VARIATIONAL ASSIMILATION AT NCEP

J Derber, W-S Wu, M Zupanski, D Zupanski, D Parrish, J Purser, E Rogers, Y Lin and G DiMego
National Centers for Environmental Prediction
Washington D.C., USA

1. INTRODUCTION

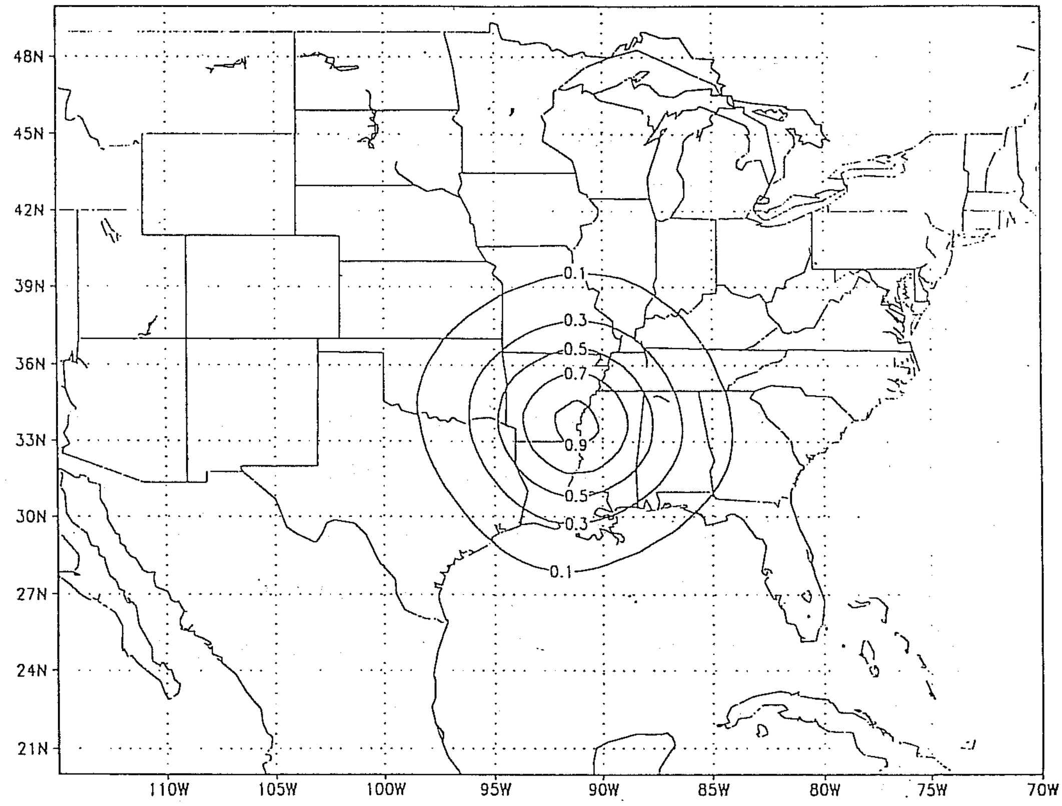
At the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center), there is a variety of variational assimilation projects under way. In this paper, four main components will be described. In the first two sections, a mesoscale 3-D analysis system and a mesoscale 4-D assimilation system which are currently under development will be discussed. In the third section, a description of the operational global 3-D analysis system will be presented followed by a description of the direct use of radiances in this global system. In the final section, future plans will be presented.

2. MESOSCALE 3-D VARIATIONAL ANALYSIS

For the 1996 Olympic games in Atlanta, a 10 km version of the eta model was created. Forecasts were produced from June 1996 and may continue over a different region in the future. The forecasts and analyses were reliably produced and showed improvement over the lower resolution eta forecasts. Unfortunately, communications were unreliable, and few of the forecasts reached the Atlanta forecast office in time for use in the forecasts for the Olympics.

A 3-D variational analysis system was developed for the 10km eta model. The analysis system performs analyses in pressure coordinates and then interpolates the analysis to the eta model coordinates. However, the initial background minus observation differences are calculated in model coordinates. The balance constraint between the mass and wind fields is a thermal wind relationship with a reference level at about 400mb where a geostrophic constraint is used. The background error covariances are defined using a recursive filter with the filter coefficients estimated using a set of 100 forecast differences. In Fig. 1, the temperature correlation with itself for two different levels is shown.

t–t correlation at eta level 19 (635mb)



t–t correlation at eta level 30 (702mb)

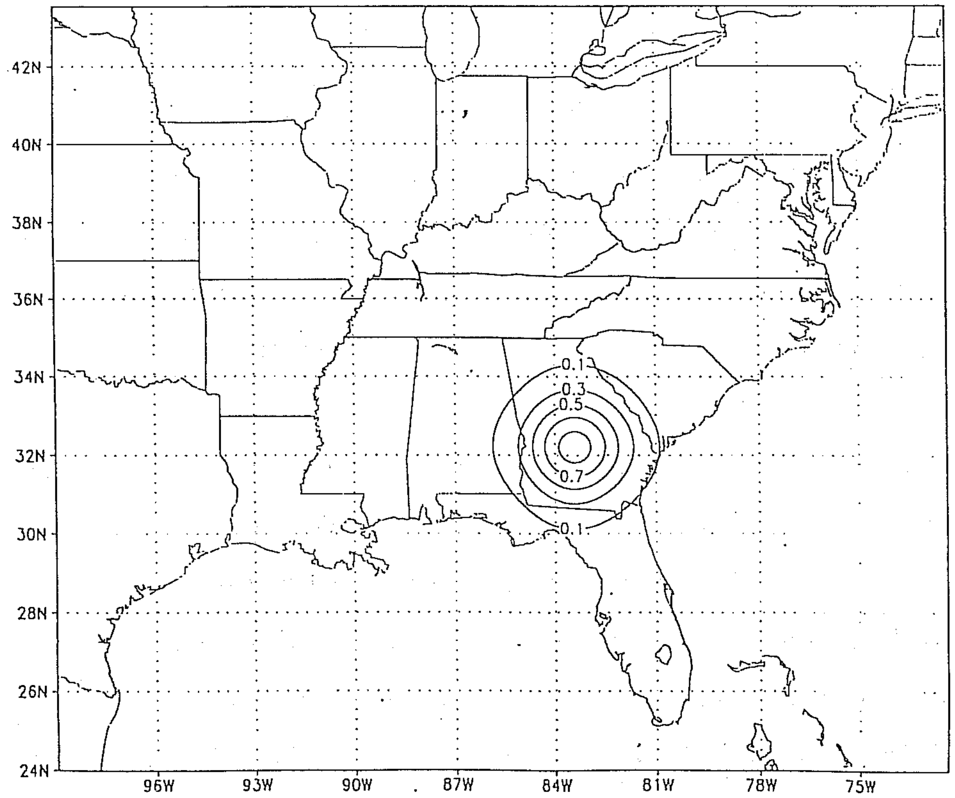


Fig. 1 Temperature correlations with itself at eta levels 19 (635hPa) and 30 (702hPa).

One of the most important aspects of the mesoscale 3-D analysis system is its ability to use additional data types. Much of this results from the higher resolution of the analysis and forecast model. The ascent/descent data from the ACARS dataset is being used to provide frequent accurate profiles of temperatures near airports. The data from a mesoscale surface network were also included in the analysis. At the time of this paper, satellite measured sounding information or imagery was not incorporated in this system.

The availability of radial velocities from the Doppler radars represents a great potential for increasing the available mesoscale information. Unfortunately, the data is not easy to acquire and use in real time. The original Doppler radar data, which includes 7-20 tilt angles with .25km by 1 degree resolution every 6-10 minutes, was not transmitted to NCEP. However, NIDS data are available. This data has been degraded to only the lowest 4 tilt angles at 1km by 1 degree resolution with the radial velocity reported only in 7 velocity ranges; 0-10, 10-20, 20-26, 26-36, 36-50, 50-64 and greater than 64 kts. The restriction to the 7 velocity ranges substantially reduces the usefulness of the Doppler radar data for data assimilation. To use this data, it was necessary to superob the information in volumes of dimension 1 hr, 10km along the radial, 6 degrees of azimuth. Only those superobs with over 100 members were used. Despite the averaging of over 100 members, there can be significant errors. For example, if the wind speed was 0 over the whole volume, the speed would be reported as in the range 0-10 and the superob value would be the mean, 5kts. In practice, this situation does not appear to be too severe. The measurement error was assumed to be equal to 1/2 the range in which the mean observation occurred. Finally, there is an altitude assignment problem. As the beam travels through the atmosphere it is refracted. To some extent, the refraction can be modeled using the background field. However, the errors in this estimate of the refraction get larger further from the radar. In addition, the cross-section of the beam gets larger at longer distances. Since the distribution of hydrometeors in the vertical is not constant, the return could be from a thin layer in the vertical or from a deep layer extending almost through the entire troposphere. For these reasons, the radial velocities from the Doppler radar can be positioned properly out to about 100km from the radar.

As an initial test of the analysis system, the 3-D variational analysis was compared to that produced by the operational Optimal Interpolation (OI) analysis system at 80km. It is difficult to perform an exact comparison, since the OI and 3-D var. systems do not use exactly the same data (e.g., the 3-D var. uses temperatures while the OI system uses heights). Also, the quality control was not the same between the systems. However, despite the unavoidable differences, approximately the same number of observations and the same information were introduced to both analyses. The resulting fit of the 3D-var analysis, OI analysis and background (guess) fields to the temperature and wind data are shown in Figs. 2 and 3. Despite the better fit to the data the analysis increments are smoother for the 3-D var. analysis (e.g., Fig. 4). Further evaluation of the 3-D var. analysis system is currently under way.

3. MESOSCALE 4-D VARIATIONAL ASSIMILATION

A mesoscale 4-D variational assimilation system has been developed for the eta model. The version of the forecast model used in this system is a grid point model with step-mountains in the vertical. In the horizontal, the resolution is 80km and in the vertical there are 17 layers with the top at about 50mb. The forecast model contains a reasonably complete set of physical parameterizations including turbulent mixing and diffusion, a viscous sublayer, cumulus convection, large-scale precipitation, radiation, surface processes and second order horizontal diffusion. Because of enhancements of the operational model there are a few differences from the current operational system in the soil model, the turbulence scheme and explicit cloud water (nonexistent in the 4-D var. version). The only significant change in the physics made for assimilation purposes is a modification of the cumulus convection scheme (Zupanski and Mesinger, 1995) which smooths some of the discontinuities. The adjoint model used in the assimilation includes all components of the physics except the radiation.

The 4-D variational analysis system is not compatible with the 3-D variational mesoscale analysis system described in the previous section. It is also not compatible with the global analysis and assimilation system described in the next section. For this reason, the system is not currently capable of assimilating the Doppler winds or the radiance data. Also, many other components of the objective function are defined differently.

The objective function has four terms: the fit of the forecast to the observations, the gravity wave

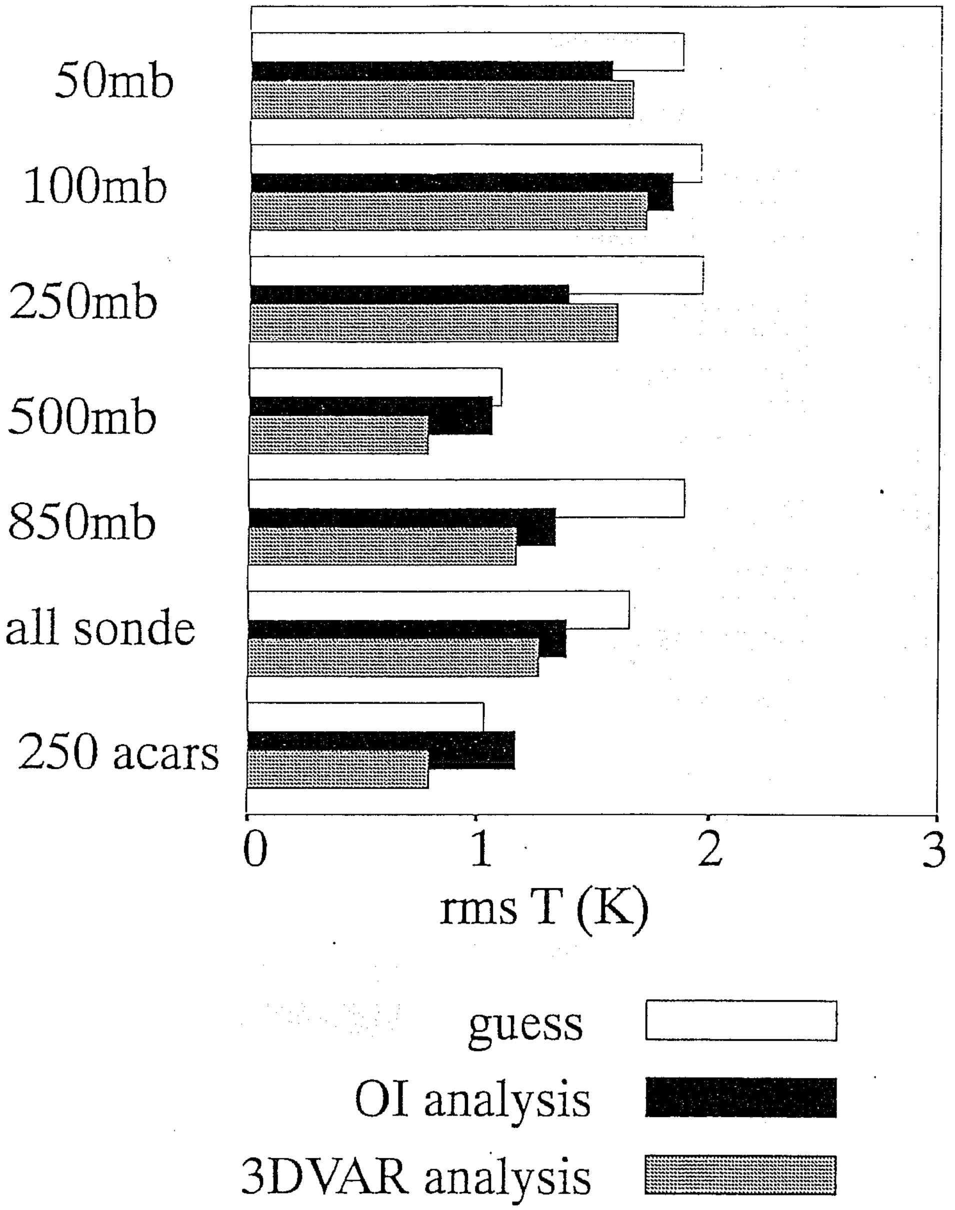


Fig. 2 RMS fit of guess, OI analysis and 3D-var analysis to radiosonde and ACARS temperatures.

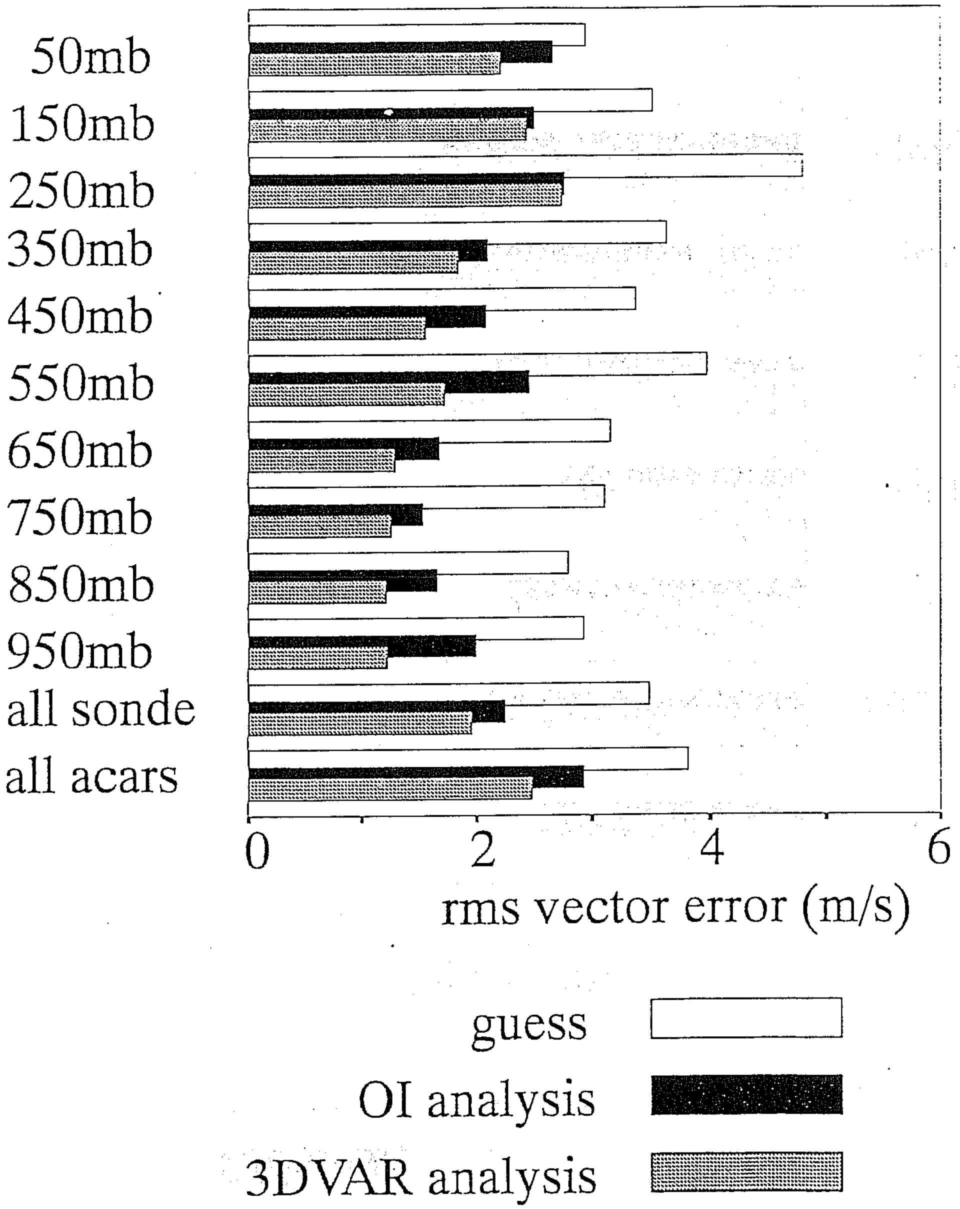


Fig. 3 Same as Fig. 2 except vector fit of winds

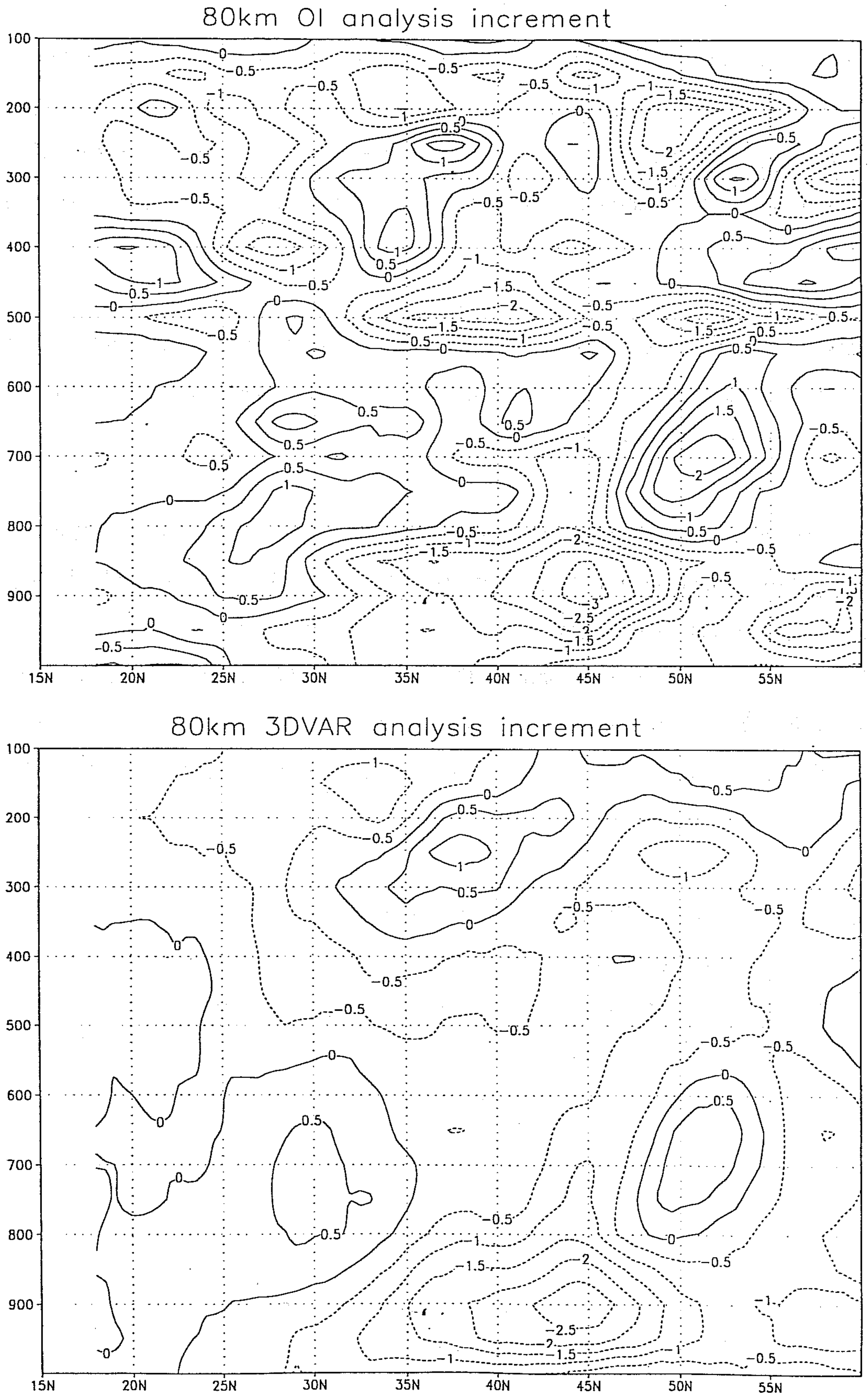


Fig. 4 Cross-section of temperature increments for OI analysis (top) and 3D-var analysis (bottom) for 0000GMT Aug. 12, 1996.

penalty term, a model error penalty term and a fit to the background term. In the observation term, all of the observations used in the operational eta data assimilation system (Rogers et al., 1995) are used. In addition, the capability to use integrated (over time) precipitation observations is also included. However, in the experiments described in this paper, the precipitation observations were not used.

To suppress unrealistic gravity waves in the solution, a gravity wave penalty term was included. The gravity wave penalty is defined through the use of a non-recursive digital filter applied to the surface pressure, temperature and wind fields.

Since the forecast model is not perfect, the assumption of a perfect model can result in the solution not sufficiently fitting the data at the beginning and end of the assimilation interval. For this reason, a model error penalty term was introduced. This term (described in more detail in Zupanski, 1996) loosens the requirement of a perfect model. The inclusion of this term increases the length of the control vector by a factor of 2 or more for a 12-hour assimilation period depending on the model error coreelation time scale. For the experiments shown here the vector was increased by a factor of 4.

The background term carries forward the information from the previous analysis period. At one time, the background error covariance matrix in this system was diagonal, a poor approximation in grid space. The inverse of the background error covariance matrix has been modified to be:

$$B^{-1}=B_0^{-1}-\sum_{k=1}^{N}\rho_k s_k s_k^T \tag{1}$$

$$\rho_k=1./(1.+Ez_k s_k) \tag{2}$$

$$s_k=B_{k-1}^{-1}Ez_k \tag{3}$$

E = 3-D recursive digital filter

B_0= Positive definite diagonal matrix

z_k = 12-hour forecast differences

N = 100

Currently, the same statistics calculated for the background error covariance are used for the model error covariance (see Zupanski, 1996). This system has been tested on several cases with positive impact when compared to a previously operational OI assimilation system. In Figs. 5 and 6, RMS differences between the forecasts and the analyses for the OI system and the 4-D var. analysis system are shown. Both the winds and the temperatures show an improvement in the forecasts. The moisture variable showed no positive or negative impact.

4. GLOBAL 3-D VARIATIONAL ANALYSIS (SSI ANALYSIS)

The global 3-D var. analysis system (known as the Spectral Statistical Interpolation, SSI analysis system) has been operational at NCEP since 1991. This system has been described in Parrish and Derber (1992) and Derber et al. (1991) with more recent modifications described in Pan et al. (1996). The formulation is typical with the objective function given by:

$$J=(x-x_b)^T B^{-1}(x-x_b)+(K(x)-y)^T O^{-1}(K(x)-y)+J_c \qquad (4)$$

where x - analysis variable

x_b - background analysis variable

B - background error covariance matrix

y - observation vector

K - transformation operator from analysis variable to observations

O - observation error covariance matrix

J_c - constraint term

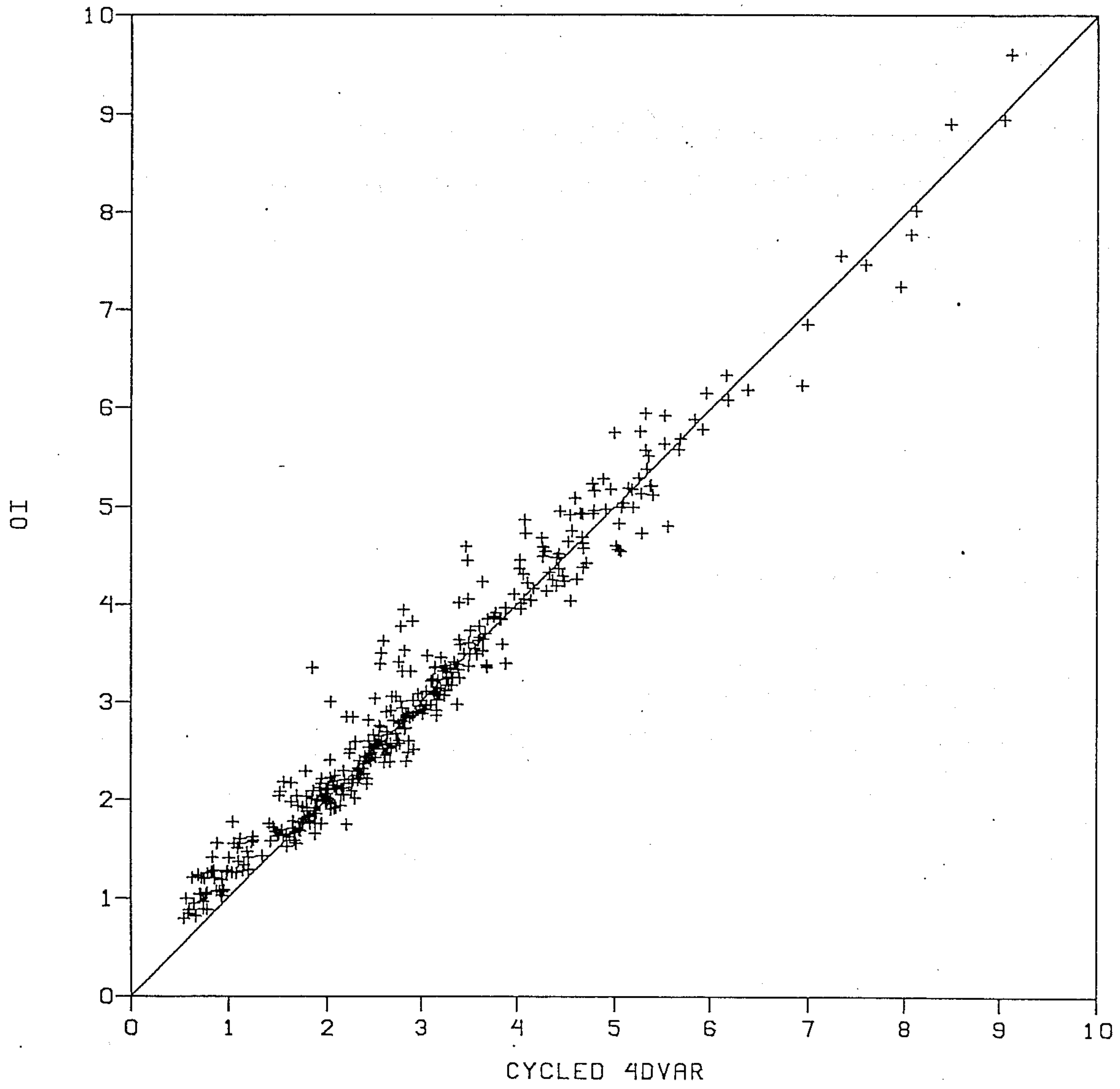


Fig. 5 RMS fit of 00, 12, 24, 36 and 48 hour forecasts to temperature analyses at 20 vertical levels for OI and 4D-var analysis.

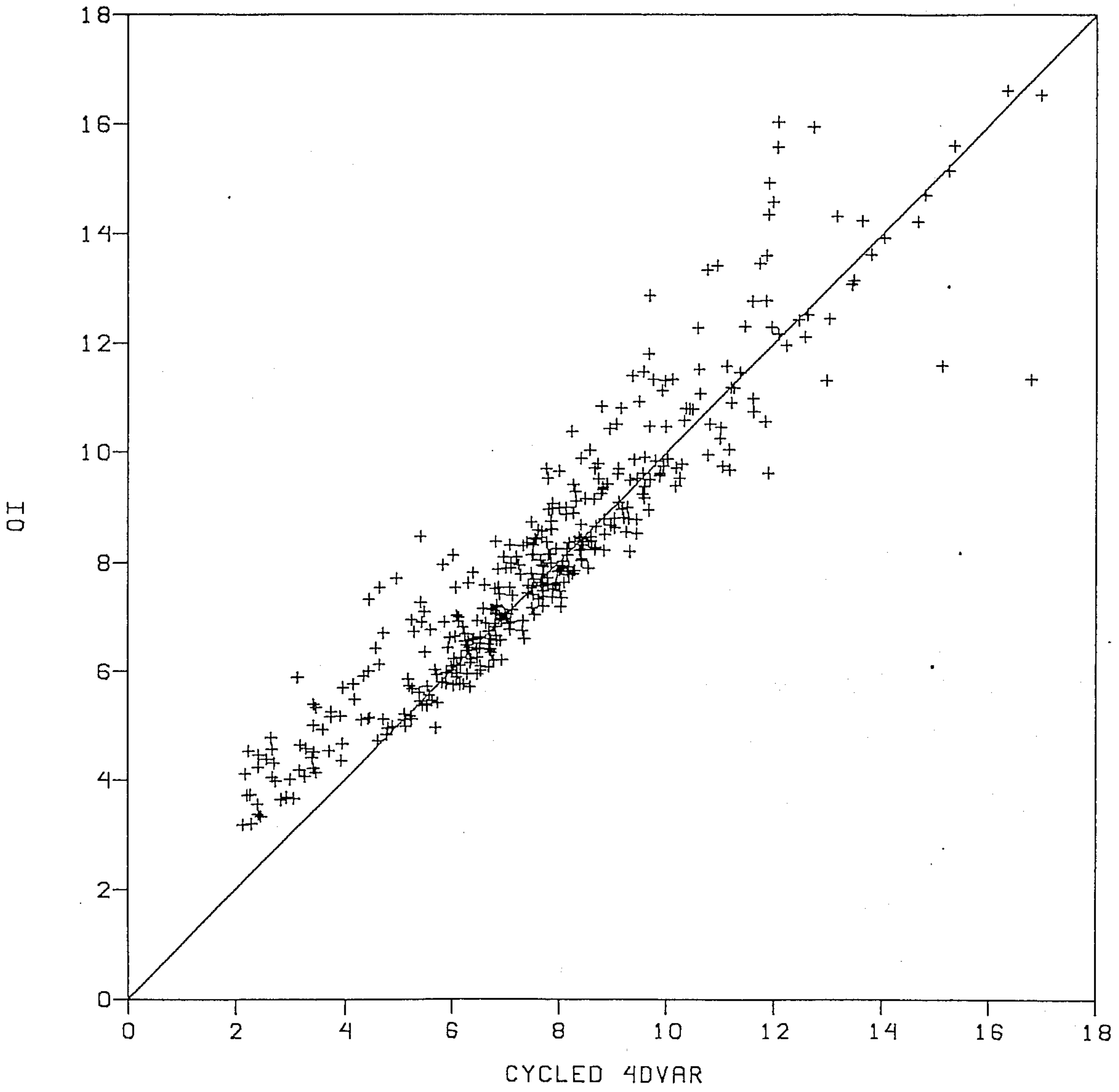


Fig. 6 Same as Fig. 5 except for winds.

The analysis variable is defined as the spectral coefficients for the scaled (by the variance) streamfunction, unbalanced temperature and surface pressure, unbalanced velocity potential and specific humidity. The analysis variables were chosen to simplify background term, speed convergence and include balance. It is not necessary to analyse in terms of the model variables, but rather to have a transformation from the analysis variable to the model variable.

The balanced part of the temperature and surface pressure ($\underline{T}$)and velocity potential ($\underline{\chi}$) are given by:

$$\lambda \boldsymbol{B}\boldsymbol{P}_l^m = \underline{\boldsymbol{T}_l^m} \tag{5}$$

$$\gamma \boldsymbol{P}_l^m = \underline{\chi_l^m} \tag{6}$$

where

$$\beta_l^m \psi_{l-1}^m + \beta_{l+1}^m \psi_{l+1}^m = \underline{\boldsymbol{P}_l^m} \textit{ for each level } k \tag{7}$$

λ and γ are empirical constants which vary with level and total wavenumber.

B is the pseudo-inverse of the T, ln(ps) to P transform.

β are constants in the linear balance equation.

The background error covariance statistics and the constants in the balance equations are derived from 45, 48-24 hour forecast differences.

The third term in the objective function (J_c) contains a penalty on the difference in the divergence tendency from the background divergence tendency. Recently it was found that the changes in the surface pressure on the very large scales were too large. For this reason, a constraint on the vertical integral of divergence tendency has been introduced which forces it to be equal to zero up to T6 truncation.

In the current operational analysis system, all observation operators are assumed linear (linearizing around the background field when necessary). A nonlinear version is available and could replace the linear version at any time. In addition to the conventional observations, SSM/I total precipitable water and wind speed, ERS-1 wind speed and direction, and NOAA-12, 14 cloud-cleared radiances are being used in the analysis. In the current operational system because of the linearity assumption, the SSM/I wind speeds are used by performing a local analysis of the wind direction and using this direction to define the u and v components at the observation locations. In the nonlinear version, the wind speed alone is used. This change in the usage of the data results in some enhancement in the forecasts in the Southern Hemisphere. The ERS-1 wind speeds and directions are used by attempting to eliminate the ambiguity in the direction before introducing the data into the analysis. The use of the cloud cleared radiances will be discussed in the following section.

5. USE OF CLOUD-CLEARED RADIANCES IN THE GLOBAL VARIATIONAL ANALYSIS

Cloud-cleared radiances rather than temperature and moisture retrievals have been used operationally at NCEP since October 1995 for many reasons. Both the 3-D analysis problem and the 1-D retrieval problem are not well-posed with the number of degrees of freedom larger than the number of pieces of independent information in the observations. To make both problems well-posed; additional information is usually provided through a background (guess) and by defining a set of background error statistics. If one uses the retrievals, two ill-posed problems must be solved, first the retrieval and then the analysis. In this case, one must ensure that the information added is correct and is not being added twice, once in the retrieval and once in the analysis. In practice, it is not practical to consistently use retrievals in the analysis system. If a consistent background field is used, then a situation dependent correlations between the background and the retrieval must be accounted for. Also, it is more difficult to define consistent background error statistics because in the analysis the statistics are 3-dimensional. In addition, when using the radiances directly, some of the undefined degrees of freedom with the radiances are defined from other types of observations in the analysis and the observational error characteristics can be defined better in terms of the radiances than the retrieved profiles. Finally, the radiances were used because they made a much simpler overall system than our previous operational system and, most importantly, gave much better forecast results.

There are four necessary components of the radiance assimilation system which will be described further: bias correction, quality control, ozone analysis and skin temperature analysis. A more complete description of the use of the radiances in the NCEP analysis system can be found in Derber and Wu (1996). Each of four described components have a significant impact on the results. However, the bias correction and quality control had the largest impact on the analysis and resulting forecast.

Bias correction of the data (or simulated data) is necessary because of inadequacies in radiative transfer, calibration, and processing of data. In our bias correction scheme, a linear prediction equation is used for the bias with predictors given by scan angle and square of scan angle, microwave channels 2, 3 and 4 brightness temperatures, solar zenith angle, and HIRS channel 1 brightness temperatures. The predictors are listed in approximate order of importance. The coefficients in the bias correction equation are estimated as part of the analysis vector (x). The advantages of this type of scheme for estimating the coefficients are quick, adaptive responses to changes in the system and a simplified system with no need for collecting a large match-up database. No problems with this scheme have been observed with this system in over 2 years of testing and operational use.

The quality control of the radiance data is vital. The cloud-cleared radiances as received from NESDIS contain many cloud contaminated points and microwave data which are improperly corrected for surface emissivity effects. It is necessary to eliminate those data which cannot be properly simulated using the current radiative transfer and forecast model. For example, if the model and real orographies are too different, it is not possible to properly simulate the brightness channels which peak near the surface. The quality control for the radiance includes a check against the background and a check against surrounding observations. This quality control as currently implemented is probably overly strict, eliminating some good observations to ensure that no bad observations are introduced.

The radiance simulations are effected by the total ozone. This can be as large as the signal in some of the HIRS longwave channels (up to .6°C). For this reason, a simple total ozone analysis has been introduced. This analysis uses the NESDIS retrieved ozone values and is done prior to the full 3-D analysis. The background for this field is the previous analysis. With this background field, the rms difference between the analysis and the observations is about 12 Dobson units.

Finally, in the control variable a spectral skin temperature variable was introduced. Many of the channels have significant contribution from the surface. Without the ability to change the skin temperature in the analysis, the signal from the skin temperature can be aliased into the temperature profile. Also, in the data there are some residual cloud effects. This field acts as a sink for those effects, reducing the resulting analysis errors.

At this time, both the NOAA-12 and NOAA-14 120 km data are being used operationally. From the HIRS instrument channels 2-7, 10-16 and 18-19 are being used, eventhough recent tests indicate that some small improvement can result from not using channels 16, 18 and 19. For the MSU, channels 2-4 are being used. For the SSU, the NESDIS values for the SSU for channels 1-3 are being used for both satellites. Since for NOAA-12, the SSU values are interpolated by NESDIS from the NOAA-14 values, the observational errors have been significantly increased for the NOAA-12 SSU values. All observations are used globally. However, the observational errors for those channels which intersect the surface are increased over land and ice, and these channels are also more likely to be rejected by the quality control. No 1-D var. retrieval step is used with all code being contained in the 3-D var. system. The horizontal and between channel error correlation are currently assumed to be zero because these correlations are not well known or modelled.

Many experiments have been performed with the direct use of radiances in the assimilation. The results from one 3-week assimilation/forecast experiment are shown in Fig 7. In the figures, anomaly correlations from assimilations using no satellite sounding data (NOSAT), the radiances (RAD), the retrievals (RET, NESDIS operational retrievals in the Southern Hemisphere and interactive retrievals, Baker et al, 1995) and the retrievals with the assigned observational error halved are shown for 5 day forecasts (RET2). In both the northern and southern hemispheres, there is an improvement in the forecast by using the radiances. This improvement in both hemispheres was very large when compared to other recent changes in the analysis/assimilation system. Increasing the weight (decreasing the observational error) given the retrievals did not substantially improve the forecasts.

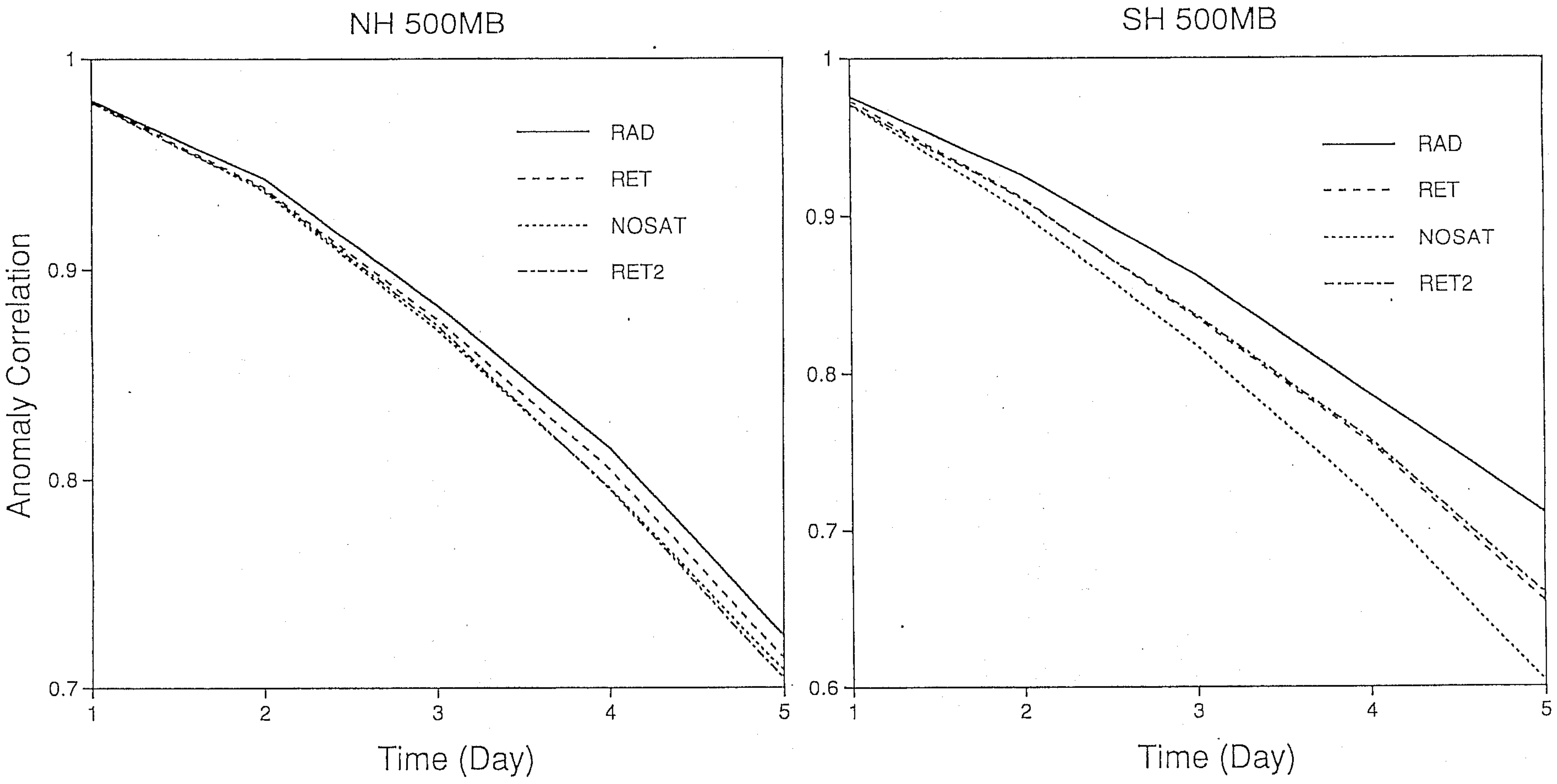


Fig. 7 Northern and Southern Hemisphere 500hPa anomaly correlations for NOSAT, RAD, RET and RET2 experiments.

6. FUTURE PLANS

One of the greatest advantages of the variational analysis and assimilation systems is the ease that improvements can be incorporated. Many improvements are planned for the NCEP analysis and assimilation systems. First, all current components of analysis system (e.g., observational and background error statistics, forward operators, etc.) can be improved. While this may seem trivial or obvious, many of these improvements will require substantial development and these details can have a very significant impact of the quality of the analysis and assimilation. Including additional data sources in all analysis systems (e.g. GOES-8,9 radiances) and enhancing usage of current data (e.g. Doppler winds) are high priorities. In the near future, it is very likely that additional analysis variables (e.g., 3-D ozone) will be introduced in the analysis and assimilation system. It is obvious that enhancements to quality control for all systems are necessary for all observation types. For the 4-D assimilation systems, there will be continued development of the mesoscale system and a revival of the global 4-D system. Parallel tests of the mesoscale 4-D system are planned soon. Finally, the mesoscale and global analysis and assimilation systems should be merged. With NCEP's limited resources, it is not appropriate to have several analysis/assimilation projects.

References

Baker, W, H Fleming, M Goldberg, B Katz and J Derber, 1995: Development and implementation of Satellite temperature soundings produced interactively., NWS Technical Procedures Bulletin, No. 422.

Derber, J C, D F Parrish and S J Lord, 1991: The new global operational analysis system at the National Meteorological Center. Wea. and Forecasting, **6**, 538-547.

Derber, J C and W-S Wu, 1996: The use of cloud-cleared radiances in the NCEP's SSI analysis system. To be submitted to Mon. Wea. Rev.

Pan, H L, J Derber, D Parrish, W Gemmill, S Y Hong and P Caplan, 1996: Changes to the 1995 NCEP operational MRF model analysis/forecast system. submitted to Wea. and Forecasting.

Parrish, D F and J C Derber, 1992: The National Meteorological Center's spectral statistical interpolation analysis system. Mon. Wea. Rev., **120**, 1747-1763.

Rogers, E, D G Deaven, and G J DiMego, 1995: The regional analysis system for the operational "early" eta model: Original 80-km configuration and recent changes. Wea. and Forecasting, **10**, 810-

825.

Zupanski, D, and F Mesinger, 1995: Four-dimensional variational assimilation of precipitation data. Mon. Wea. Rev., **123**, 1112-1127.

Zupanski, D, 1997: A general weak constraint applicable in operational 4DVAR data assimilation systems. Submitted to Mon. Wea. Rev.