Assimilation of TOVS data at NMC

John C. Derber
Development Division
National Meteorological Center
Washington D.C., U.S.A.

1. INTRODUCTION

The production of weather forecasts and the study of climate problems requires a complete and accurate description of the atmospheric state. Unfortunately, no single component of the observing system measures the atmosphere with sufficient accuracy and completeness. It is necessary to combine the information from many different observing systems and from many different times to create a reasonably accurate estimate of the atmospheric state. The information in the data is combined in space and time through a data assimilation system. Until recently, satellite data has not had a very strong impact on numerical weather prediction in the northern hemisphere. This lack of impact can be traced to the inability to properly incorporate the information from the satellite observations into the data assimilation system. Recent advances in data assimilation have made it possible to better use the information in this data.

In the following sections, some components of the current global data assimilation system will be presented followed by a description of the current state, planned near term enhancements, and the longer term future (i.e., > 1 year) of the use satellite data at the National Meteorological Center (NMC).

2. THE USE OF DATA AT THE NMC

In the global data assimilation system, all data is incorporated through the use of NMC's Spectral Statistical Interpolation (SSI) analysis system (Parrish and Derber, 1992, Derber et al., 1991). This system is equivalent in spirit, if not in many details, to ECMWF's 3-D variational analysis system (see articles this volume). The SSI analysis system is based on minimizing the equation:

$$J = (x-x_g)^T B^{-1} (x-x_g) + (H(x)-y)^T O^{-1} (H(x)-y)) \tag{1}$$

Where x is the resultant analysis vector, x_g is the background or first guess vector (in this case a 6 hr forecast), B is the background error covariance matrix, y is the observation vector, and O is the observational error covariance matrix.

The first term on the right hand side of the equation represents the fit of the background or first guess field to the analysis. While this term is extremely important for producing a high quality analysis, it is not directly involved in the use of satellite data. Therefore, only the second term on the right hand side will be discussed.

The second term on the right hand side represents the fit of the analysis to the observations. The H operator is a transformation from the analysis variables to the observed quantities. Thus, if the analysis variable were of the same type as the observed quantity, for example if both were temperature, then the H operator would only involve an interpolation to the observation location. However, the H operator can be much more complex including, for example, an integration of the radiative transfer equation to produce radiances. Some of the specific transformations included in the H operator will be discussed when the specific satellite observation types are presented.

The Observational error covariance matrix (O) is extremely important, providing the weights for the data in the analysis procedure. For many conventional data, the O matrix can be assumed to be diagonal (errors uncorrelated) to a reasonable degree of accuracy. However, there are often horizontally correlated errors in the satellite data. One reason for the correlated error may be that the same instrument is being used for the observations. Thus, any calibration errors will result in correlated errors in the data. A second source of correlated error in the satellite data may be from inadequate forward models (the H operator). If the forward model contains errors, the errors are likely to be strongly correlated to the errors in nearby locations. Finally, when the forward problem is not uniquely invertible, any attempt to invert the data (the retrieval process) requires auxilary information. The addition of this auxilary information will also result in correlated errors. For example, when temperature retrievals are created from satellite measured radiances, a guess profile must be introduced. The differences of this guess profile from the truth are usually strongly correlated in the horizontal since the same or similar guess profiles are usually chosen for nearby points. Since the vertical resolution of the radiances is inadequate to uniquely determine the temperature profile, much of the correlated error in the guess is carried through to the temperature retrieval. In this situation, it is very difficult to account for the correlated error especially since the guess profile is often not available to the analysis program.

3. CURRENT USE OF SATELLITE DATA AT NMC

Currently, only four types of satellite data (sea surface temperatures, surface wind speeds, cloud motion winds, and satellite based temperature profiles) affect the global forecast model. The Sea Surface Temperatures (SSTs) are not directly used in the SSI analysis system. They affect the analysis only through the lower boundary condition of the forecast model. The SSTs are updated daily in the manner described in Reynolds and Smith (1993). Since these satellite observations do not directly affect the analysis they will not be discussed further. However, note that correlated errors are a significant problem with this data due to the presence of aerosols (Reynolds, 1993).

Surface wind speeds from the Special Sensor Microwave / Imager (SSM/I) instrument are used in the global assimilation system. The current use is far from optimal. First, because of the very large amount of data, superobs (with a very crude quality control) are made from the data on a 1° x 1° grid at the beginning of the processing. In the subsequent quality control, a local analysis of the wind direction is performed around the observation location. This direction is then combined with the SSM/I wind speed to create a wind vector for insertion into the SSI analysis system. Since the SSM/I wind speeds are only available over the poorly observed oceans, the wind direction is often close to the background wind direction. This results in an overemphasis of the direction from the background field. The use of the local analysis of the wind direction undoubtebly results in a correlated error in the winds. However, currently the errors are assumed to be uncorrelated and an error of 2.2 m/s is assigned to each of the wind components. An improved version of the analysis procedure which directly uses the wind speed has been developed and will be discussed in the next section.

Cloud motion wind vectors are available from the GOES, Meteosat and the Himawari satellites. While the algorithms for tracking the winds and assigning the heights varies considerably between the satellites, the same error formulation is used for each platform in the analysis. It is assumed that there is no horizontal error correlation between the winds and there is no consideration of a speed dependent bias. Thus, the cloud motion winds are being used in the same manner as a single level aircraft observation (with a different observational error).

The largest satellite based data set currently being used is made up of TOVS temperature retrievals. On 11 August 1993 in conjuction with the change from 18 to 28 levels, the global analysis system switched from using the 15 layer NESDIS retrievals to the 40 level NESDIS retrievals. Note that no moisture information from the retrievals are currently being used. The 15 layer retrievals were derived directly from the 40 level retrievals. The averaging procedure which created the 15 layer retrievals from the 40 level retrievals caused some degradation in the solution. However, the primary reasons for switching to the 40 level retrievals were the availability of information at the higher levels of the new model and as a backup for the interactive retrievals described later. The interactive retrievals use the 40 level retrievals for defining the guess in the upper levels and thus can be passed to the analysis procedure in case of failure of the interactive retrievals. The use of the 15 layer retrieval as backup would require considerably more extensive programming and file manipulation.

The 40 level retrievals are used in the SSI analysis in a somewhat different manner than the other data. First all observations over land and below 100 mb are eliminated. Then the background (0-6 hr forecast) is interpolated in space and time to the observation location. The interpolation in time only occurs if the observation was taken before the end of the 6 hr assimilation forecast. If it was taken before the end of the forecast period, a linear interpolation of the fields between the 0 hr forecast and the 6 hr forecast to the observation time is made. The difference between the observation and the guess is then calculated. This calculation of the background - observations is identical to that for all other data in the system. From this point on, the treatment of the satellite data varies from that of the other conventional data.

In order to allow for the correlated nature of the satellite data to be approximately accounted for in the analysis, superobs are created from the differences on the model Gaussian grid. This is done by first interpolating the differences vertically to the model sigma levels. Then all the clearest type of satellite profiles around a grid point are averaged and applied to the grid point. These superobs of the satellite data are used as if they were the actual background - observation differences.

The observational error for the satellite data is extremely difficult to model. The error is three dimensional and in reality is probably not separable. However we have chosen to model the error in the form:

$$O_S^{-1} = LNM^T S^{-1} MNL^T \quad (2)$$

where L is a lower Cholesky factorization of inverse of vertical observational error covariance matrix, M is the grid to spectral transformation, S is the spectral representation of the horizontal error correlation, and N is a diagonal renormalization matrix that insures that $M^T S^{-1} M$ is a correlation in grid space. The horizontal correlation matrix S is defined as the transformation into spectral space of the correlation function:

$$c(r) = (1.+r/L)\exp(-r/L) \qquad (3)$$

where L=400 km and r is the distance between any two points. Note that for total wavenumbers greater than 30, the value of the diagonal of S is kept constant to keep from overemphasizing the smallest scales.

4. NEAR FUTURE IMPROVEMENTS IN THE USE OF SATELLITE DATA

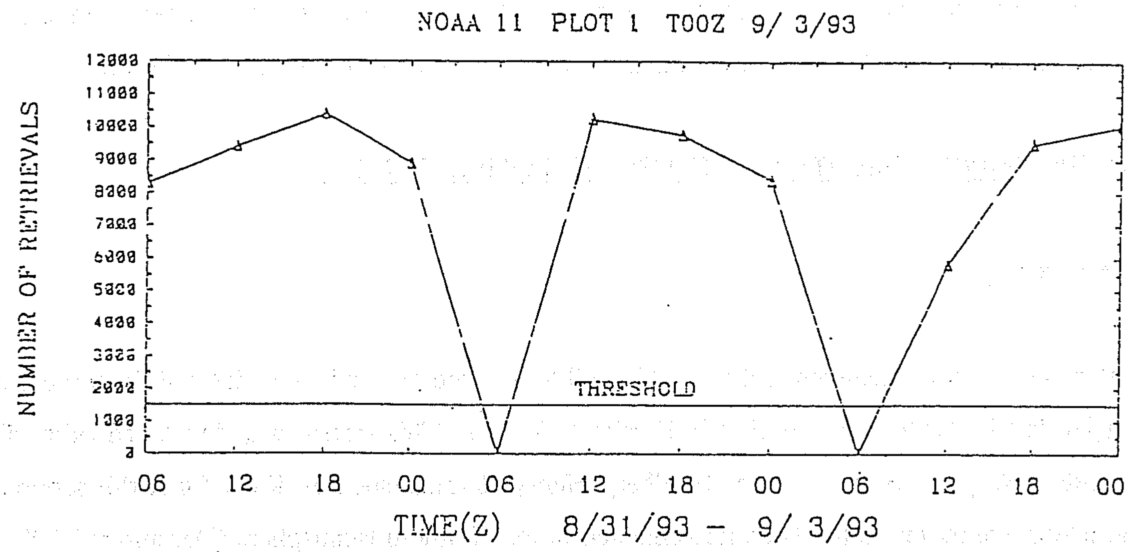
4.1 Interactive retrievals

In the near future several enhancements in the use of satellite data are planned. The first will be the use of interactive retrievals (similar to what the ECMWF calls 1-D var.). This system was developed primarily through the efforts of Wayman Baker, Mitchell Goldberg, Henry Fleming, and Bert Katz. Since this seminar, the use of the interactive retrievals has been implemented in the Northern Hemisphere (December 7,1993).

One of the most important aspects of the interactive retrievals is the real time monitoring of the data and the interactive retrievals. This monitoring was instituted for two main reasons, the inadequacy of the current monitoring system and to provide a back-up procedure if problems develop in the interactive retrievals (e.g., revert to using model independent retrievals). In the monitoring system, the Senior Duty Meteorologist (SDM) in the Meteorological Operations Division of the NMC has the ability to examine 274 different maps and line plots. For routine monitoring, the SDM examines a subset of 16 of these plots. Unfortunately, the plots are created in the operational job stream immediately before the data is inserted in the quality control and analysis system. By the time the data are examined, the data has already been incorporated into the analysis. Thus, the monitoring cannot remove transient groups of bad data, but rather is used for detection of longer term problems. The monitoring system has been operating for about 1 month in anticipation of the implementation of the interactive retrievals. Fig. 1 shows the data counts for NOAA-11 and NOAA-12 for a portion of the period. One problem is immediately apparent from this plot, NESDIS had difficulty in providing the satellite data in time for the 06Z data cut off. In addition to the problem with the 06Z data cutoff, the test of the monitoring system has twice detected a large group of miscalibrated radiances which had gone into the operational and interactive retrieval systems. No failures in the interactive retrieval system have been detected.

The creation of the interactive retrievals differs somewhat from what is being done at the ECMWF. The procedure for creating the retrievals begins by interpolating the 6 hr forecast to the observation locations.

AMOUNT OF DATA RECEIVED FROM INTERACTIVE RETRIEVAL SYSTEM VS. TIME



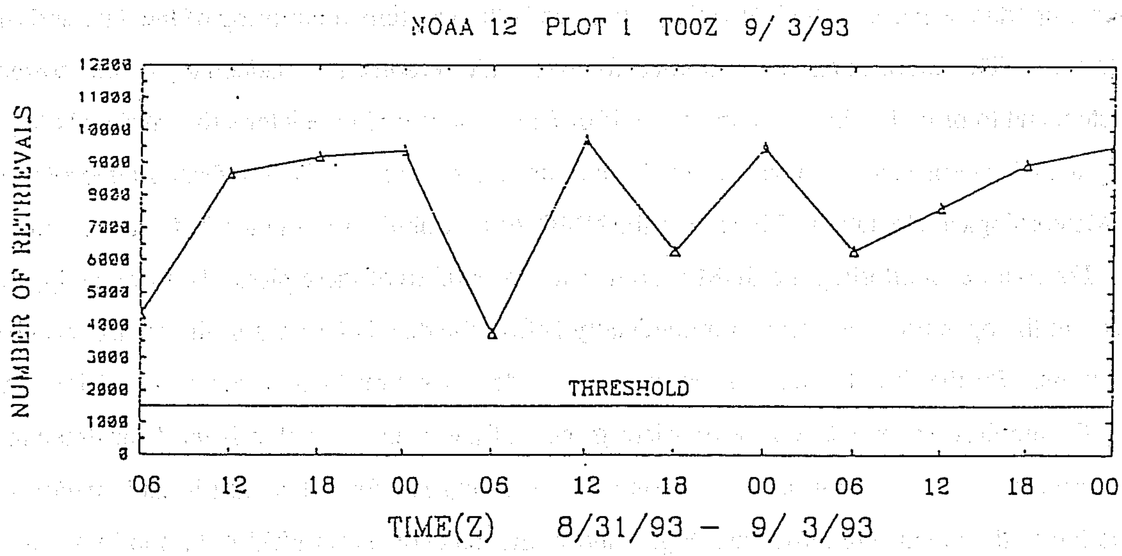
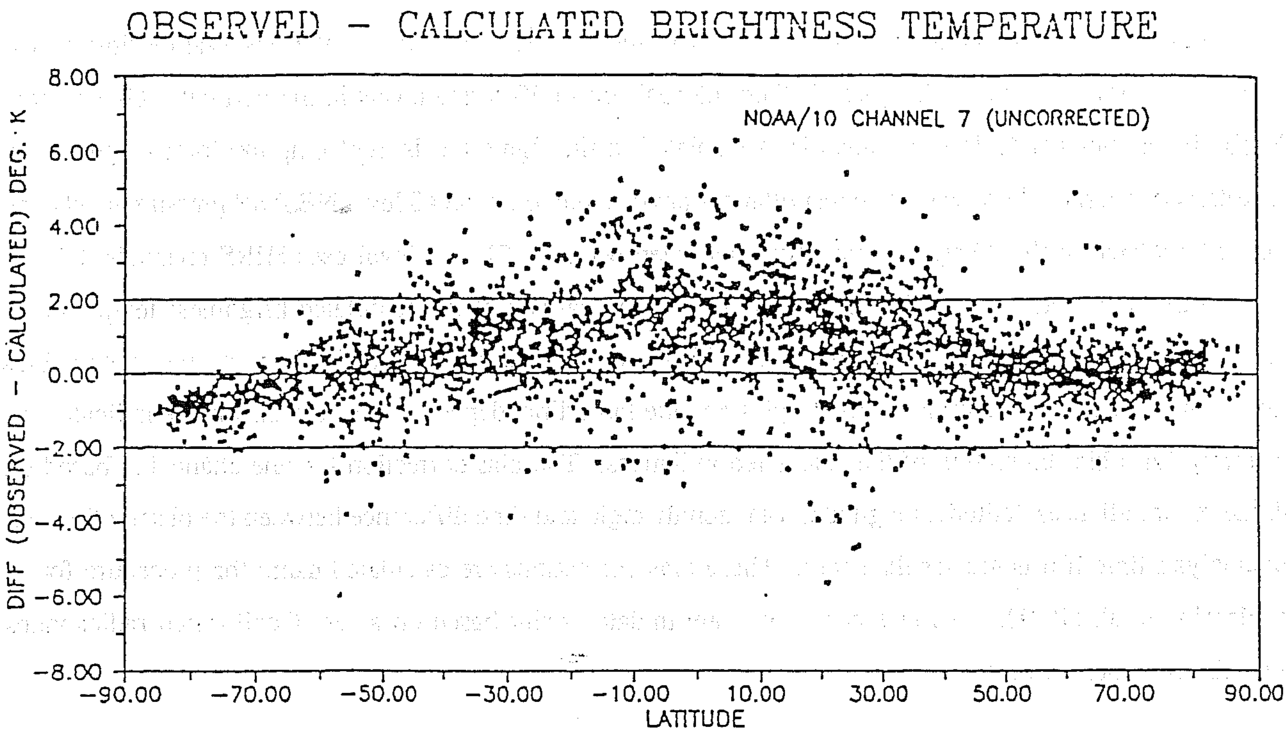


Fig. 1: Data counts for NOAA 11 and NOAA 12 from 06Z Aug. 31, 1993 to 00Z Sept. 3, 1993

This includes a time interpolation identical to that in the analysis procedure, if the observation time is less than the 6 hr forecast time. The guess is then interpolated to 70 sigma levels in the vertical. Above about 70mb, the operational 40 level retrieval is interpolated to the sigma levels, replacing the forecast guess. In the interactive retrieval process, the transmittances are calculated on the 40 level NESDIS pressure levels and then interpolated to the 70 sigma level locations when needed. The retrieval uses HIRS channels 2-7 and 13-16, MSU channels 2-4 and SSU channels 1-3. A comparison of the calculated brightness temperatures and the observed brightness temperatures for HIRS channel 7 is shown in Fig. 2 with and without bias correction. The increased scatter in the tropics and the latitudinal dependence of the difference indicates the necessity for a bias correction of the calculated radiances. The bias correction for one channel is based on all the other radiances, latitude, longitude, solar zenith angle and time difference between the observation and the analysis time if it is greater than zero. These bias corrections are calculated using the procedure found in Fleming et al. (1991). The bias corrections are updated daily based on a set of collocated radiosondes from the previous 14 days.

Since the interactive retrievals are solving essentially the same problem as the SSI analysis (except only in the vertical), the solution is dependent on the background error covariance matrix and the observational error covariance matrix. These statistics are updated daily based on the previous 14 days of collocations with radiosondes. The background error covariance matrix is estimated as a single global error covariance matrix. The observational error covariance matrix is defined as a diagonal matrix of variances for each channel. These statistics are estimated from the differences between the radiances calculated from the analysis using the bias correction statistics after they have been updated.

The ECMWF seminar occured at the beginning of the final testing of the interactive retrievals before operational implementation. Figs. 3 and 4 show the average anomaly correlations for the Northern and Southern Hemispheres from the final test. In the Northern Hemisphere, a small positive impact from the interactive retrievals can be seen. In the Southern Hemisphere, slightly negative impacts can be seen. Earlier results showed very large positive impacts in the Southern Hemisphere with the operational forecasters noting large improvements in the predictions. Some of the reason for the change in the impact of the interactive retrievals from the earliear tests to the current test can be attributed to improvements in the operational retrieval system. Since the earlier tests, NESDIS has been using the forecast near surface temperatures to choose the guess profiles. This appeared to substantially improve the operational retrievals. However, since this is a small step in the same direction as the interactive retrievals, one would hope that the full interactive retrievals would produce even better results. The reason for the lack of improvement in the Southern



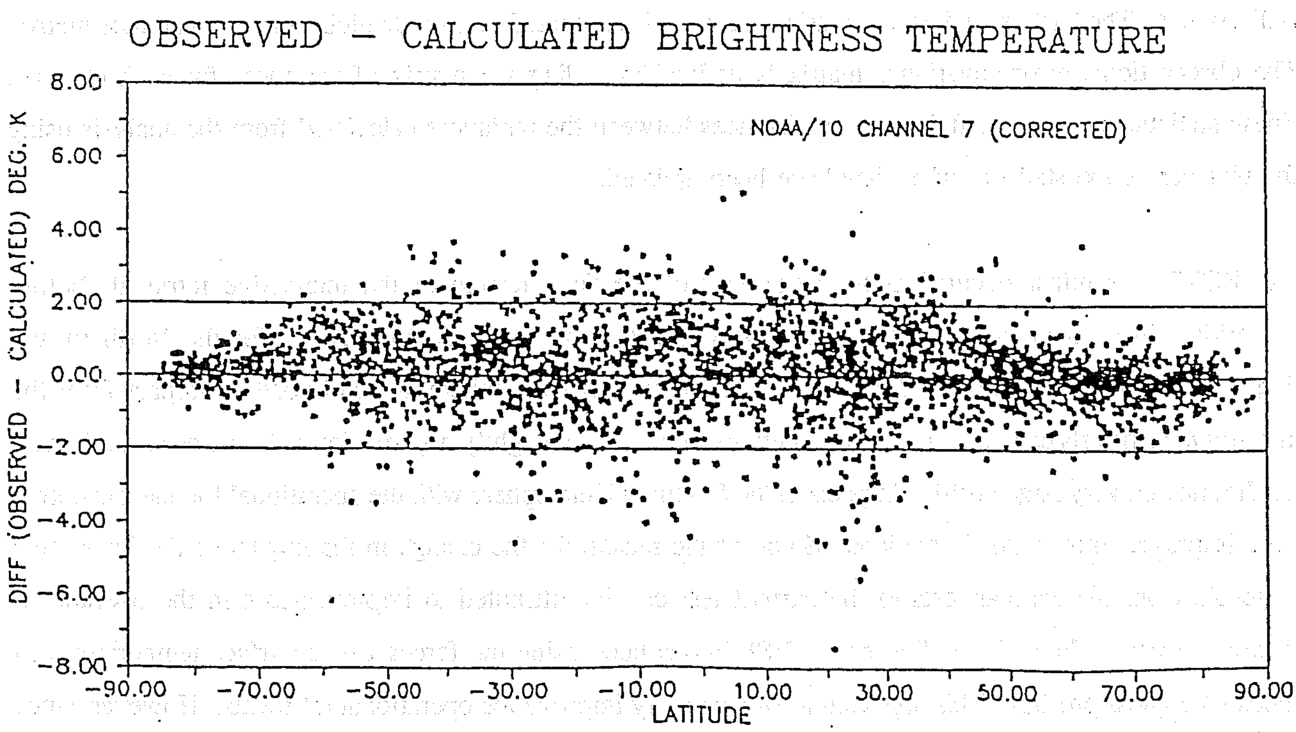


Fig. 2: Differences between observed and calculated brightness temperatures with and without bias correction.

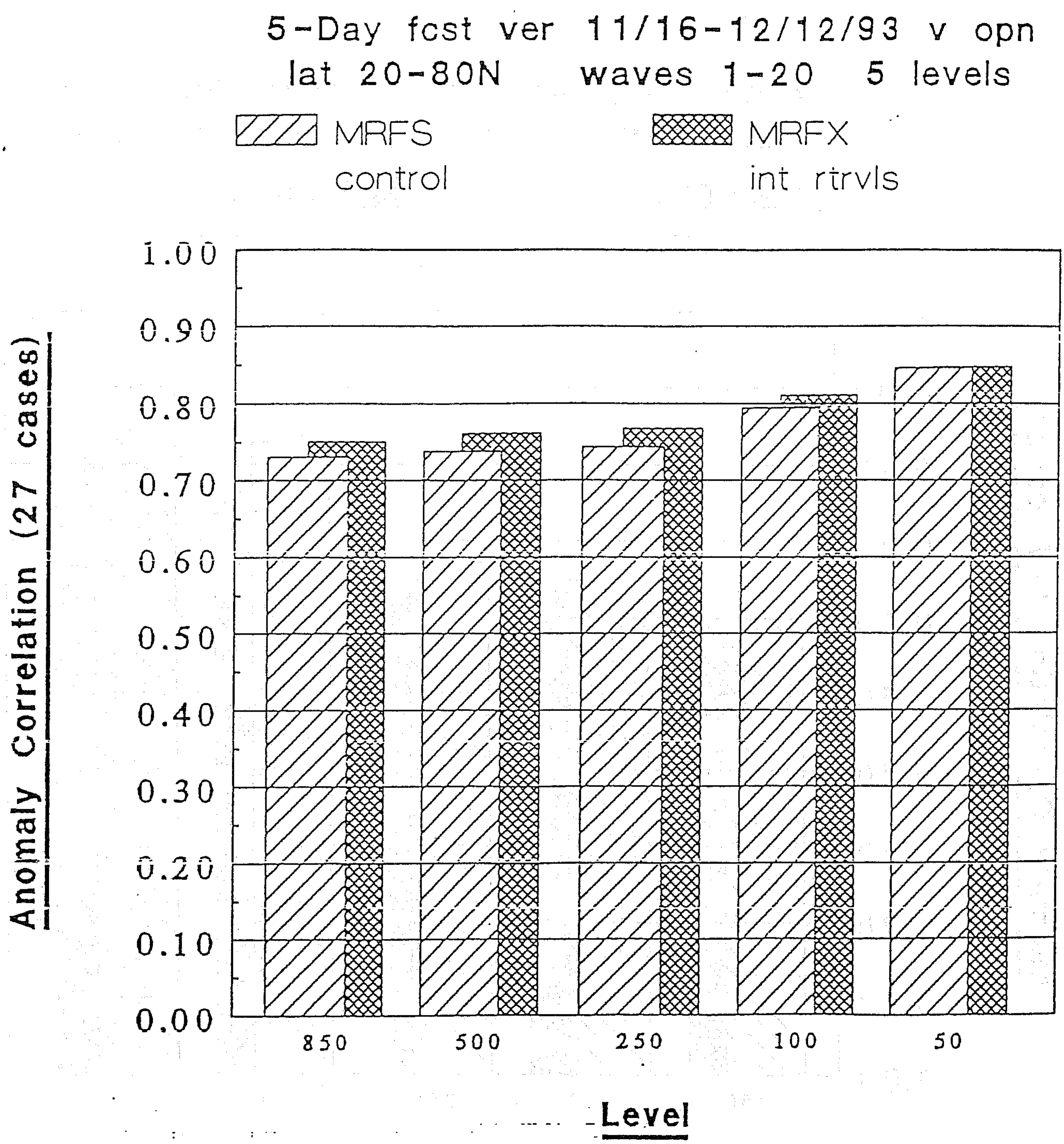


Fig. 3: Northern Hemisphere Anomaly correlations for the control and interactive retrievals. Results are from 27 cases from Nov. 16 to Dec. 12, 1993.

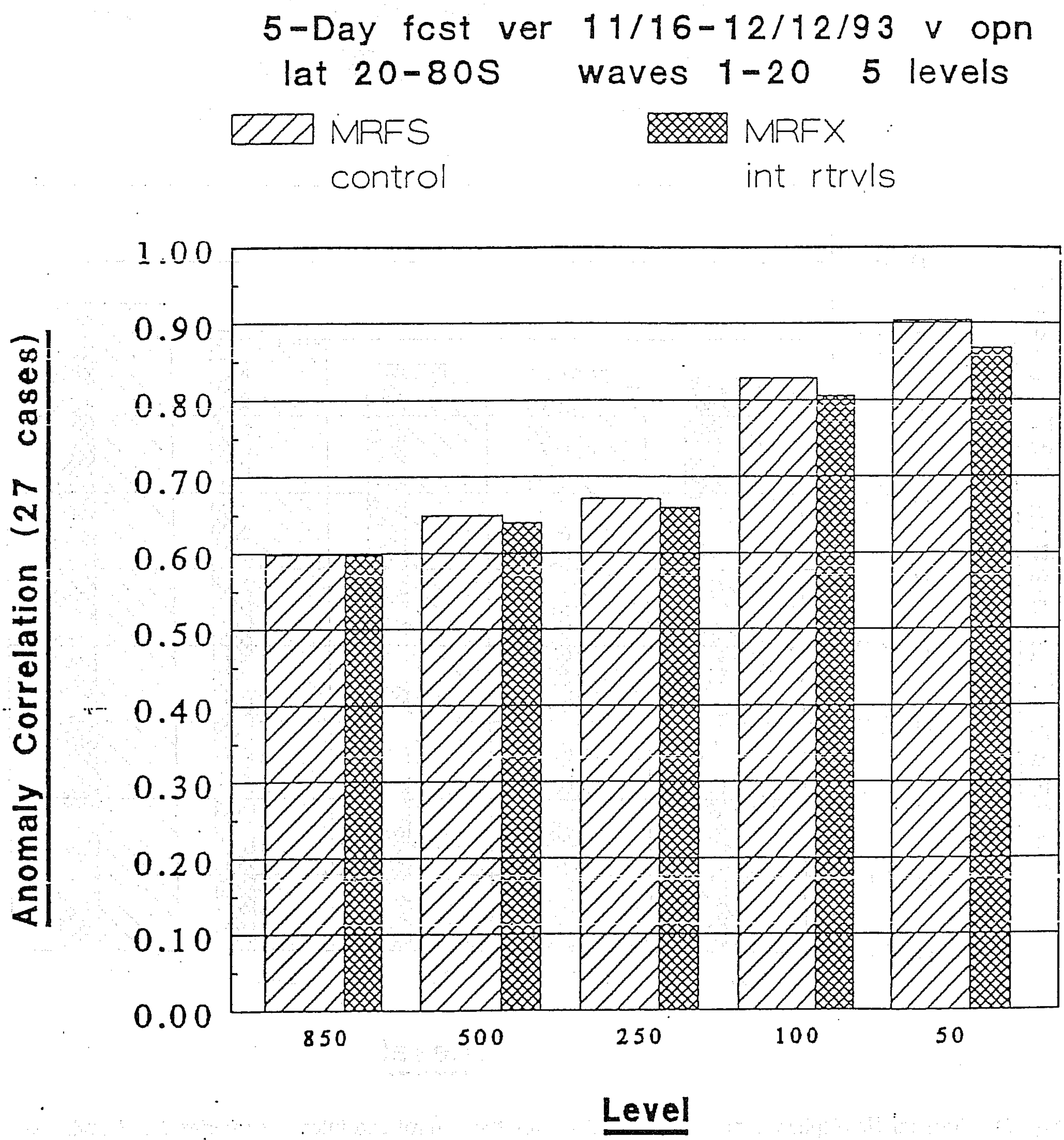


Fig. 4: Same as Fig. 3 except Southern Hemisphere.

Hemisphere is still under investigation.

4.2 Improved cloud cleared radiances

The 1-D var. retrievals at the ECMWF and the interactive retrievals at NMC depend on the cloud clearing algorithm being performed at NESDIS. An improved version of this algorithm is being developed by Larry McMillian, Sisong Zhou and Joel Susskind. The improved version was created by combining some of the best elements from both of the NESDIS and NASA algorithms. This resulted in three major differences from the current NESDIS algorithm. First, only a local angle correction is being performed before the cloud clearing. After the cloud clearing, a global angle correction can be performed. Second, the algorithm attempts to create N^* cloud cleared radiances before searching for a clear spot. This change is intended to reduce the number of supposedly clear radiances which have a small amount of cloud contamination. As a result of this change, a substantial increase in the number of N^* soundings can be expected. Finally, an attempt is made to screen spots for uniform heights and thus reduce the errors in the cloud clearing that result from using clouds from different elevations. This final aspect of the improved cloud clearing appears straightforward when manually performed, but has not yet been coded in a completely satisfactory manner and must be improved before implementation.

4.3 Improved use of SSM/I wind speeds

As mentioned in the previous section, the SSM/I wind speeds are currently being used by assigning a direction based on a local analysis. By making the H operator nonlinear and transforming the analysis variables into wind speeds as well as u and v components, then the SSM/I wind speeds can be directly used in the analysis. A version of the analysis code has been developed to do this. However, by making the H operator nonlinear, a simple linear conjugate gradient algorithm for solving (1) can no longer be used. The more complex algorithm, currently being used, requires too much memory to be performed at the full T126 operational resolution. Also, the computation costs are almost twice those of the current operational model. Thus despite encouraging results at T62, some further memory and computational optimization will be required before operational implementation.

4.4 SSM/I Total Precipitable water

The SSM/I Total Precipitable Water (TPW) should be extremely useful data for defining the global moisture field. Analysis systems like the SSI analysis system are ideal for incorporating this type of data because there is no need to project the information in the vertical before using. The necessary changes to the H operator involve only a vertical integration of the moisture variable. An earlier attempt at using the TPW was not successful due to a dry bias in the forecast model. By including the TPW measurements, the moisture was increased in the tropics. Since this increased moisture was incompatible with the model, the parameterizations immediately rained out the additional moisture out of the atmosphere. In the assimilation cycle, this increase in moisture and resultant increase in precipitation repeated itself in each cycle. The result was a very strong Hadley circulation. Since this attempt, several changes in the model and assimilation system have been made. The most important was the recent change to 28 levels which included an improved convective parameterization scheme (Pan and Wu, 1994) and the 40 level NESDIS retrievals. This version of the model has very different moisture biases.

Because of these changes, Wan-Shu Wu has been recently been attempting to incorporate this information in the NMC analysis system. While the system is still undergoing testing, the results have been encouraging. A series of analyses have been created without cycling and a 2-day assimilation cycle has been performed. While the model still appears to have a dry bias, an overprediction of the Hadley circulation has not yet been observed. In Fig. 5, the vertical means of ten 00Z differences between the analyses with and without the TPW are shown. No cycling was performed in this experiment. Note that the global mean of the corrections are positive at almost all levels, reflecting the continued presence of a dry bias in the model. The minimum in the corrections near the surface is primarily because the analysis procedure does not allow the resulting analysis to become supersaturated. The minimum in the global mean around $\sigma = .633$ is a result of an averaging of positive and negative corrections. Fig. 6 shows the horizontal distribution of the mean corrections at $\sigma = .883$ (the maximum in Fig. 5). Note that most of the largest maximums are positive, however significant areas are negative. These patterns are consistent with known and suspected problems in the moisture analysis. The pattern in this horizontal distribution has many similar characteristics to the signal seen in the TOVS moisture channel data as those presented by Eyre and McNally in this seminar. Since these instruments are independent, additional confidence is given to both sets of results.

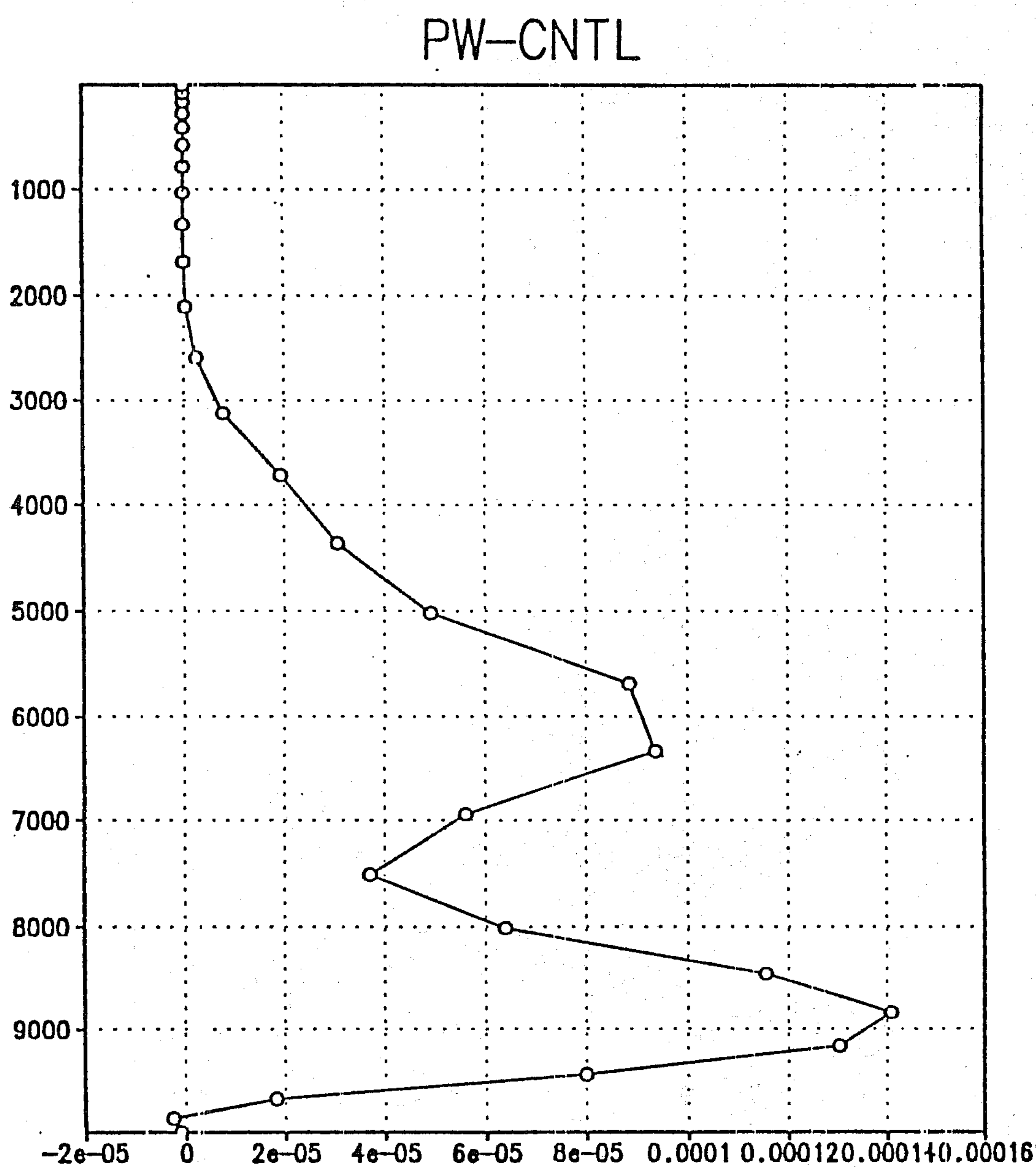


Fig. 5: Vertical mean differences between analyses with and without the SSM/I TPW data in the specific humidity field averaged over globe and 10 cases. All cases were at 00Z and without feedback from previous analysis.

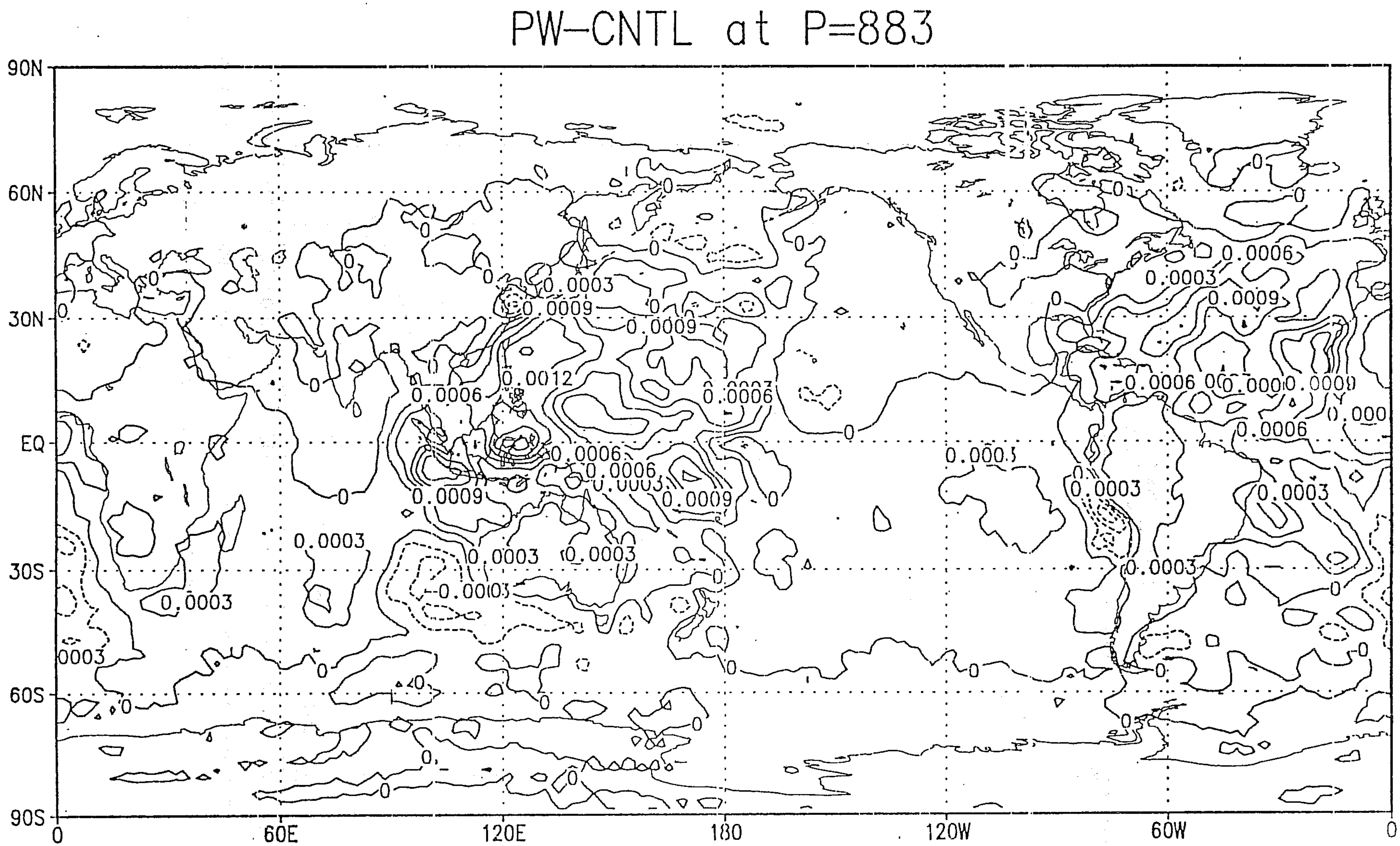


Fig. 6: Same as Fig. 5 except horizontal mean at σ = .883.

4.5 ERS-1 Scatterometer data

ERS-1 Scatterometer data is being incorporated into the SSI analysis system by Tsann-Wang Yu in collaboration with Ross Hoffman. The backscatter measurements (σ^os) are inserted directly into the analysis procedure. Most of the effort, until recently, has been expended in data handling problems. The σ^o data has been put into the analysis procedure and all necessary coding changes have been made. We expect it make significant progress in the next few months.

5. FUTURE PLANS FOR USE OF SATELLITE DATA

One of the major advantages of the SSI or 3-D var. analysis systems is the ability to use unconventional types of data. Even with the enhancements described in the previous section, only a very small portion of the available satellite data will be used. Unfortunately, the addition of each type of data requires considerable effort not only for the incorporation in the analysis but also for quality control and for data base management. With the advanced data assimilation systems, satellite data is starting to have a positive impact on numerical weather prediction in all regions. At NMC, we intend to continue to incorporate new types of data and attempt to improve the usage of the data.

With the positive impact of the interactive retrievals, the direct use of the radiances is the obvious next step in improving the use of the TOVS data as pioneered by the ECMWF. Since the interactive retrievals and the variational analysis are basically solving the same problem, it should be straightforward to combine the two problems. Unfortunately, the solution algorithm currently used in the interactive retrieval is not compatible with the solution technique used in the SSI analysis. The interactive retrieval problem must be modified before it can be included directly into the analysis procedure. We expect that this effort will take at least a year even with some generously provided radiation code from ECMWF.

Much of the additional effort in the use of satellite data in the analysis will be directed towards the improved definition of the moisture field in the analysis (including cloudiness and precipitation analyses). Currently, this moisture field is probably the least accurate of the analysed variables. The use of the TPW from SSM/I should somewhat improve this field. However, there is a large amount of additional satellite data which contains information on the moisture fields which is not being used. For example, the SSM/T2 instrument should contain substantial additional moisture information. The visible and IR channels on the geostationary satellites contain information, at a minimum, on the location of clouds (or the lack of clouds) which could be used in the moisture analysis. Of course, the TOVS instrument contains substantial moisture information in the currently unused moisture channels. With the improve utilization of this satellite data, along with improved moisture parameterizations in the forecast model, substantial improvement in the analysed and predicted moisture fields should be possible in the next few years.

6. References

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