figures 13 and 14 show the average forecast errors at 12 and 24 hours, respectively, for the 21 forecasts initiated from these two sets of analyses.

Clearly, the radiosondes (RAOBS) observations play a major role in the short term accuracy of the forecast. However, differences in the analyses not detected in Fig. 12 are responsible for the differences in behaviour of the two sets of integrations. A possible explanation, reinforced by the differences in error patterns between the Eastern and Western part of North American shown in Fig. 15 and 16, is that analysis differences over the Pacific Ocean, i.e. upwind of the region of verification, are advected over the area of interest during the course of the forecast. Figure 17 shows for one case (Feb. 6 2001 0Z) the differences over the Northern Hemisphere for the 250 hPa zonal wind between the analysis performed with the operational data set, and the one that included only the radiosondes. The differences over North America are negligible, as can be expected from Fig. 12, but are significant over the oceans.

For this particular period, an improvement in the quality of the forecast is gained from adding to the radiosonde data one of two data sources. Figures 18 and 19 show the average errors when the ATOVS data, and the AMDAR and ACARS data are added to the RAOBS, respectively. The impact of either one of these data sets, which offers data coverage over the oceans, is significant, and leads to short term large-scale forecasts over North America of comparable quality to those obtained when the full operational data set is used. The ATOVS data have the advantage of offering a global coverage, but rely on complex radiative transfer models (RTTOV), and are effective only in areas where cloud opacity does not exceed a given threshold. The radiances provide information on temperature, and to a lesser degree specific humidity. Wind information is indirectly inferred from these observations through the multivariate formulation of the background error statistics used in the analysis. This is not the case for the wind data included in the AMDAR and ACARS data sets, which directly measures the dominant component of the slowly evolving solution (Browning and Kreiss 1996).

5 Conclusion

Browning and Kreiss (2002) pointed out that the balanced large-scale atmospheric flow should satisfy a particular hyperbolic system of equations forced by the large-scale part of the atmospheric forcing for a certain period of time. In general, forcing is included in atmospheric model through the use of approximations known as physical parameterizations. To ascertain which of these parameterizations play a significant role in the short term accuracy of large-scale forecasts, several numerical simulations were made with the operational forecast model GEM of the Canadian Meteorological Centre (CMC). The results obtained show that the inclusion of a simple parameterization of the eddy viscosity in the planetary boundary layer is sufficient to obtain large-scale forecasts of up to 24 hours that are of comparable accuracy to those obtained from the operational model with its full set of parameterization.

The accuracy of the hyperbolic system also depends on the accuracy of the initial conditions. A number of observational data sources are used operationally in the analysis process. Each contributes to a various degree to the quality of the analysis, and the forward models used to obtain model equivalent of the different observations range greatly in complexity. The dependency of the accuracy of the large-scale forecast on the data used in the three dimensional data assimilation of CMC was investigated. Results confirmed the importance of the radiosonde data to the quality of the forecast. They also show the necessity to update the large-scale information upwind from the area of interest to maintain forecast accuracy. This was done by adding to the radiosondes data either the ATOVS data which require a complex radiative transfer model but offer global coverage, or the AMDAR and ACARS observations for which the forward model is trivial (interpolation), but whose coverage especially in the Sourthern Hemisphere is not as extensive.

On the basis of these results, it is clearly possible with a simplified system where parameterizations have been reduced to a simple vertical diffusion in the boundary layer, and periodic updating incorporates only two data sets, to obtain short range large-scale forecasts of the same accuracy as those provided by a more complex system.

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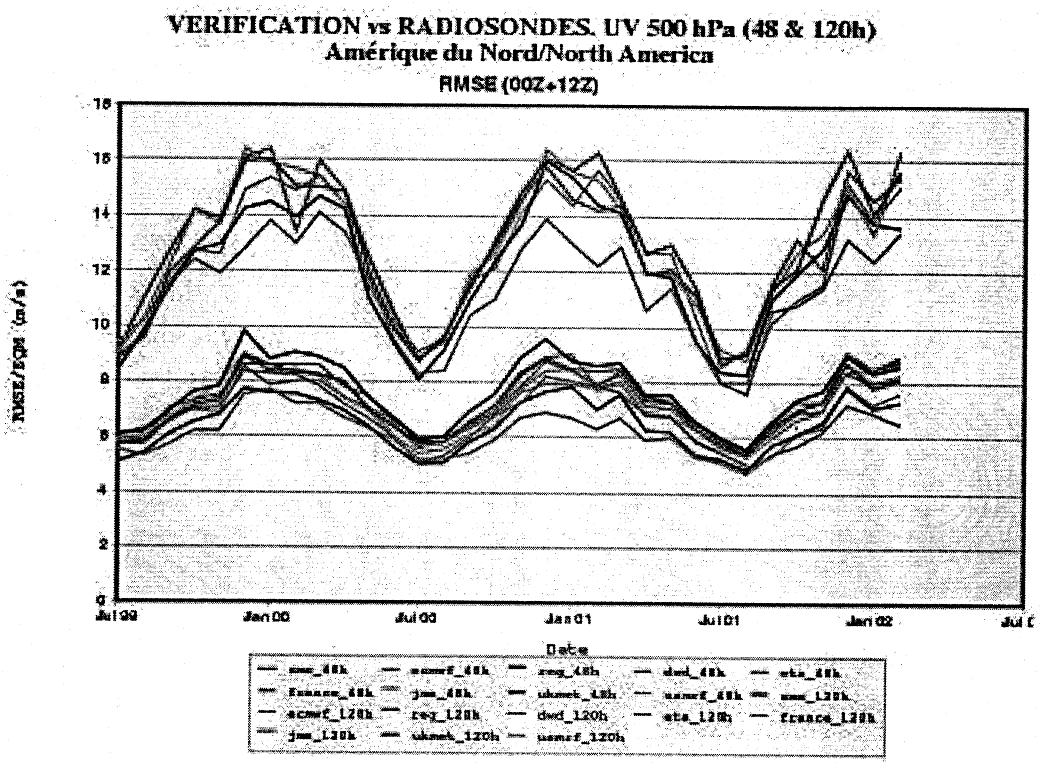


Figure 1: Verifications against radiosondes over North America of 500 hPa winds.

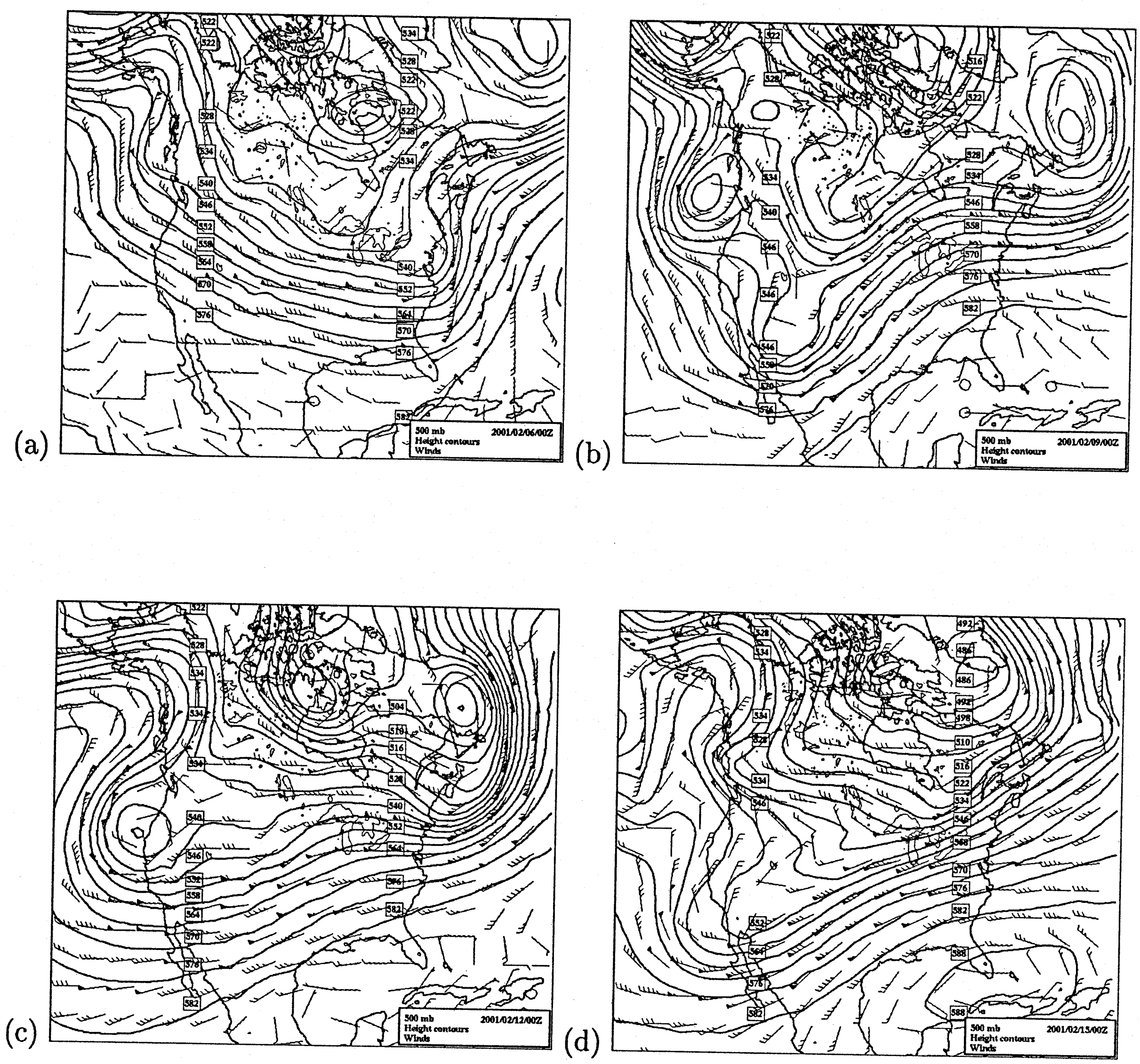


Figure 2: Synoptic situation over North America for (a) Feb. 06, (b) 09, (c) 12, and (d) 15, 2001.

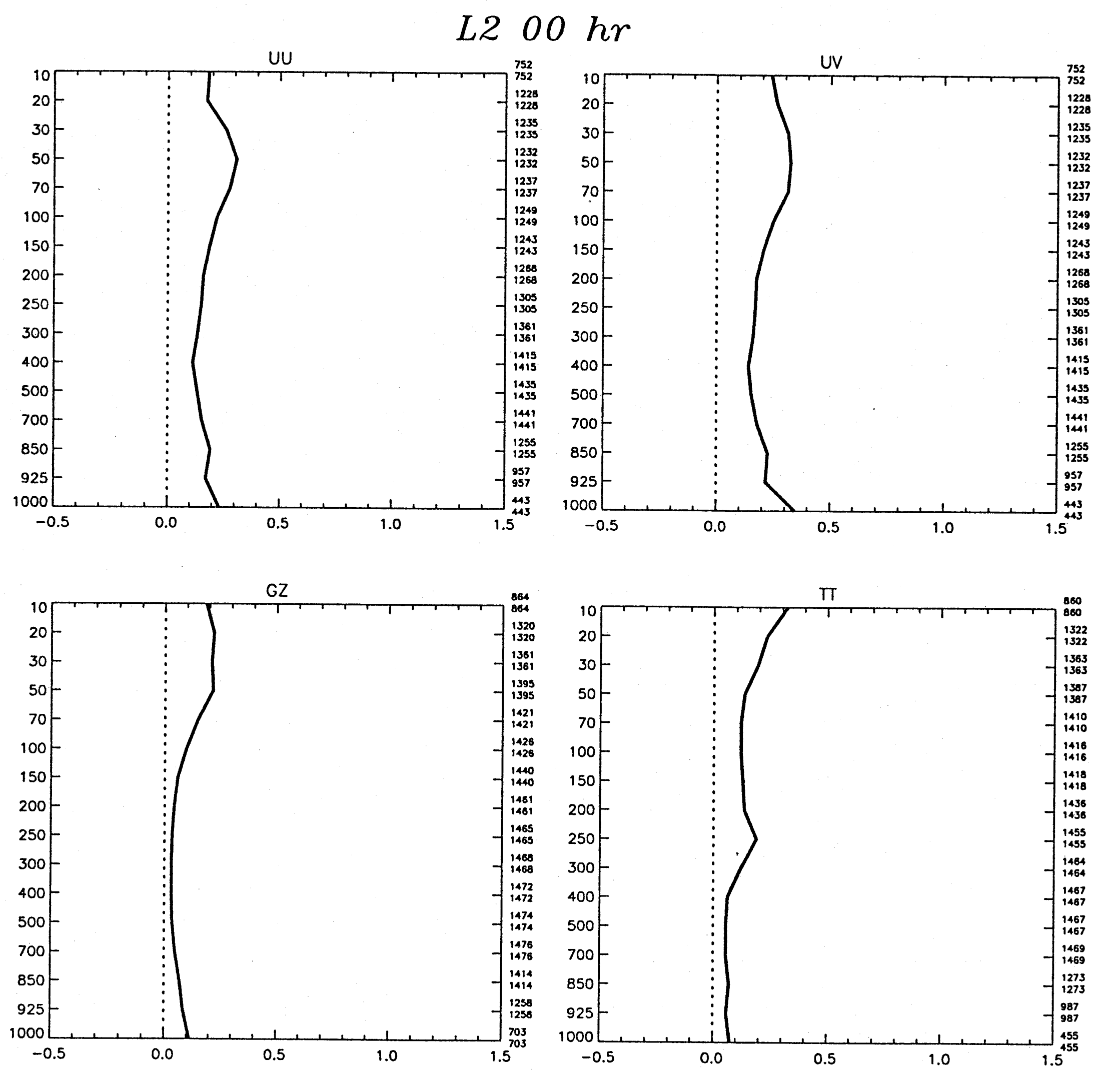


Figure 3: Operational model vs "no physics" model; average of 21 forecasts; verification against radiosondes at 0hr over North America.

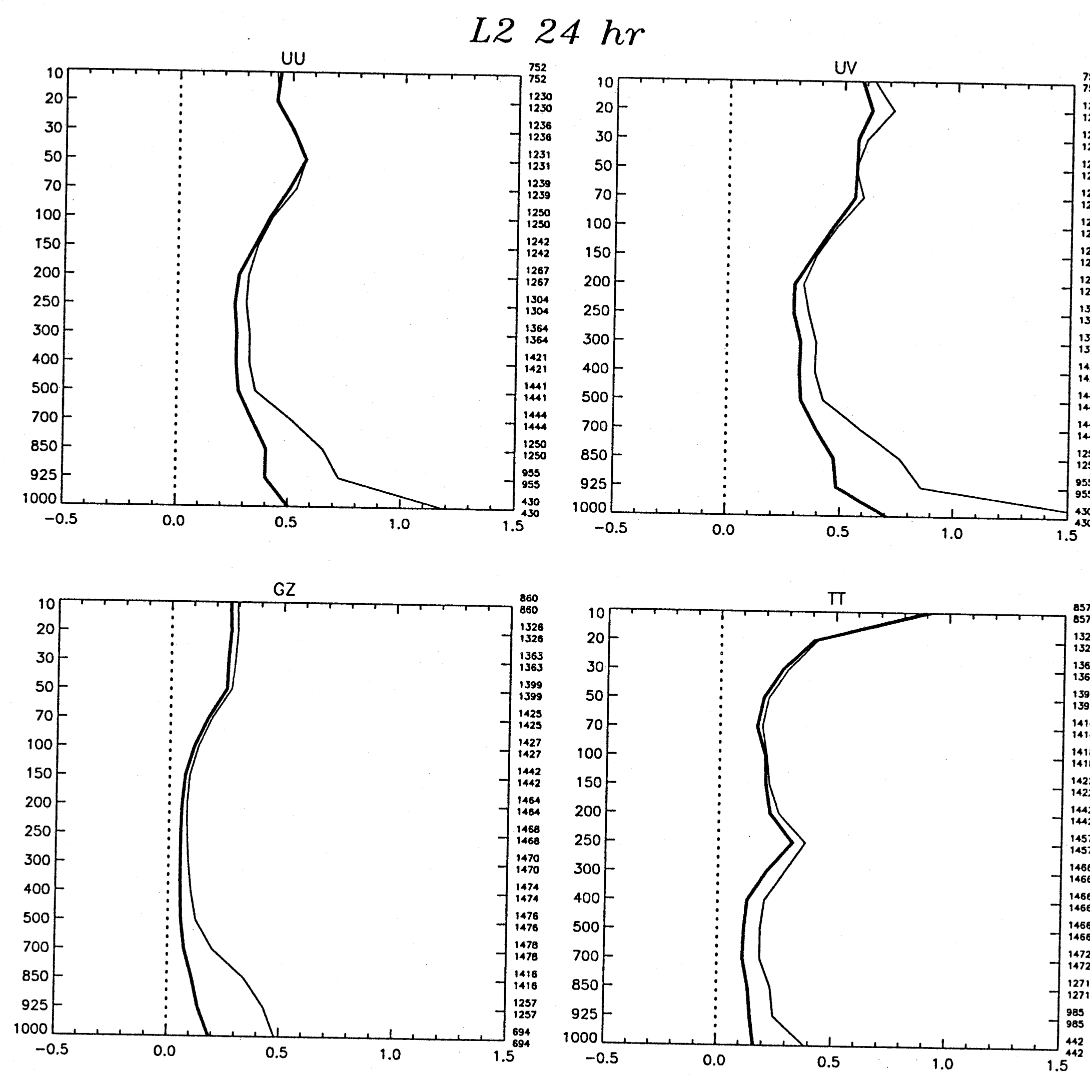


Figure 4: Operational model vs "no physics" model; average of 21 forecasts; verification against radiosondes at 24hr over North America.

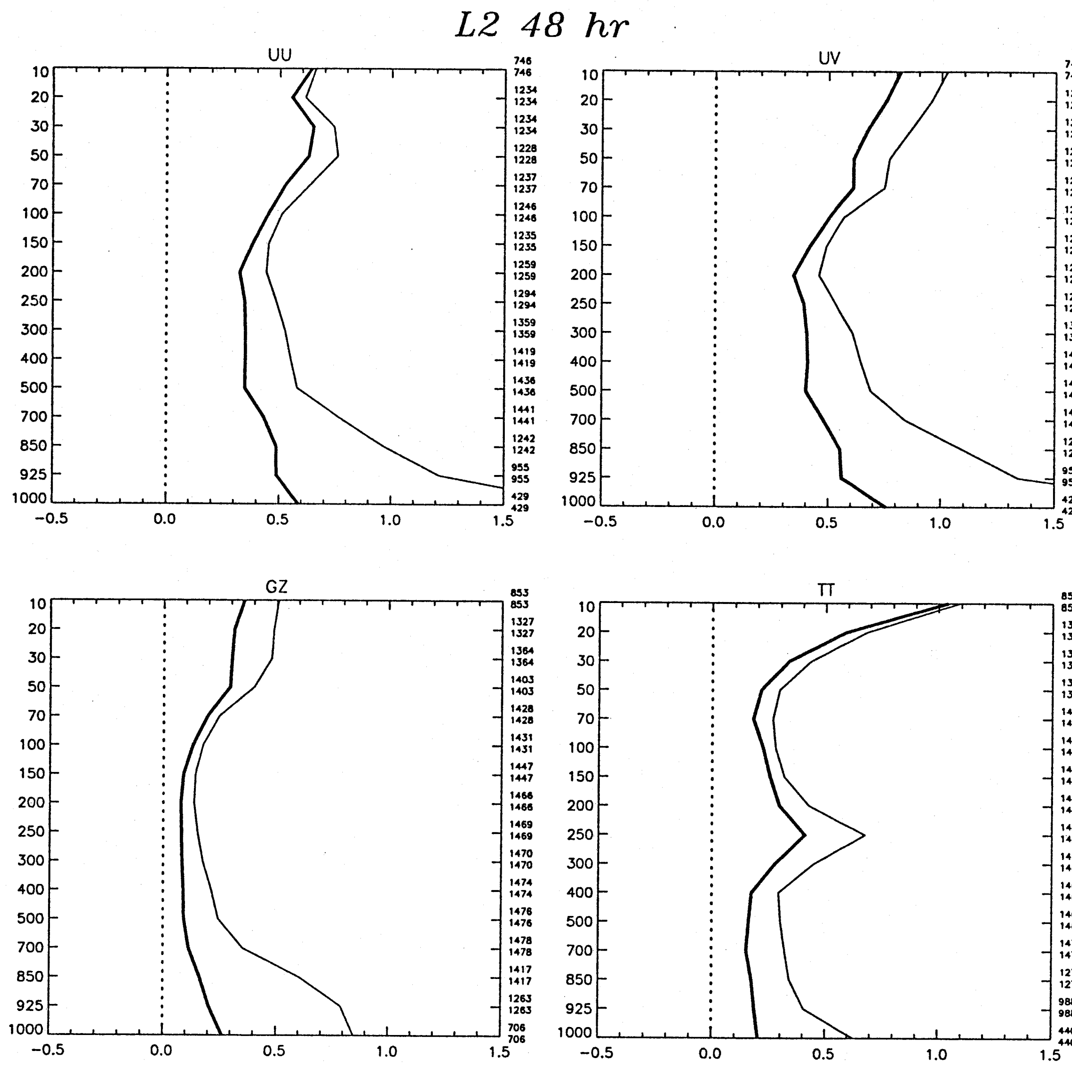


Figure 5: Operational model vs "no physics" model; average of 21 forecasts; verification against radiosondes at 48hr over North America.

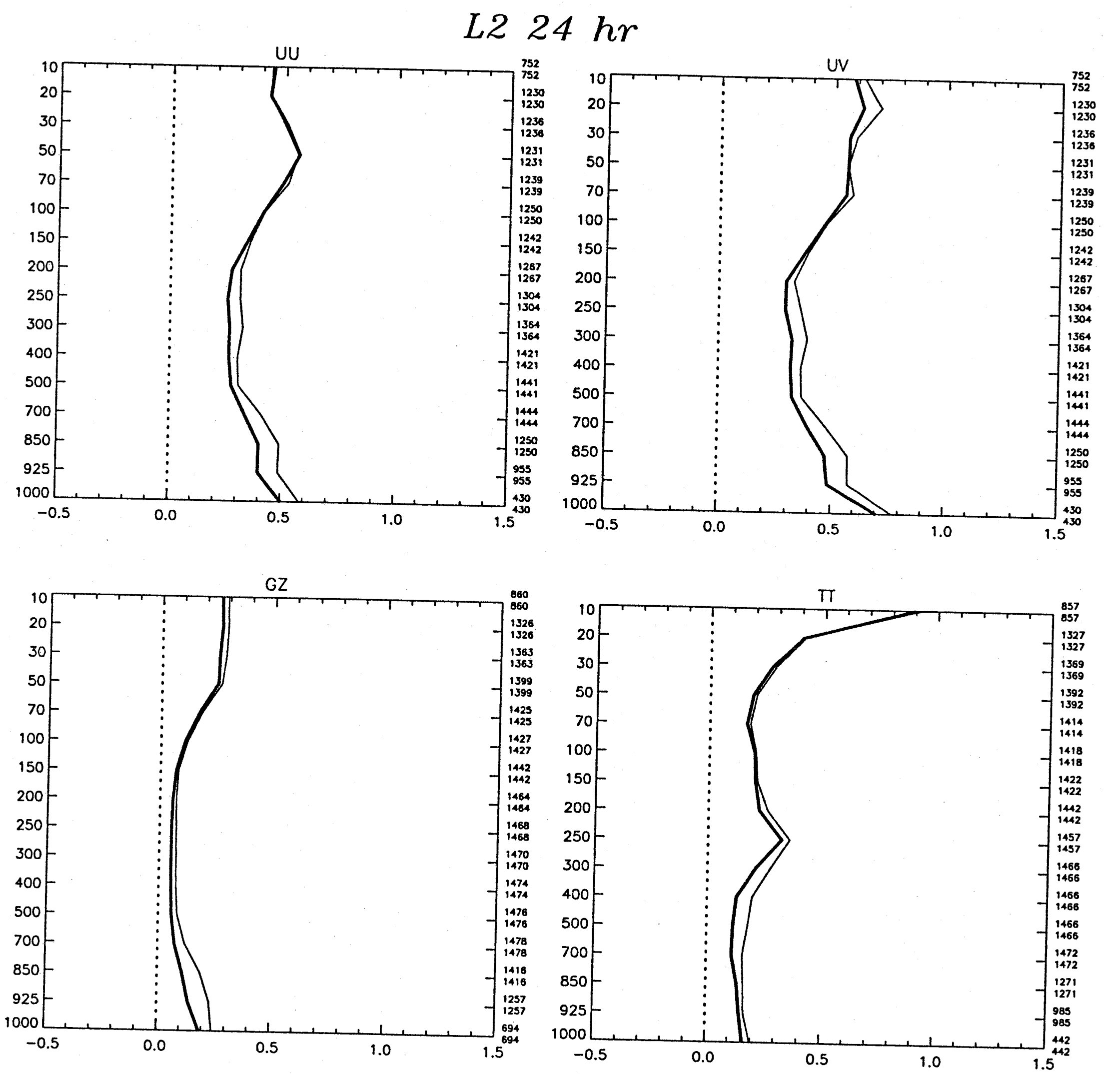


Figure 6: Operational model vs operational PBL model; average of 21 forecasts; verification against radiosondes at 24hr over North America.

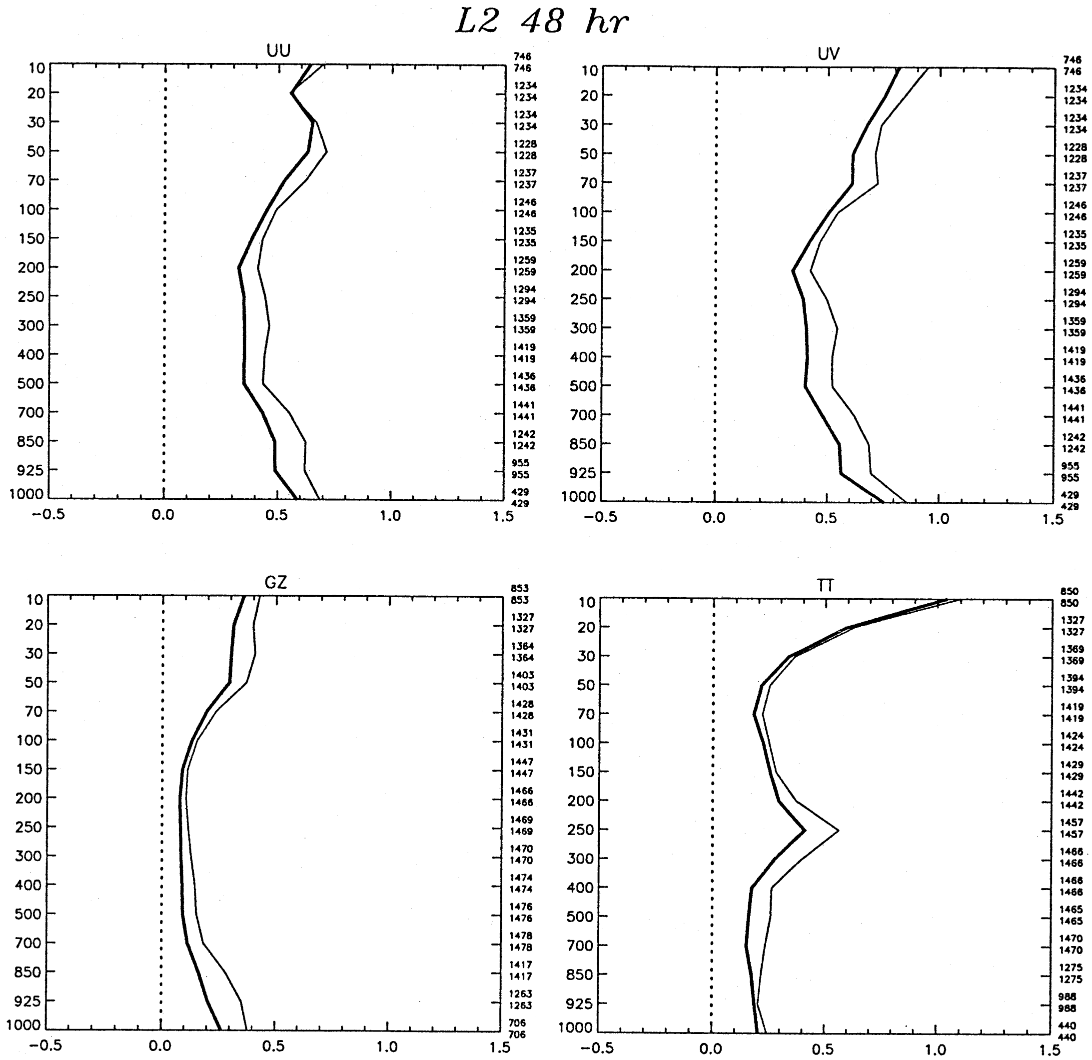


Figure 7: Operational model vs operational PBL model; average of 21 forecasts; verification against radiosondes at 48hr over North America.

L2 24 hr

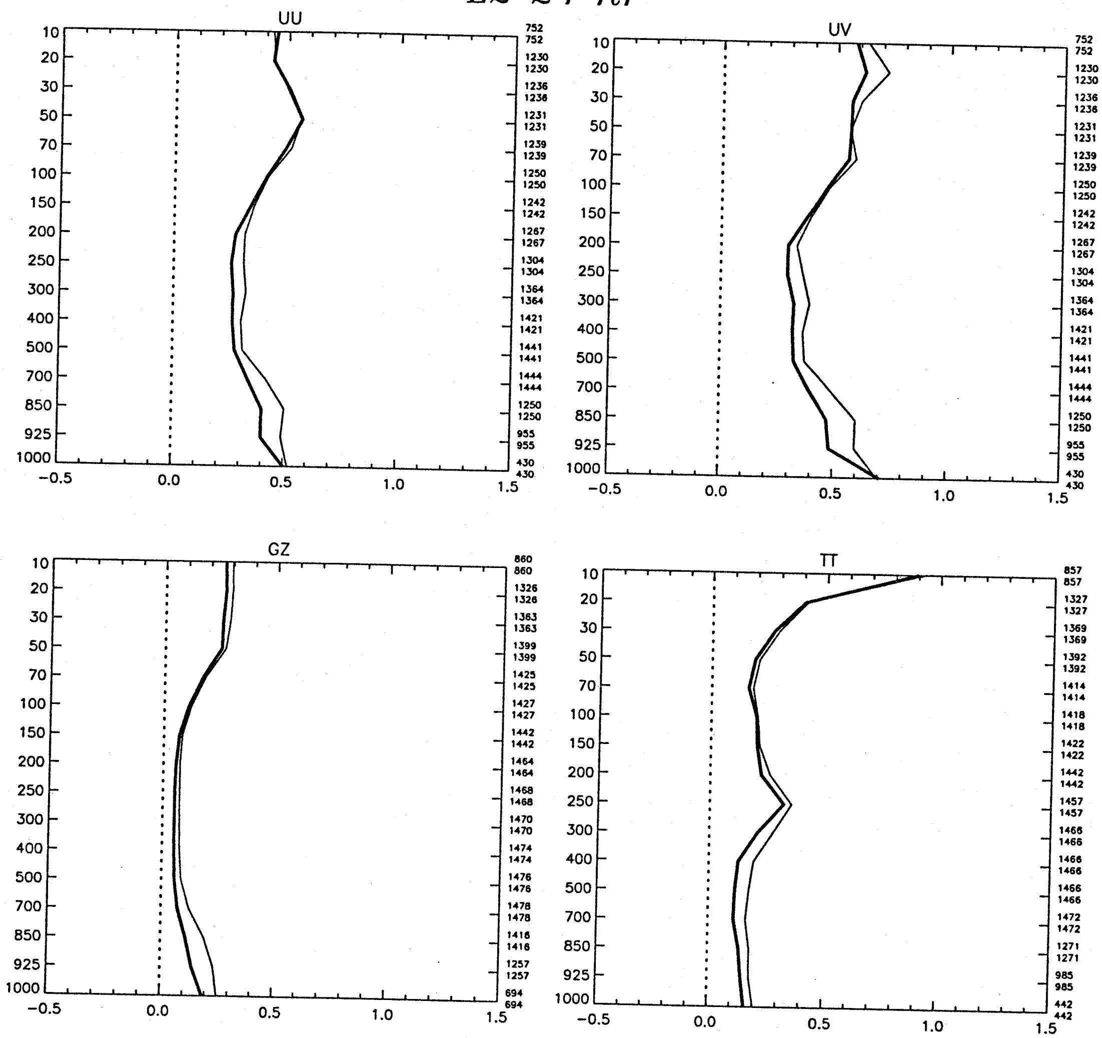


Figure 8: Operational model vs simple PBL model; average of 21 forecasts; verification against radiosondes at 24hr over North America.

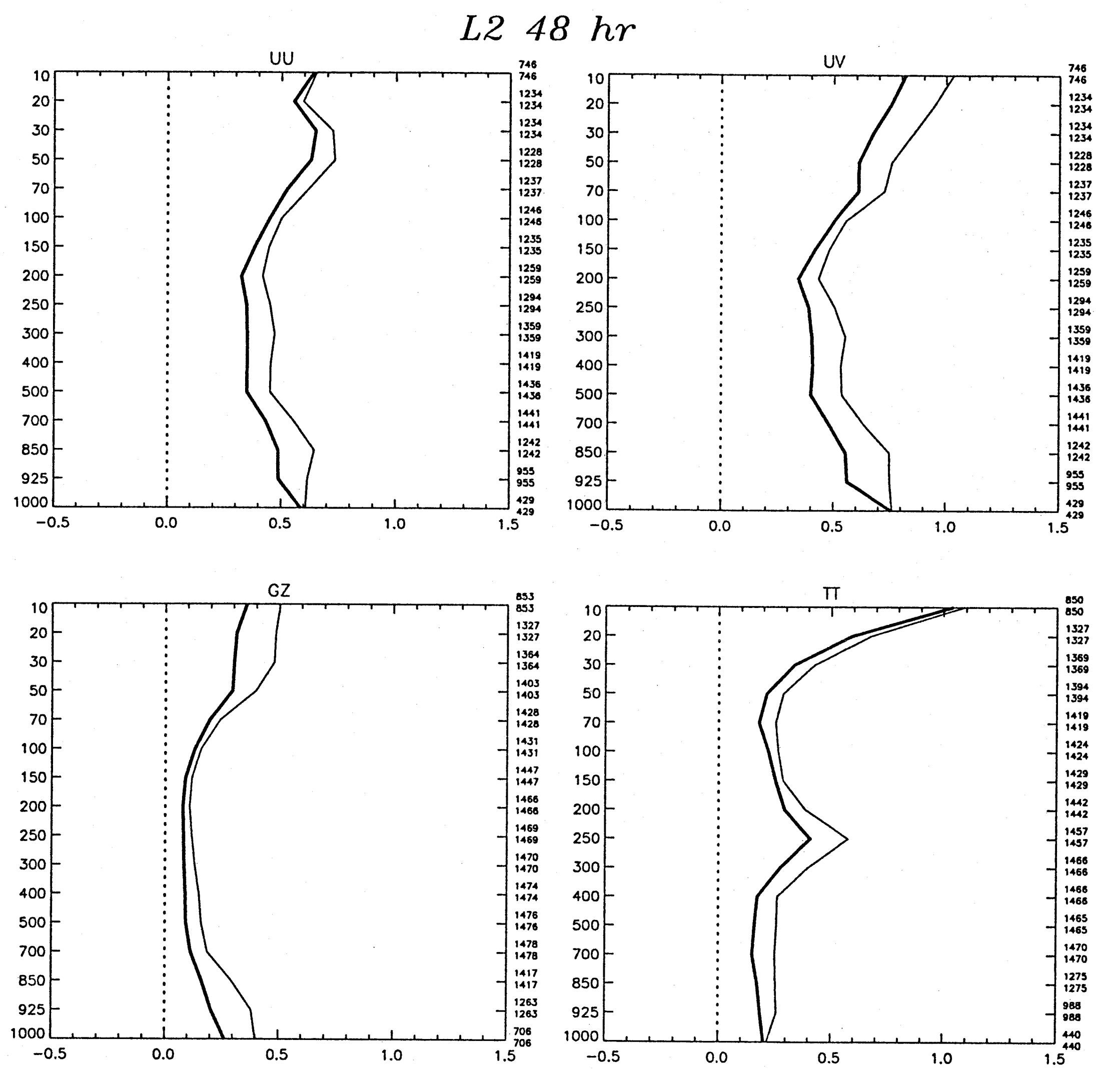


Figure 9: Operational model vs simple PBL model; average of 21 forecasts; verification against radiosondes at 48hr over North America.

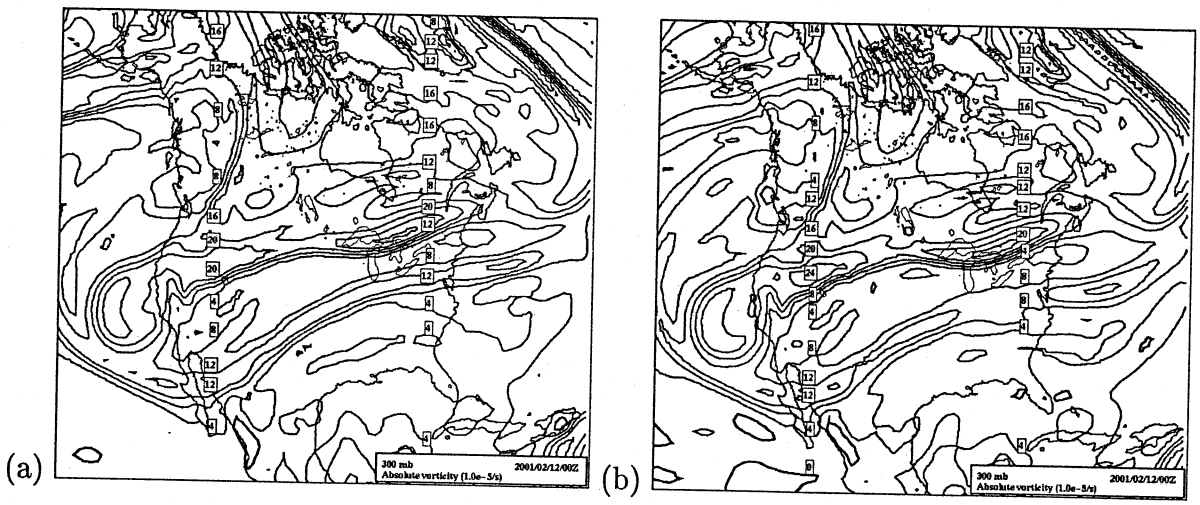


Figure 10: 24 hour forecast of absolute vorticity at 300 hPa over North America from (a) operational model, (b) model with only a simple boundary layer parameterization.

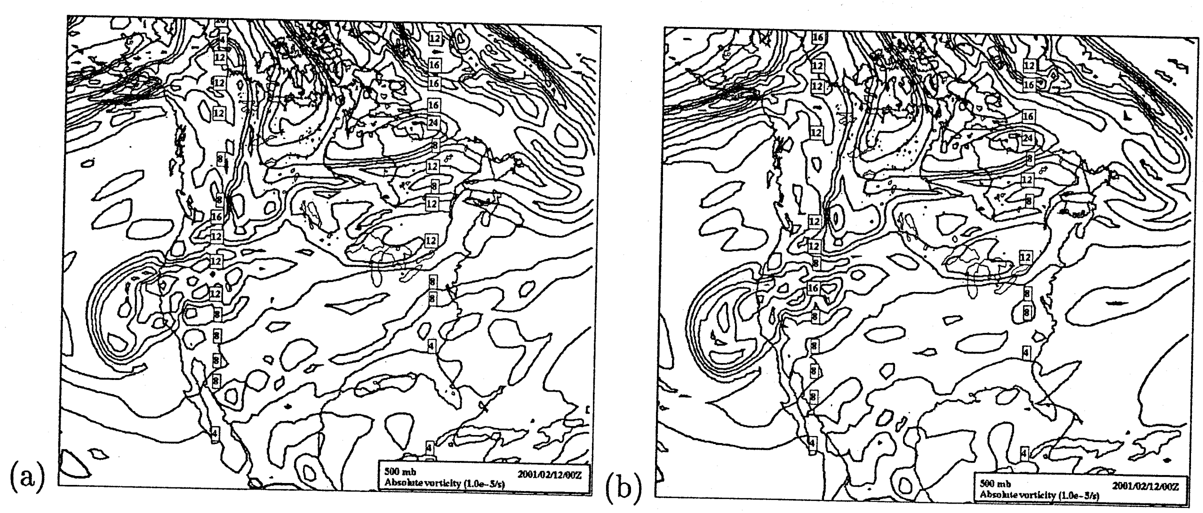


Figure 11: Same as Fig. 10, but at 500 hPa.

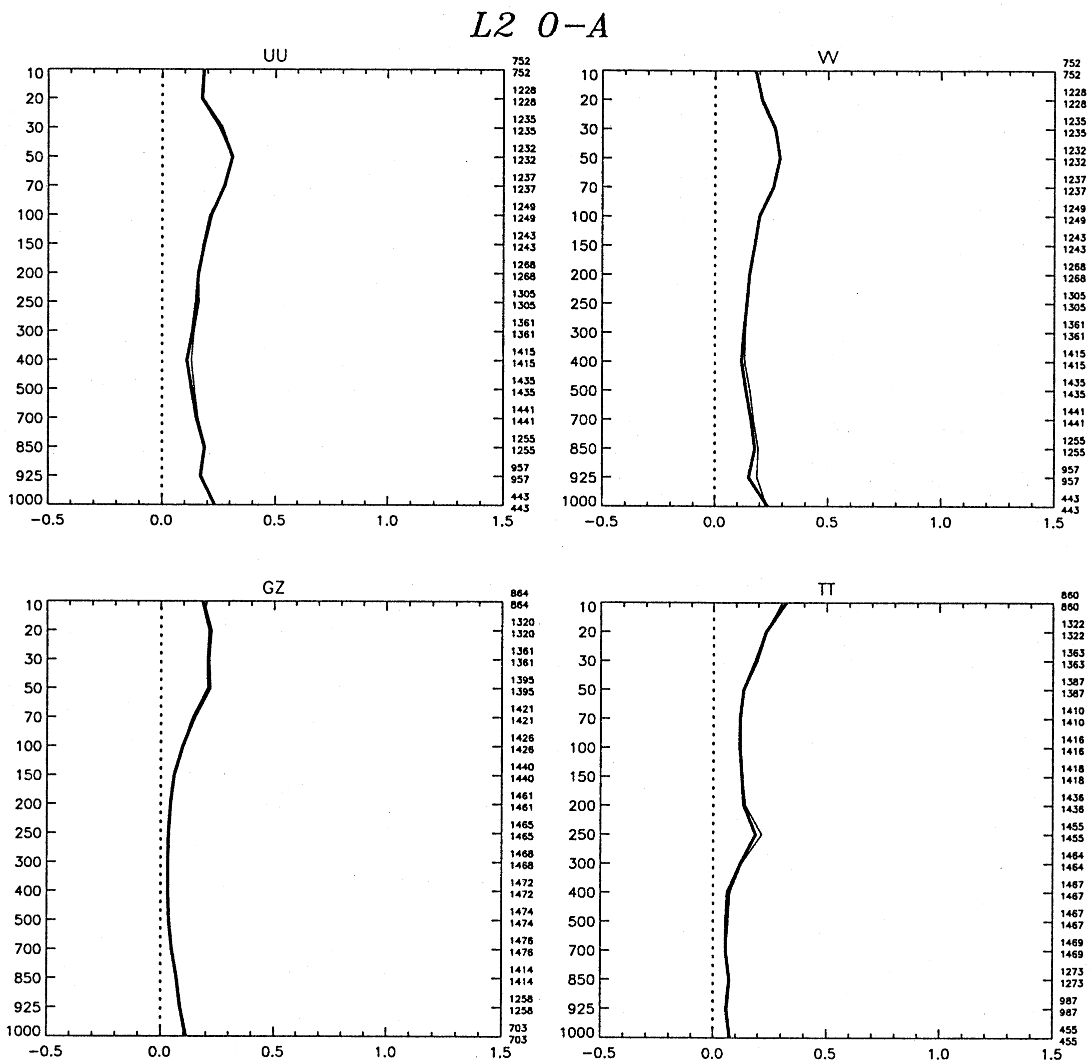


Figure 12: Analyses using complete operational data set vs analyses using only radiosonde data; average of 21 analyses; verification against radiosondes over North America.

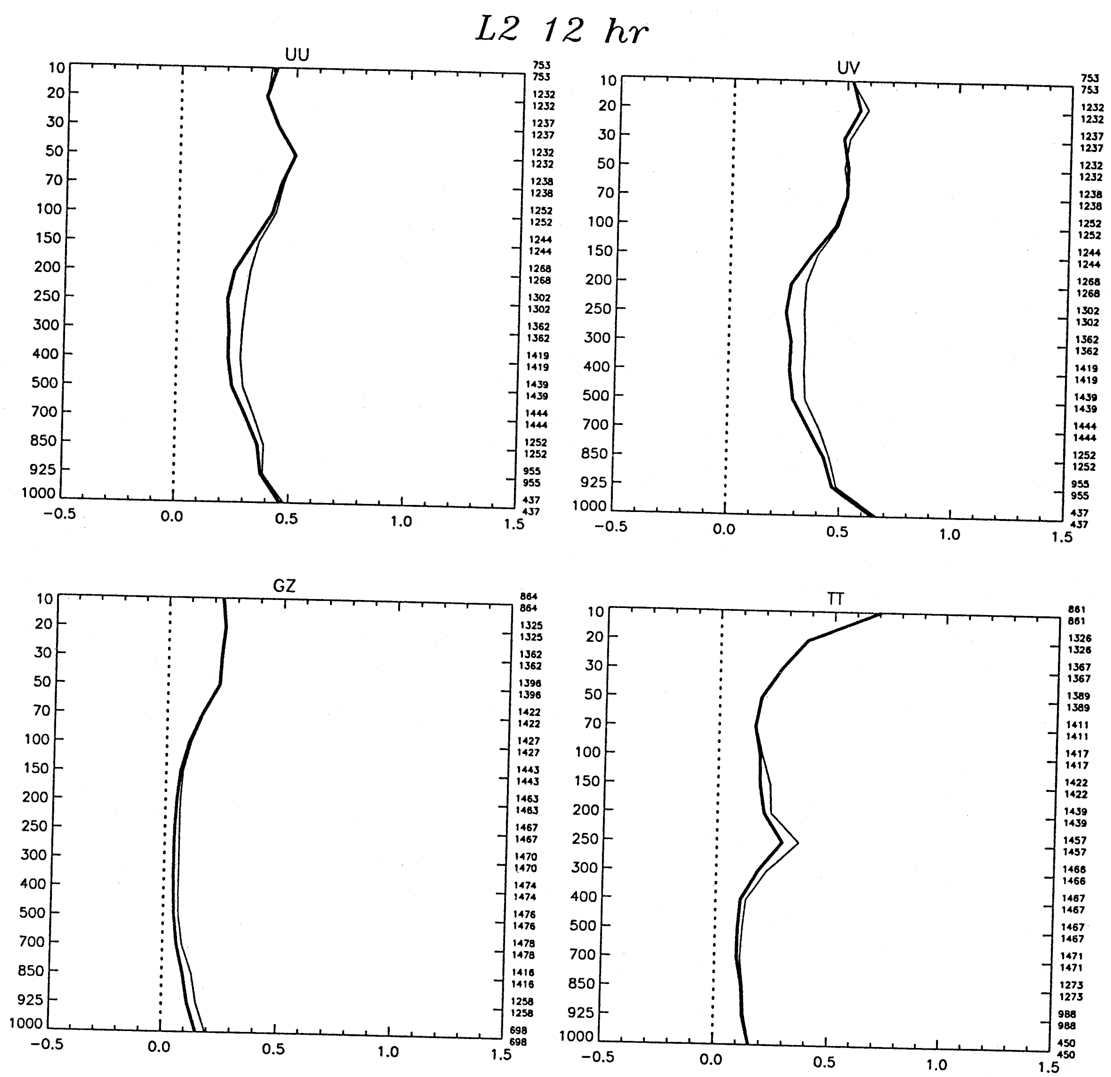


Figure 13: Forecasts initialized from the operational data assimilation system vs those initialized from an assimilation cycle using only the radiosondes; average of 21 forecasts; verification against radiosondes at 12 hour over North America.

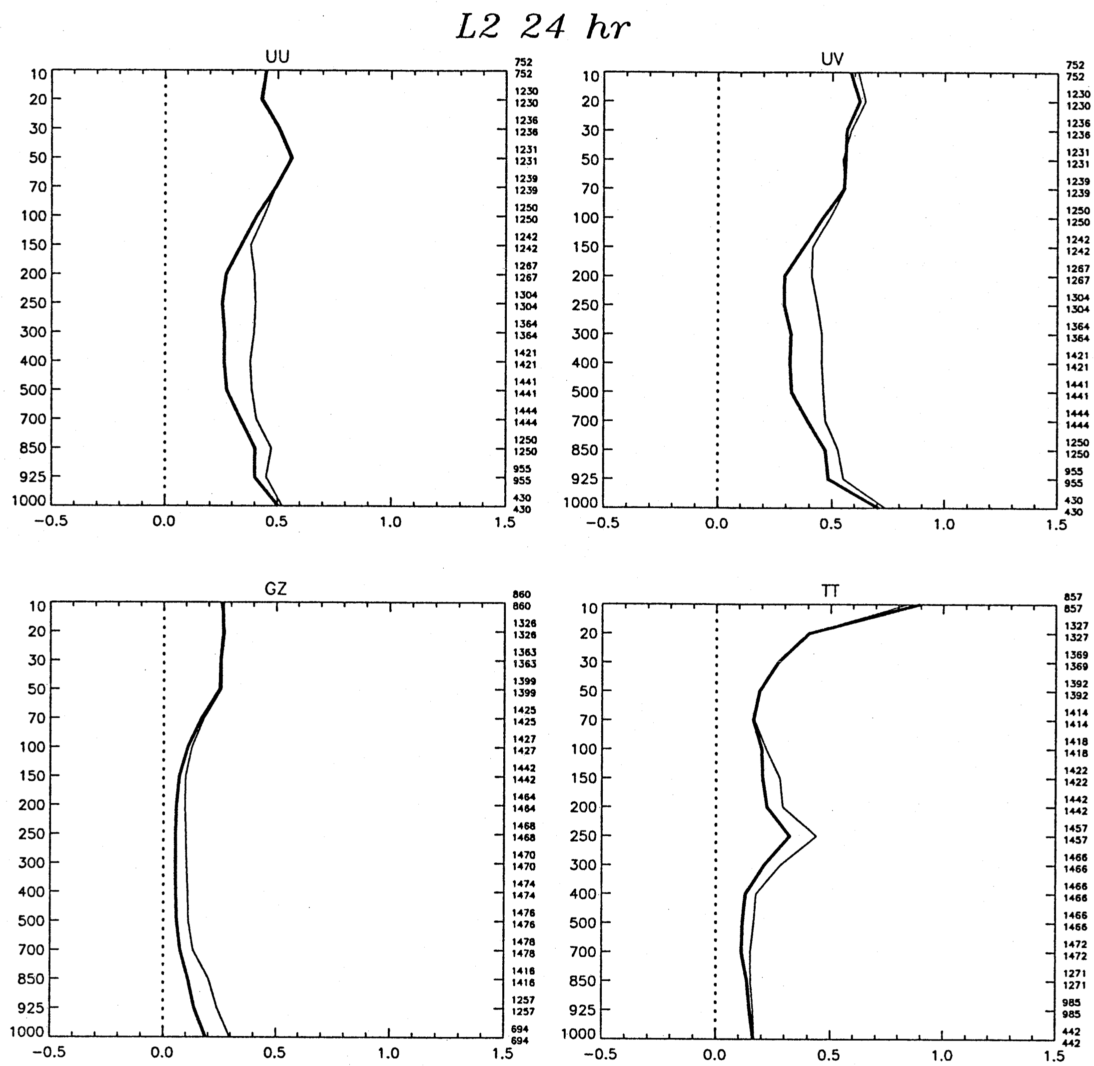


Figure 14: Forecasts initialized from the operational data assimilation system vs those initialized from an assimilation cycle using only the radiosondes; average of 21 forecasts; verification against radiosondes at 24 hour over North America.

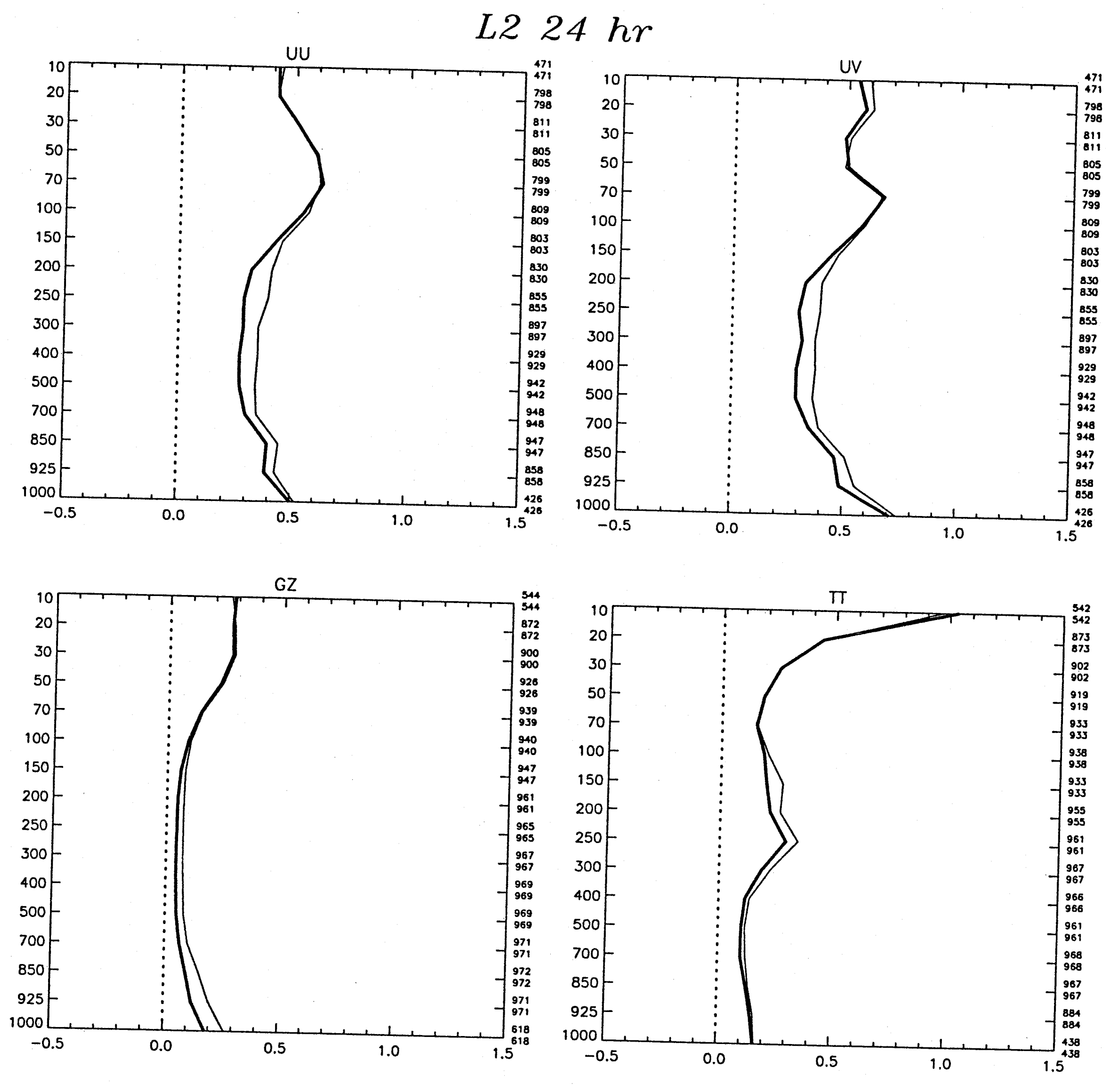


Figure 15: Same as Fig. 14, but verification over Eastern North America.

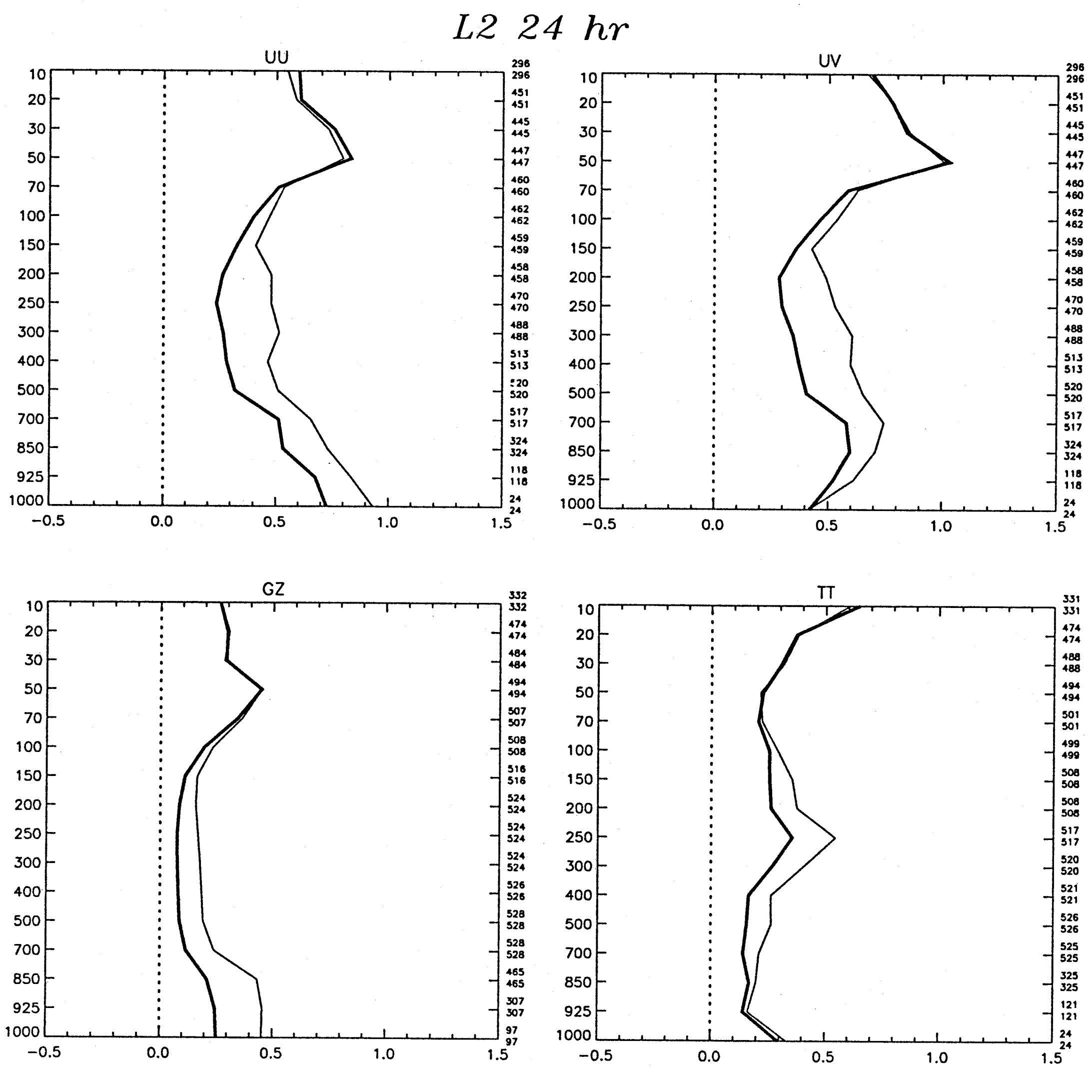


Figure 16: Same as Fig. 14, but verification over Western North America.

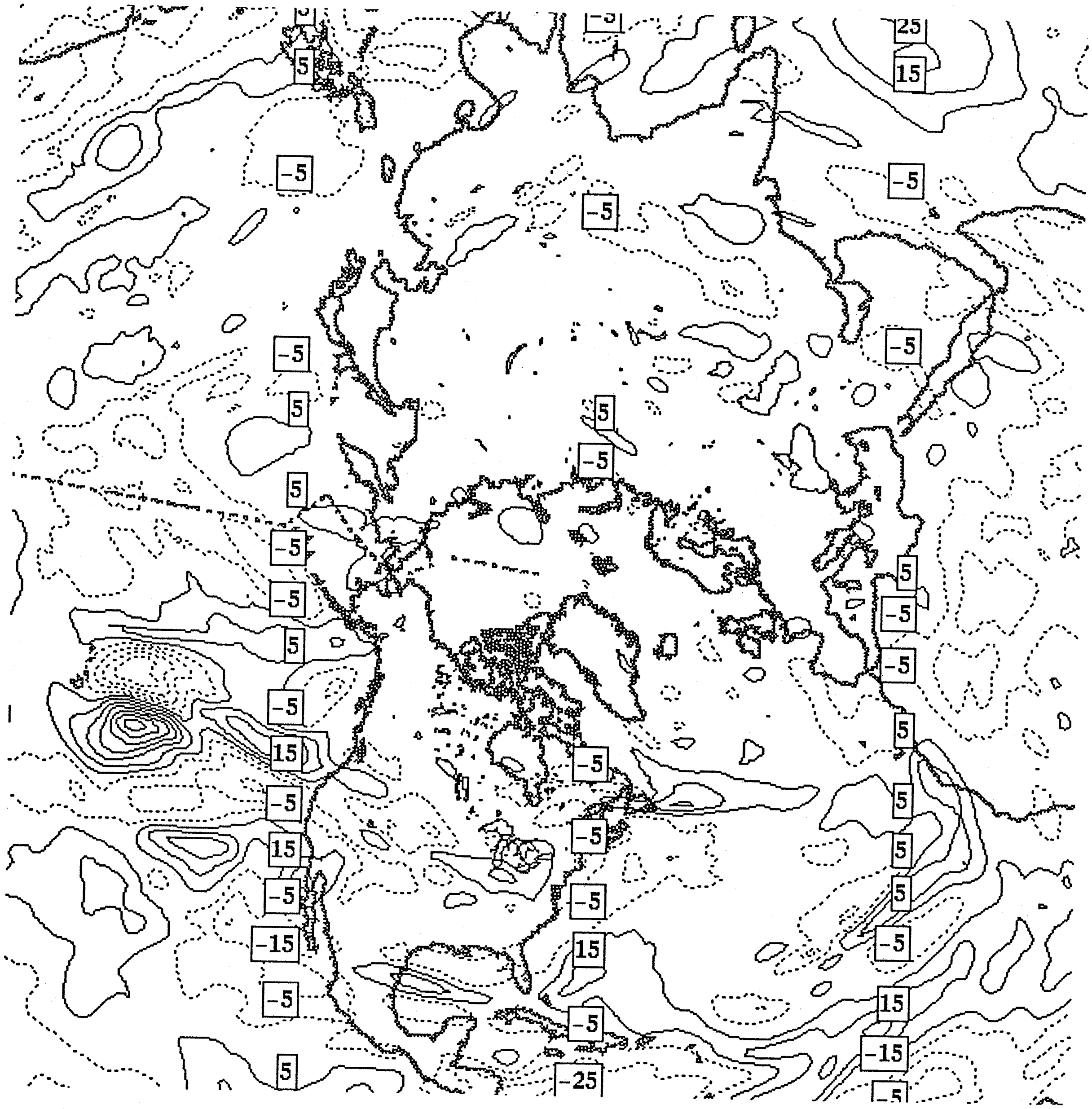


Figure 17: Differences between operational analysis and analysis using only radiosonde data of zonal wind at 250 hPa for Feb. 6 2001; contour interval=10 knots .

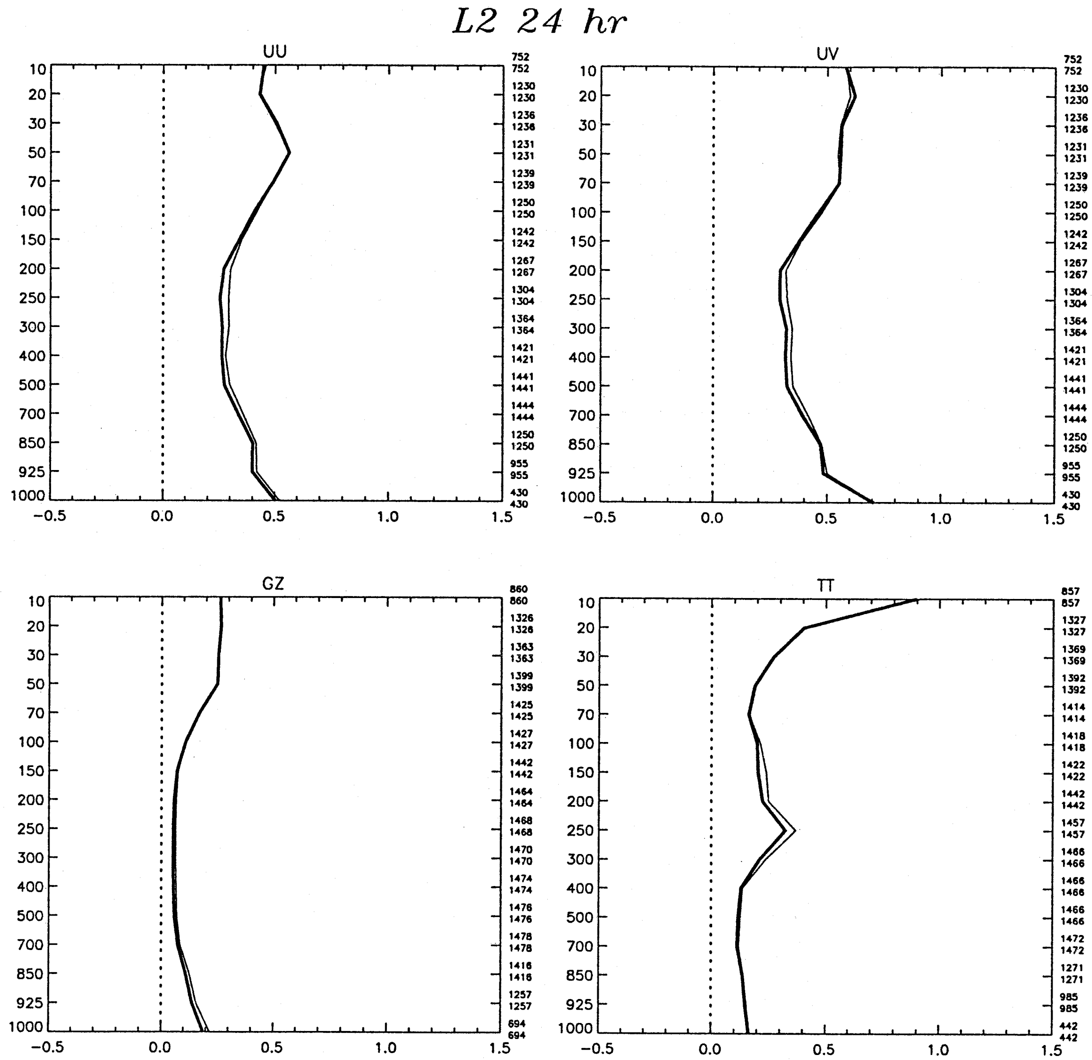


Figure 18: Forecasts initialized from the operational data assimilation system vs those initialized from an assimilation cycle using only radiosonde and ATOVS data; average of 21 forecasts; verification against radiosondes at 24 hour over North America.

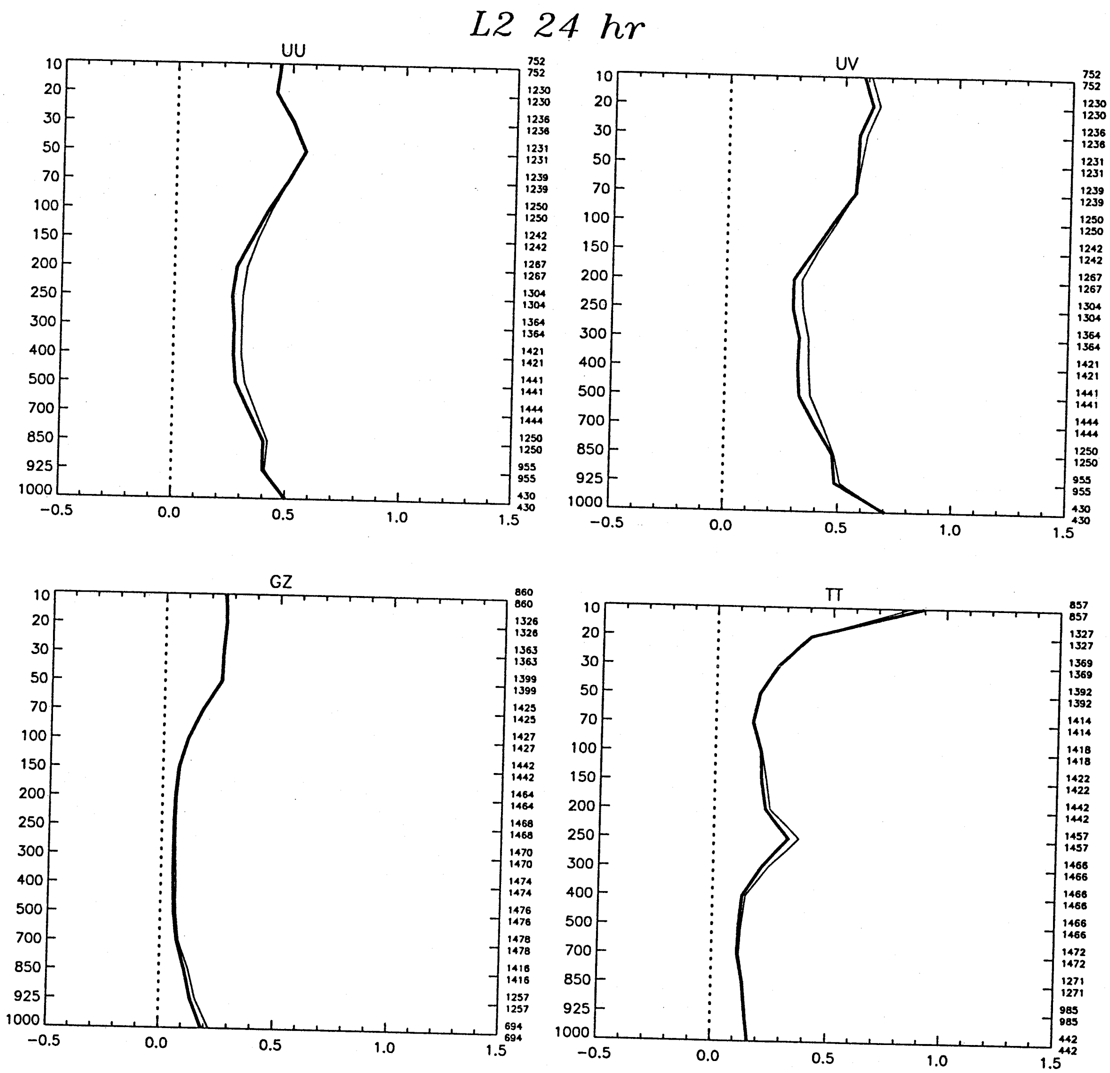
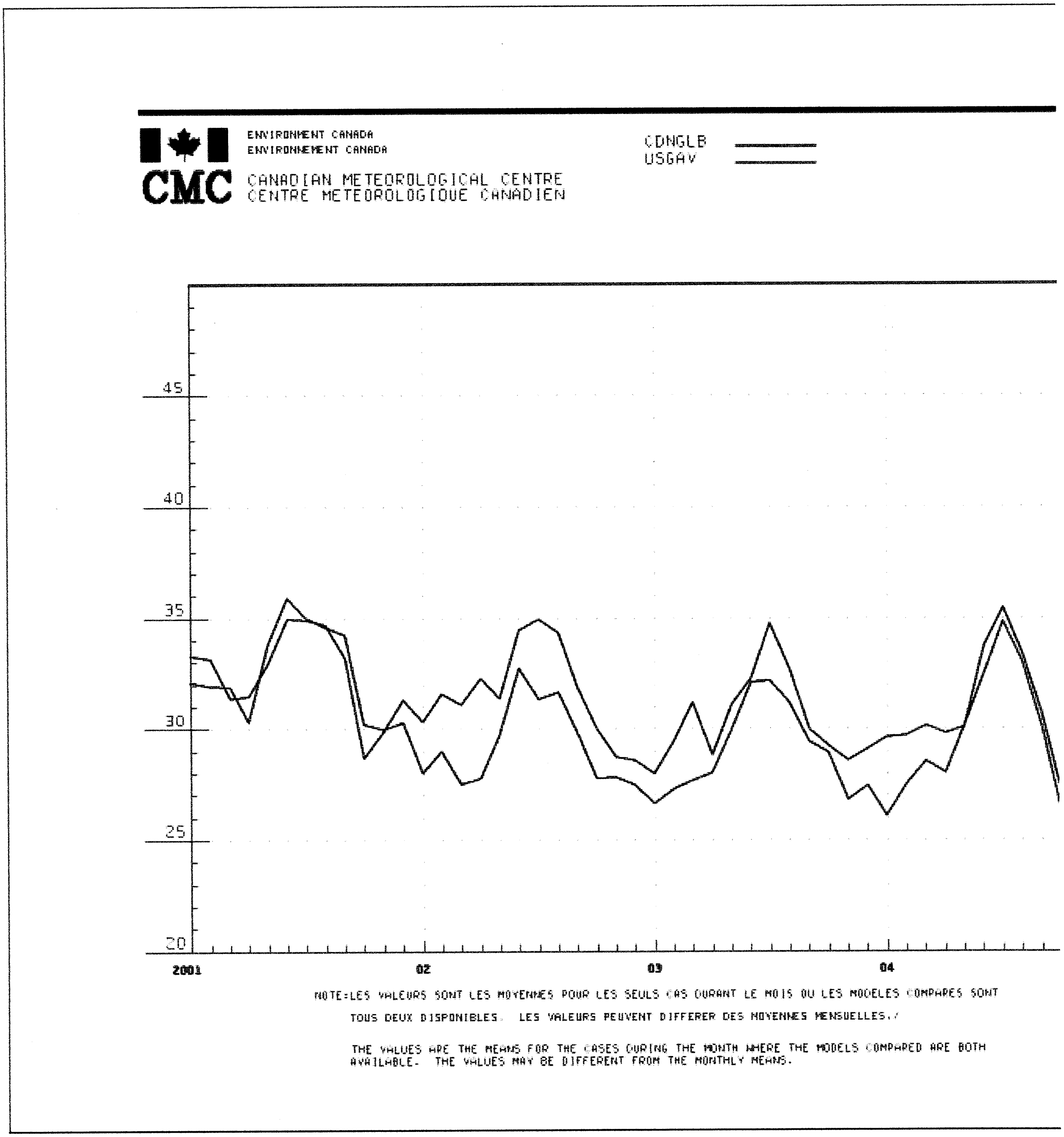


Figure 19: Forecasts initialized from the operational data assimilation system vs those initialized from an assimilation cycle using only radiosonde, AMDAR, and ACARS data; average of 21 forecasts; verification against radiosondes at 24 hour over North America.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NOTE:LES VALEURS SONT LES MOYENNES POUR LES SEULS CAS DURANT LE MOIS OU LES MODELES COMPARES SONT TOUS DEUX DISPONIBLES. LES VALEURS PEUVENT DIFFERER DES MOYENNES MENSUELLES./
THE VALUES ARE THE MEANS FOR THE CASES DURING THE MONTH WHERE THE MODELS COMPARED ARE BOTH AVAILABLE. THE VALUES MAY BE DIFFERENT FROM THE MONTHLY MEANS.