SOME EXPERIMENTS WITH NON-LINEAR OPTIMAL ESTIMATION RETRIEVALS FROM RAW TOVS RADIANCES USING CLIMATOLOGICAL CONSTRAINTS

J.D.Steenbergen, B.T.Greaves, and T.C.Yip
Atmospheric Environment Service
Downsview, Ontario, Canada

1. INTRODUCTION

A great deal of interest has been generated in the proposal by Smith et.al. (1985) that temperature and water vapour soundings could be improved by simultaneously considering the effects of these parameters on measured TOVS radiances. Given the success of statistical retrieval techniques in operations, it appeared likely that a simultaneous solution for temperature and water vapour profiles which included statistical constraints from climatology would produce promising results. Fleming et.al.(1986) introduced such a method, and in 1988 reported on its progress toward operations in NESDIS; while Eyre et.al.(1986) discussed the use of a model forecast and model error statistics in a simultaneous retrieval. These schemes, however, still required preliminary processing of the measured TOVS radiances to correct for the effects of cloud on the infrared measurements. This was addressed by Huang and Smith (1986), who extended the approach of Smith et.al. (1985) to retrieve temperature, water vapour, and cloud height and amount directly from measured TOVS radiances; and by Eyre (1987a), who described the application of non-linear optimal estimation (Rodgers, 1976) to this problem and investigated the characteristics of such a scheme using simulated data.

In this paper, we report on several experiments with non-linear (quasi)optimal estimation (NLOE) retrievals of temperature, water vapour, and cloud using climatological statistics as constraints. Although the retrievals follow the overall framework described by Eyre (1987a), there are a number of differences which are described in the first section. In subsequent sections, we investigate the impact of in-situ surface-based measurements on the retrievals, and compare the NLOE retrievals with retrievals made by a regression method. We also compare the error covariance estimate produced by the retrieval with retrieval-radiosonde differences; compare the results of retrievals done using slant-path radiances to retrievals using limb-corrected measurements, and report on a preliminary attempt to include information on relative humidity derived from cloud parameters in the retrievals.

2. METHOD

After ITSC-3 we attempted to extend Huang and Smith's approach to include statistical information by using eigenfunctions of temperature and relative humidity covariance matrices as basis functions. The method was essentially the same as we used for clear conditions only (Steenbergen et. al. 1986), except that the profile vector **b** was extended to include the cloud top pressure, cloud amount, microwave emissivity, and the difference between the surface skin temperature and the surface air temperature. (More precisely, **b** included the differences of these quantities from their a priori values.) As before, the eigenfunctions of the vertical covariance matrix of temperature corresponding to the six largest eigenvalues were used to describe the temperature profile, and three eigenfunctions were used to describe the relative humidity profile.

The inverse solution we used was an application of the constrained linear inversion technique using empirical orthogonal functions described by Twomey (1977). The solution is given by

$$\mathbf{b} = (\mathbf{A}^t\mathbf{A} + \gamma\Lambda^{-1})^{-1}\ \mathbf{A}^t\mathbf{g} \tag{1}$$

The diagonal elements of the constraint matrix Λ were the eigenvalues corresponding to the temperature and relative humidity eigenfunctions, and estimates of the variance of the other profile vector elements. All the off-diagonal elements of Λ were zero. γ was a Lagrangian multipier which was determined by trial and error. (We obtained a value of 1.0 although the results were not very sensitive to this value.) The measurement vector $\mathbf{g}$ contained the differences between the observed brightness temperatures and the brightness temperatures calculated from the first guess, normalized by the standard deviations of differences between observed brightness temperatures and forward calculations from collocated radiosondes. In-situ measurements of surface air temperature and surface relative humidity could also be optionally added to $\mathbf{g}$. The elements of $\mathbf{A}$ ($A_{ij}=\partial g_i/\partial b_j$) were calculated by perturbing the profile vector.

When the measurements are normalized by their expected error and $\gamma=1$, Twomey's solution can be written

$$\mathbf{b} = \Lambda\, \mathbf{K}^t(\mathbf{K}\Lambda\,\mathbf{K}^t + \mathbf{S}_m)^{-1}\ \mathbf{y} \tag{2}$$

where $K_{ij} = \partial y_i/\partial b_j$, $\mathbf{y}$ contains the differences between observed and calculated brightness temperatures, and $\mathbf{S}_m$ contains the "error" variances of the measurements on the diagonal. This is equivalent to the linear maximum-likelihood approach described by Rodgers (1976) except for the truncation of the eigenfunctions of the covariance matrices.

The retrievals were carried out in three steps in a manner similar to that used by Huang and Smith (1986). In the first step, only the microwave channels were used to obtain an updated temperature profile, and the relative humidity was held fixed. In the second step, cloud detection tests were applied and the CO_2 slicing method (Smith and Platt, 1978) was used to obtain an initial estimate of the cloud height and amount. In the third step, both the HIRS and MSU channels were used and all the elements of the profile vector were solved for by applying equation (1) to the changes from the previous step.

Although we were able to produce retrievals in this way (Steenbergen et. al., 1987) the approach was not statistically optimal because the constraint was applied incorrectly on iterations after the first. When the linear maximum-likelihood method is applied iteratively, the solution is constrained to the output of the previous guess rather than the a priori mean (Rodgers,1976). Rodgers described a Newtonian iteration method which applies the statistical constraints correctly in problems with non-linear physics, which has been applied to TOVS retrievals from cloudy radiances by Eyre (1987a). (We would like to thank Dr. John Eyre for a very helpful discussion on this topic and for providing a copy of his work in draft form.)

Following Eyre's approach, we modified equation (2) to

$$\mathbf{b}_{n+1} = \mathbf{b}_n - \mathbf{I}^r\mathbf{b}_n + \Lambda^r\mathbf{K}_n{}^t(\mathbf{K}_n\Lambda^r\mathbf{K}_n{}^t + \mathbf{S}_m)^{-1}\ (\mathbf{y} - \mathbf{y}_n + \mathbf{K}_n\mathbf{I}^r\mathbf{b}_n) \tag{3}$$

where Λ^r contained reduced values of variance for the cloud top pressure and cloud amount (as used by Eyre to control oscillation in the retrieved cloud parameters)[1] and I^r was a unit matrix except for the elements corresponding to the cloud parameters, which were $\Lambda^r_{ii}/\Lambda_{ii}$.

3. DATA

The results shown here are based on 551 collocated rawinsonde and NOAA-8 satellite measurements during May and June 1984. For purposes of analysis, the collocated measurements were sorted according to an independent estimate of the cloud amount obtained by subjective analysis of the AVHRR imagery. In order to minimize sampling differences, we used only cases in which the satellite and rawinsonde observation times differed by one hour or less. The satellite radiances were centred at the closest scan spot to the location of the rawinsonde station according to orbit model calculations. The time constraint combined with our use of direct readout satellite data limited the suitable radiosonde observations to 00Z ascents in eastern North America.

4. RESULTS

4.1 Effect of adding surface observations to the retrievals

RMS layer mean temperature differences between radiosondes and NLOE retrievals with and without surface air temperature and relative humidity added to the measurement vector are shown in figure 1a. The RMS differences increased with increasing cloud throughout the profile whether surface data were used in the retrieval or not, with the largest increases (other than below 850 mb) occurring between 300 and 500 mb. When ancillary surface data were not used in the retrievals, the 850-1000 mb RMS difference increased markedly with increasing cloud. The increase in the 850-1000 mb RMS difference was presumably caused by the loss of surface skin temperature information from the HIRS as the cloud amount increased. This information could not be provided by the MSU due to the uncertainty in the surface emissivity.

We assumed the a priori distribution of microwave surface emissivity was quite wide, with a mean of 0.80 and a standard deviation of 0.20 (as in Eyre (1987a)). The variation of retrieved emissivity values when surface air temperature measurements were used in the retrievals provides an indication of the actual variations in the emissivity. 67% of the retrieved emissivities fell between 0.83 and 0.96, in a nearly Gaussian distribution around the mode of 0.90. The other 1/3 of the retrieved emissivities were in a long tail extending from 0.83 down to 0.52. The retrievals in this tail were collocated with island or coastal radiosonde stations, so that a substantial part of the

---

[1] The variances of the cloud top pressure and cloud amount which had been used in our non-optimal retrievals were close to the "reduced" values used by Eyre. Λ was changed to increase the background variances of the cloud parameters to the values used by Eyre. No terms involving the background value of b appear above since this value is zero. It was expedient to continue to use truncated sets of eigenvectors as bases for the temperature and relative humidity profiles. Because the full a priori covariance matrix of temperature and relative humidity is not used, this solution is not quite optimal. However, as long as the neglected eigenfunctions explain very little variance and their effect on the radiances is small, the difference should be small.

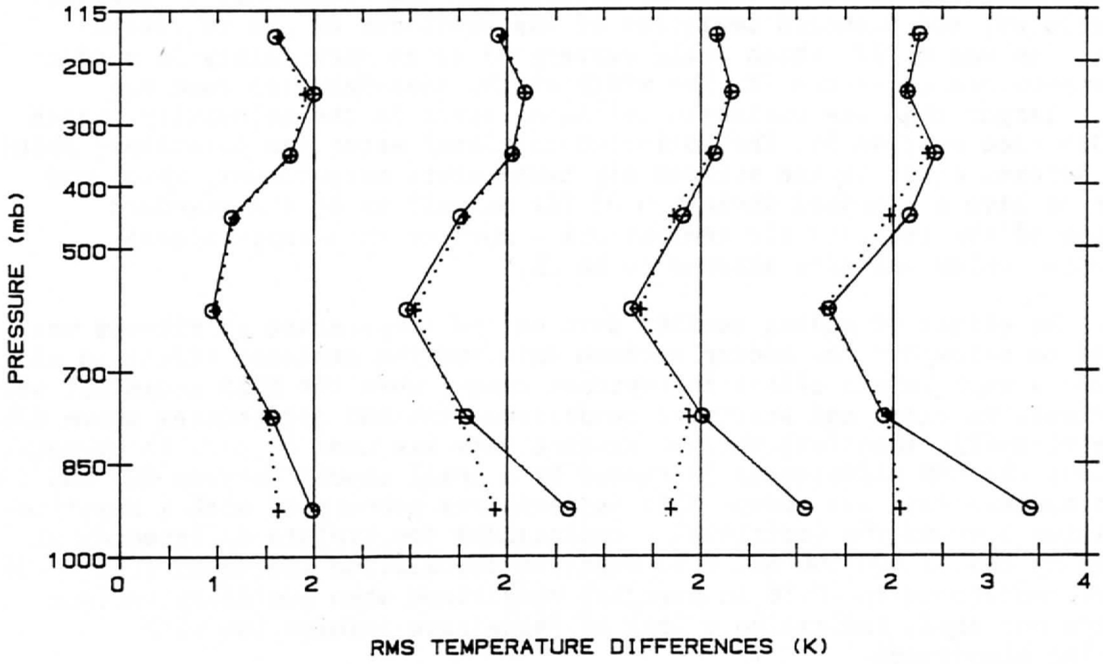

Figure 1a. RMS layer mean temperature differences between radiosondes and: NLOE retrievals with ancillary surface data (dotted lines); NLOE retrievals without ancillary surface data (solid lines). From left to right, 99 clear cases, 106 scattered cloud cases, 127 broken cases, 151 overcast cases.

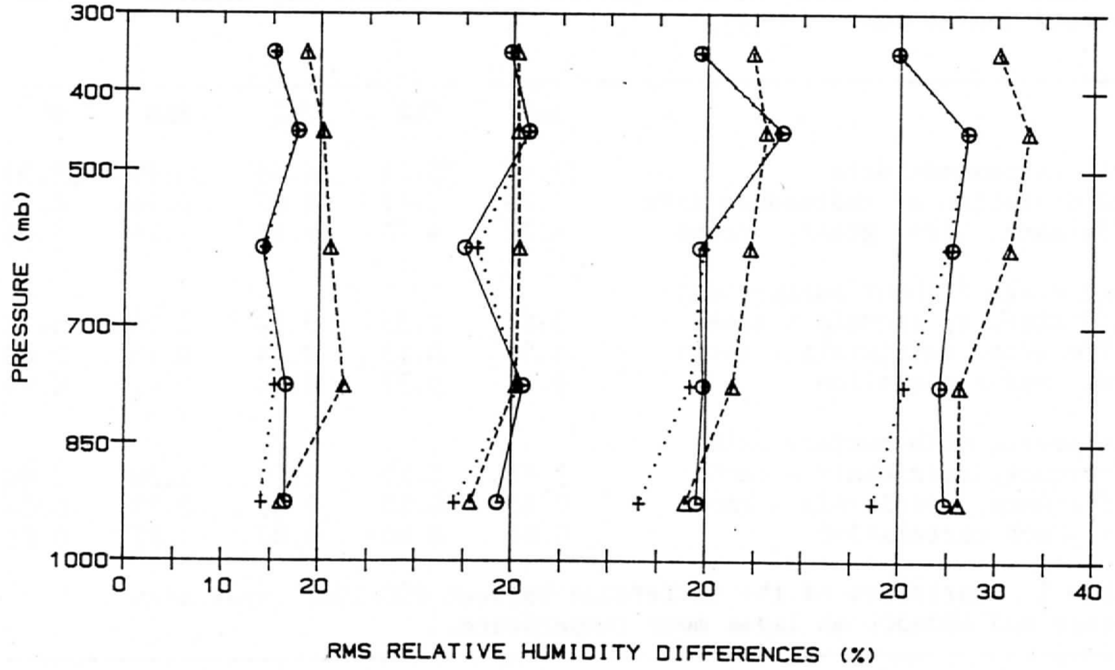

Figure 1b. As in figure 1a for layer mean relative humidities, plus RMS difference between first guess relative humidity profile and radiosondes (dashed lines).

surface in the MSU field of view was water. When the retrievals in the tail were excluded, the standard deviation of the remainder of the retrieved emissivities was 0.027, which would correspond to an uncertainty in surface skin temperature of around 7K. The width of the near-Gaussian peak was somewhat larger than the estimated retrieval error in the emissivity, which was 0.016 (see section 5). The estimated retrieval error was determined mainly by the assumed error in the surface air temperature measurement, which was assumed to have a standard deviation of 2K; as well as by the standard deviation of the (surface air temperature - surface skin temperature) difference, which was also assumed to be 2K.

Most of the effect of adding surface data on the temperature retrievals was confined to below 850 mb. Adding surface data had the smallest effect in clear cases and a much larger effect in overcast cases, when the HIRS could not see the surface. In clear and scattered conditions, the RMS differences above 850 mb were virtually identical whether surface data was used or not. In overcast conditions the RMS differences decreased by a small amount between 300 and 500 mb when surface data was added. This decrease was associated with a negative correlation between the (retrieval - radiosonde) temperature differences at 850-1000 mb and at 400-500 mb. This negative correlation increased from -0.07 in clear conditions to -0.36 in overcast conditions when ancillary surface data were not used, indicating a loss of lapse rate information with increasing cloudiness.

The loss of lapse rate information can be seen in statistics of the vertical temperature difference between the 850-1000 mb layer and the 400-500 mb layer. The correlation between this vertical temperature difference from the retrieved profiles and from the radiosonde data (table 1) decreased sharply as the cloud amount increased when no surface data were used in the retrievals. When surface data were used the correlation stayed relatively constant as the cloud amount increased.

	ALL	CLR	SCT	BKN	OVC
Mean from radiosonde data	33.40	35.61	34.46	33.99	29.93
Standard deviation of radiosonde data	4.78	3.67	4.07	4.26	4.65
RMS difference, first guess - raobs	4.82	4.10	4.15	4.26	6.05
NLOE retrievals without surface data					
RMS difference, retrievals - raobs	3.81	2.35	3.14	3.98	4.78
Mean difference, retrievals - raobs	0.59	-0.13	0.44	0.18	2.08
Retrieval-raob correlation	0.62	0.77	0.64	0.49	0.49
NLOE retrievals with surface data					
RMS difference, retrievals - raobs	2.61	2.19	2.50	2.58	2.80
Mean difference, retrievals - raobs	0.11	-0.15	0.42	-0.23	0.34
Retrieval-raob correlation	0.84	0.80	0.80	0.81	0.81

Table 1. Statistics of the difference between 850-1000 layer mean temperature and 400-500 mb layer mean temperature.

The RMS differences between the relative humidity retrievals and radiosondes (figure 1b) also increased with increasing cloud, as one would expect. The effect of the surface relative humidity measurement (assumed to have an uncertainty of 15%) increased as the cloud amount increased and the sensitivity of the HIRS radiances to relative humidity changes went down.[2]

4.2 Comparison with statistical retrievals

Comparisons were made between the NLOE retrievals (without ancillary surface data) and statistical retrievals using regression coefficients generated locally from synthetic data. The retrievals were sorted according to whether the cloud detection/correction routine in the statistical scheme (which generally followed the approach of McMillin and Dean (1982)) was able to produce clear radiances; as well as according to the cloud cover estimated by AVHRR. The results are presented in figure 2.

When the statistical cloud-clearing scheme succeeded, two temperature retrievals were available from the statistical scheme (one from MSU data only and the other from HIRS aided by MSU). In these conditions, the NLOE retrievals improved over the statistical retrievals below 400 mb (figure 2a). The statistical cloud-clearing scheme was unable to produce clear radiances in 25 of 99 clear cases identified by AVHRR, 14 of 106 scattered cases, 27 of 127 broken cases, and 78 of 151 overcast cases. (In overcast conditions clear radiances should not have been produced.) When the cloud-clearing failed, the MSU-only statistical retrievals (which were the only product available from the statistical scheme) performed noticeably worse than they did when the cloud-clearing succeeded. The NLOE retrievals were also degraded in these conditions but not by as large a margin (figure 2b). The association between the performance of the MSU-only retrievals and the cloud-clearing scheme is not surprising because of the heavy dependence of the cloud-clearing on statistical relationships between the HIRS and MSU channels.

RMS differences between retrieved layer mean relative humidities and radiosonde values for the NLOE and statistical retrievals are shown in figures 2c and 2d. Also shown are the RMS differences between the radiosonde measurements and the first guess relative humidity profile. In clear conditions, the NLOE retrievals improved substantially over the first guess. The improvement was smaller (and absent or negative for some layers) in scattered and broken conditions. In overcast conditions, there was an improvement over the first guess in the higher troposphere, although the RMS differences were still large. In general, the NLOE retrievals improved over the first guess in conditions when a moisture retrieval was unavailable from the statistical scheme due to failure of the cloud correction scheme (figure 2d). The statistical scheme failed to improve over the first guess even in clear conditions. In overcast conditions when the statistical scheme produced clear radiances (and probably should not have) the statistical scheme was noticeably worse than the first guess in the 500-700 mb layer.

Examination of the AVHRR imagery and mean radiosonde profiles showed that the overcast cases in which clear radiances were produced generally had lower

---

[2] The impact of the surface measurements in these retrievals may be overestimated because the surface measurements were obtained from the radiosonde reports against which the retrievals were subsequently compared. However, in assigning errors to these measurements we tried to keep the variability of surface temperature and relative humidity in mind.

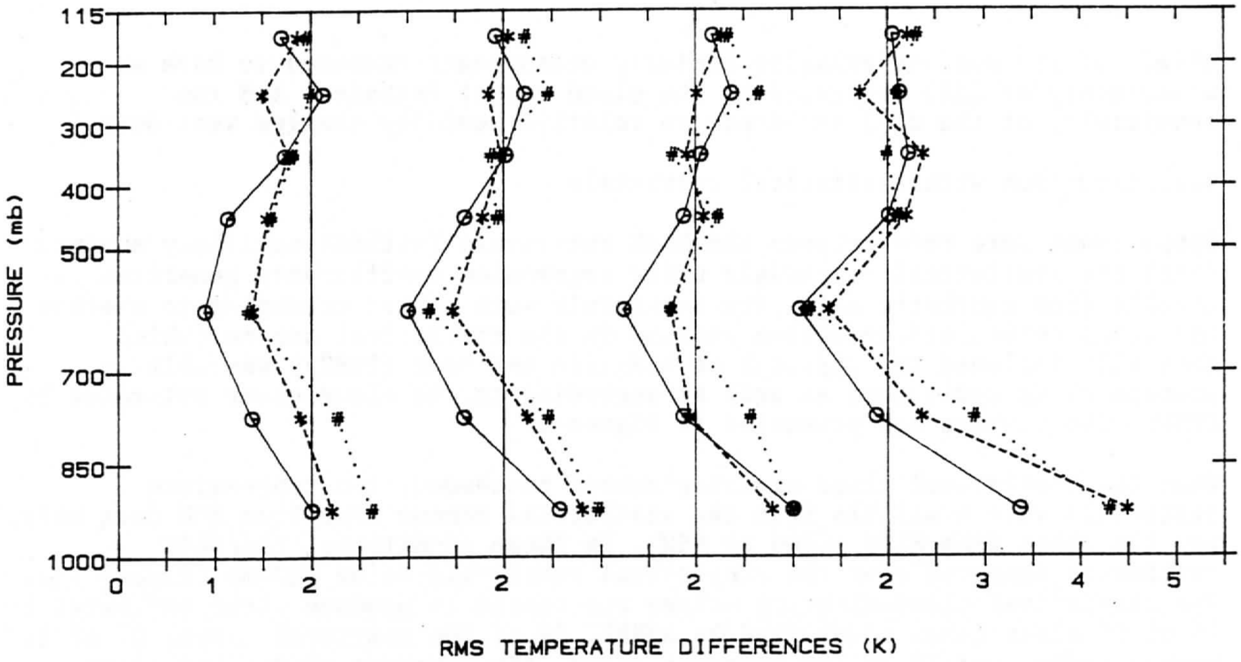

Figure 2a. RMS layer mean temperature differences between radiosondes and: NLOE retrievals (solid lines); HIRS statistical retrievals (dotted lines); MSU-only statistical retrievals (dashed lines); when statistical cloud-clearing succeeded. From left to right, 74 clear cases, 92 scattered cases, 99 broken cases, 73 overcast cases.

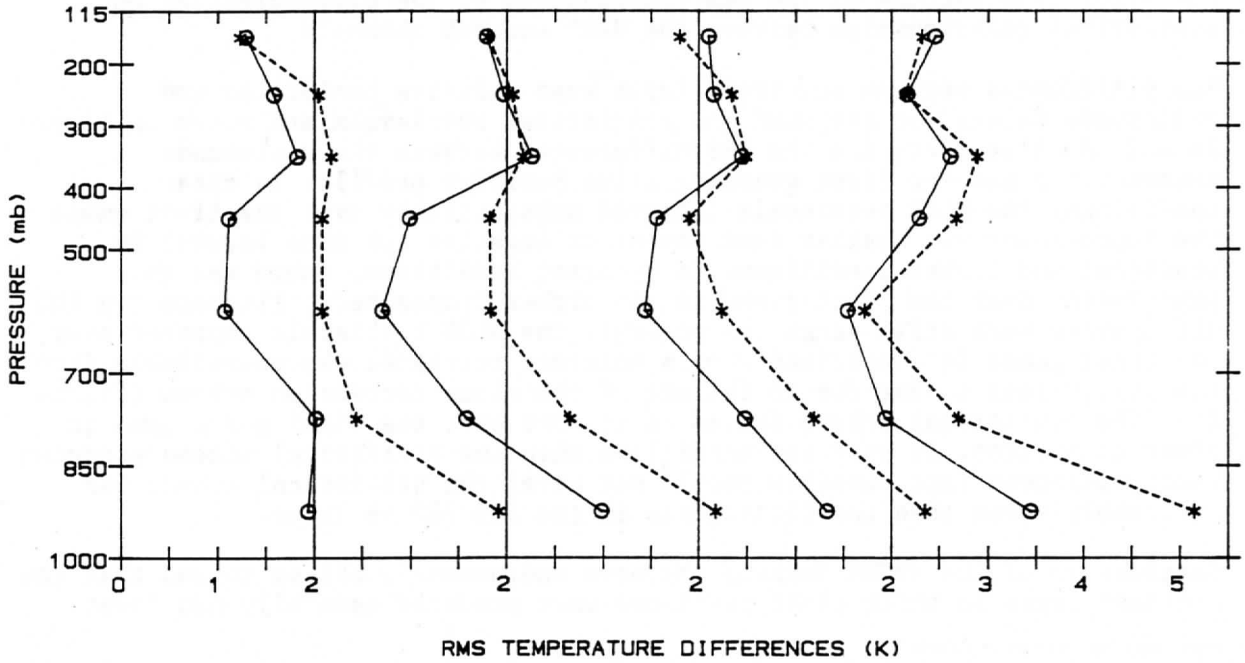

Figure 2b. RMS layer mean temperature differences between radiosondes and: NLOE retrievals (solid lines); MSU-only retrievals (dashed lines); when statistical cloud-clearing failed. From left to right, 25 clear cases, 14 scattered cases, 28 broken cases, 78 overcast cases.

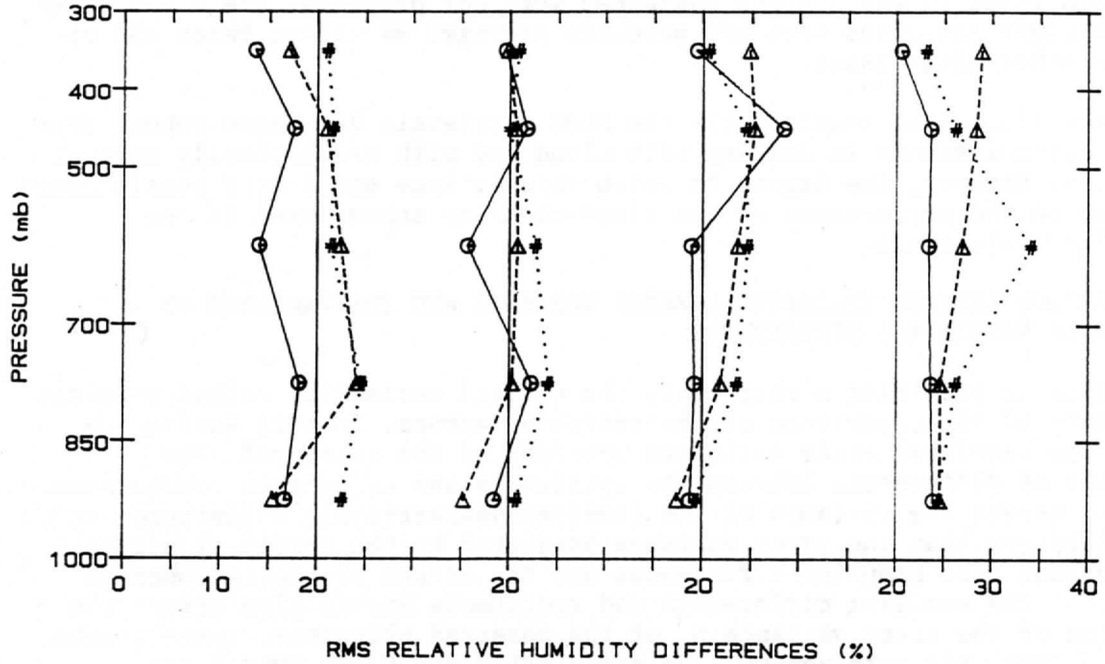

Figure 2c. RMS layer mean relative humidity differences between radiosondes and: NLOE retrievals (solid lines); HIRS statistical retrievals (dotted lines); first-guess relative humidity profile (dashed lines); when statistical cloud-clearing succeeded. From left to right, 74 clear cases, 92 scattered cases, 99 broken cases, 73 overcast cases.

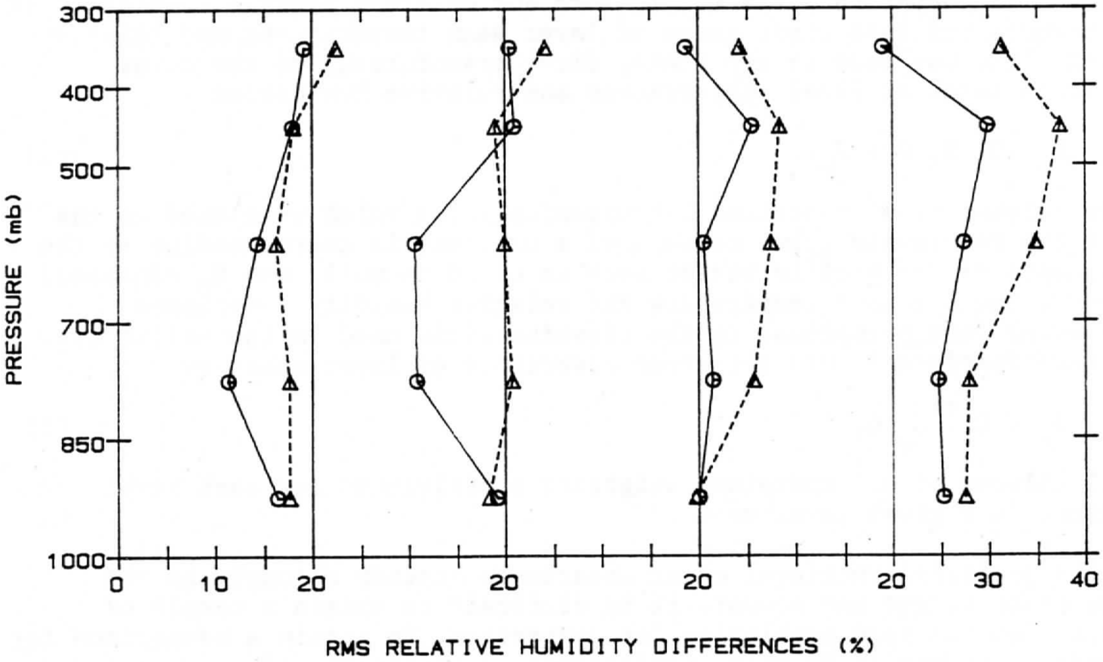

Figure 2d. RMS layer mean relative humidity differences between radiosondes and: NLOE retrievals (solid lines); first-guess relative humidity profile (dashed lines); when statistical cloud-clearing failed. From left to right, 25 clear cases, 14 scattered cases, 28 broken cases, 78 overcast cases.

cloud than those in which clear radiances were not produced. The clear cases in which clear radiances were not produced averaged 9K colder below 400 mb than the other clear cases.

It appears from these results that the NLOE retrievals were more robust than the statistical scheme in dealing with cloud and with statistically unusual situations. However, the degree to which this is true could vary considerably depending on the performance of the cloud-clearing scheme used in the statistical retrievals.

5. COMPARISON BETWEEN THEORETICAL ERROR VARIANCE AND THE VARIANCE OF (RADIOSONDE-RETRIEVAL) DIFFERENCES

In addition to providing a retrieval, the optimal estimation method provides an estimate of the covariance of the retrieval errors. In this section we compare the retrieval error estimates provided by the retrieval with statistics of differences between the retrievals and collocated rawinsondes. One would expect the variance of the (radiosonde-retrieval) differences to be somewhat larger than the error variance predicted by the retrieval due to contributions from sampling differences and the errors of the radiosondes themselves. The sampling differences and radiosonde errors also affect the estimation of the error variance S_m of the observed brightness temperatures. To try to take this into account, we arbitrarily set S_m to 50% of the (observed brightness temperature minus forward model) variance.

The error covariance of **b** was calculated (following Rodgers(1976)) by

$$S_b = (\Lambda^{-1} + K_n{}^t S_m{}^{-1} K_n)^{-1} \tag{4}$$

For purposes of comparison, the temperature and moisture profile components of S_b were transformed into covariances of layer mean temperatures and relative humidities. This was done in two steps, first transforming to the error covariance in terms of level temperatures and relative humidities

$$S_p = Q^t\, S_b\, Q + S_0 \tag{5}$$

where the columns of Q^t contained the eigenfunctions which were used as the basis for the retrievals (plus columns of a unit matrix corresponding to the other elements of the profile vector such as cloud amount), and S_0 contained the parts of the a priori temperature and relative humidity covariance matrices which were orthogonal to the eigenfunctions used in the retrievals. S_p was then transformed into the error covariance of layer means by

$$S_l = Q_l{}^t\, S_p\, Q_l \tag{6}$$

where the columns of $Q_l{}^t$ contained weighting coefficients for each level contributing to a given layer mean.

Because the predicted retrieval error covariance depends strongly on the retrieved cloud height and amount, it is difficult to obtain a sample of retrievals from the same population for comparison. To obtain a comparison for the diagonal elements of S_l only, (radiosonde - retrieval) differences for each layer were sorted according to the predicted error variance for that layer; and then sliced into six equal groups, each of which contained a relatively narrow range of predicted error variance. The variance of the (radiosonde - retrieval) difference and the mean predicted variance were calculated for each group and plotted against each other (figures 3a - 3f). The error bars on the observed variances are 95% confidence limits assuming the samples are drawn from a normal population.

The observed 500-700 layer mean temperature variances fit the predicted values quite reasonably (figure 3b). For the two levels above 500 mb (of which one is shown in fig 3a), the observed layer mean temperature variances increased more rapidly than predicted. When the predicted 850-1000 mb temperature variance was small, it was systematically much smaller than the observed (radiosonde - retrieval) variance (figure 3c). Above 700 mb, the observed variances of (radiosonde - retrieval) layer mean relative humidity were consistently higher than the predicted ones (figures 3d,3e).

It seems likely that the differences between the error variances predicted by the retrievals and the observed (radiosonde - retrieval) variances for relative humidity and 850-1000 mb temperature are due to sampling differences, since one would expect radiosonde measurements of these quantities to be less representative than measurements of temperature above 850 mb. However, the predicted 850-1000 mb temperature variance might also be quite sensitive to the size of the correlation assumed between the surface skin temperature and the surface air temperature. Systematic errors in the retrieved cloud amount or cloud top pressure would also cause biases in the predicted error variance.

6. USE OF CLOUD INFORMATION IN RELATIVE HUMIDITY RETRIEVALS

Examination of the radiosonde data for the 1984 collocated set showed that, not surprisingly, the mean relative humidity profile in clear conditions (as determined by AVHRR) was much drier than the overall mean, while in overcast cases the reverse was true (figure 4). If one used the same a priori constraints in all cloud conditions, the a priori relative humidity profile would be systematically too wet in clear conditions and too dry in overcast conditions. Consequently, one would expect (based on the conclusions of Eyre (1987b)) a corresponding bias in the relative humidity retrievals, particularly in the lower atmosphere where the radiance measurements contain less relative humidity information. We wondered if it might be possible to improve the relative humidity retrievals by using a background relative humidity profile which depended on the cloud conditions. Although the subjective classification into four categories based on AVHRR data which was used above provides very crude cloud information, we felt that it would be adequate for a preliminary test of this idea.

The 1984 radiosonde observations were used to generate overall mean temperature and relative humidity profiles and covariance matrices, as well as separate ones for each cloud amount class obtained by sorting the data according to the AVHRR cloud estimates. A set of NOAA-10 TOVS measurements (chosen to coincide with radiosonde locations) from the same season in 1987 were sorted into the same four cloud categories based on the AVHRR imagery. Two sets of retrievals were carried out from the 1987 radiances. The first set used the overall statistics from the 1984 data as the constraint, and the second set of retrievals used different constraints for each cloud class, again calculated from the 1984 data.

When the overall 1984 statistics were used as the constraint, the clear 1987 retrievals were more than 10 % too wet (compared to the radiosondes) below 700

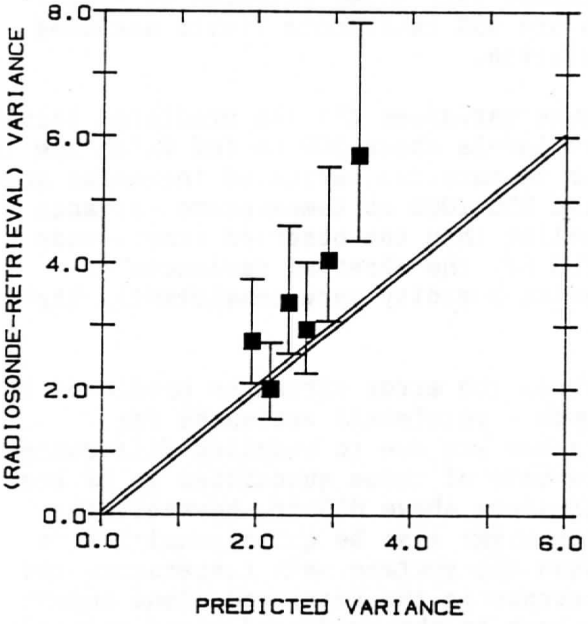

Figure 3a. Variance of (retrieved minus radiosonde) 300-400 mb layer mean temperatures vs. error variance predicted by NLOE retrievals. The x=y line is shown for reference.

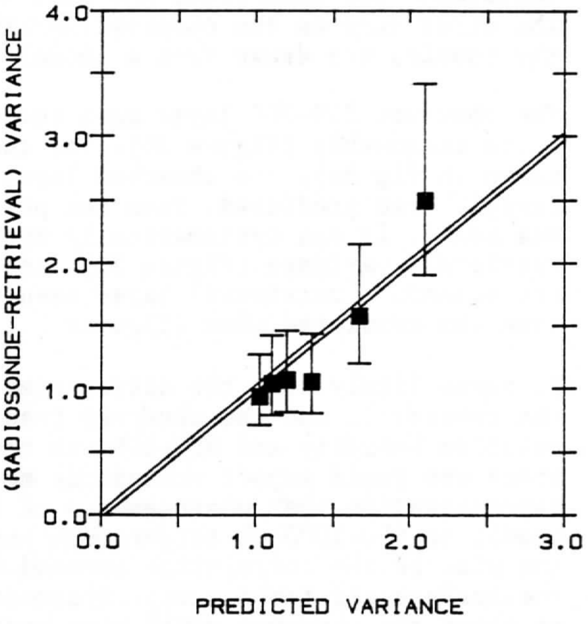

Figure 3b. As in figure 3a for 500-700 mb layer mean temperature.

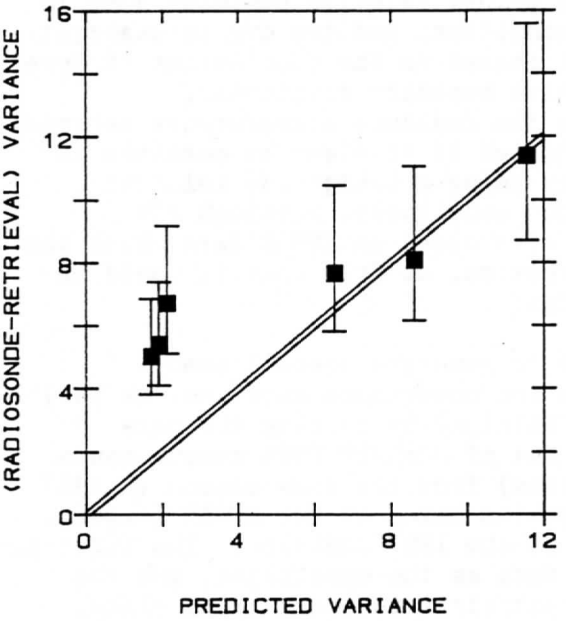

Figure 3c. As in figure 3a for 850-1000 mb layer mean temperature.

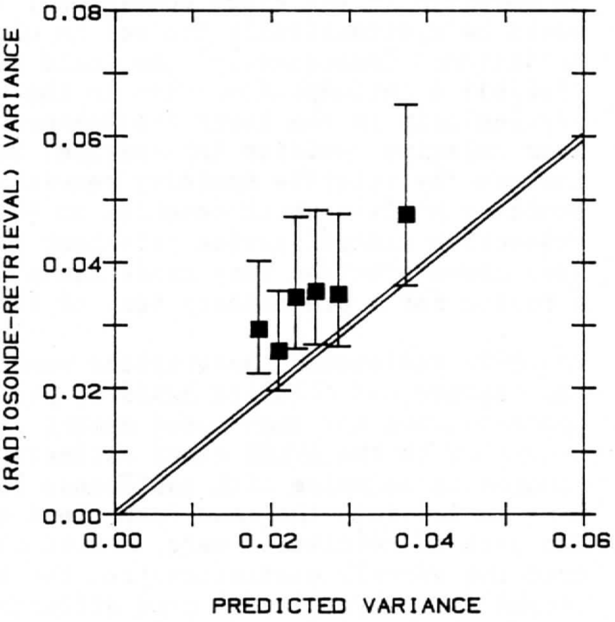

Figure 3d. As in figure 3a for 300-400 mb layer mean relative humidity.

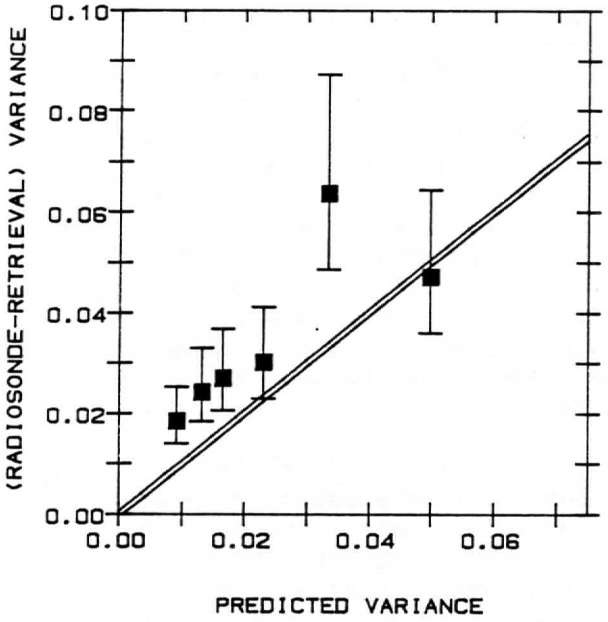

Figure 3e. As in figure 3d for 500-700 mb layer mean relative humidity.

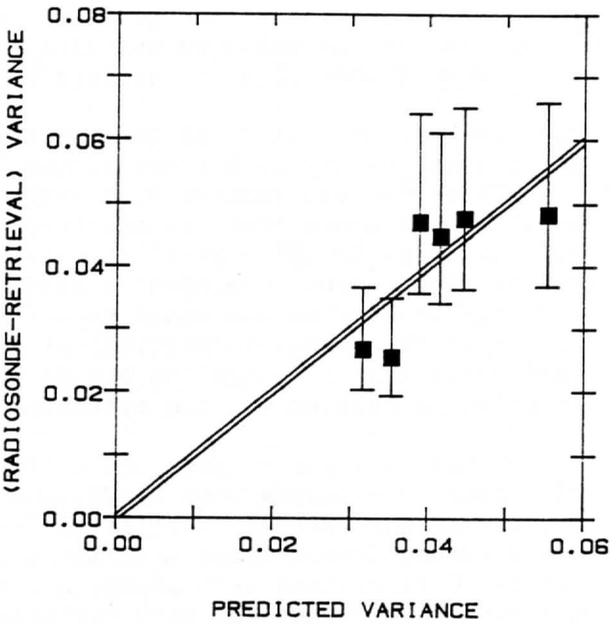

Figure 3f. As in figure 3d for 850-1000 mb layer mean relative humidity.

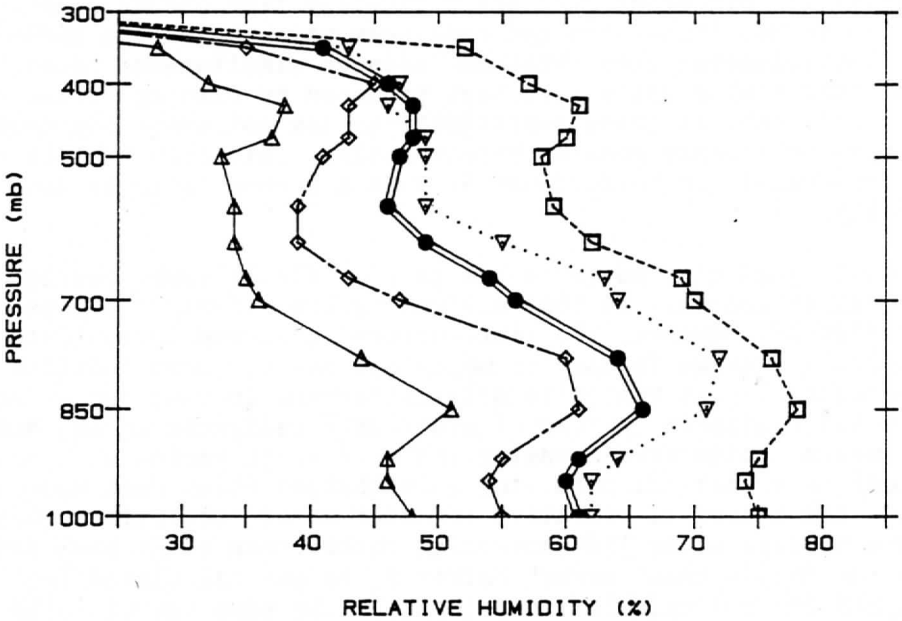

Figure 4. Mean relative humidity profiles from May-June 1984 radiosondes over eastern North America. From left to right: clear cases, scattered cloud, overall mean (double solid line),broken cloud, overcast cloud.

mb (figure 5). This bias was reduced by two-thirds when 1984 statistics from clear cases only were used as the constraint. Above 600 mb, the clear retrievals were biased toward being too dry. This may have been due to the truncation of the relative humidity covariance matrix. Bias in this region was also reduced when clear statistics were used as the constraint.

With overall statistics as the constraint, the 1987 retrievals in overcast cases were too dry by between 10 and 20% through the entire column (figure 5d). This bias was reduced by a large amount in the lower 300 mb and by a small amount above that. In scattered and broken conditions (for which the mean relative humidity profiles were not too different from the overall mean) use of cloud-amount dependent statistics had smaller effects on the relative humidity biases. As one would expect from Eyre's (1987) results, the main effect of the change in statistical constraints on the relative humidity retrievals was to change the biases. The correlations between the retrieved relative humidities and the radiosondes were not affected in most cases.

In general, the RMS temperature differences (not shown) increased by a couple of tenths of a degree when cloud-amount-dependent constraints were used. We found that when overall statistics for temperature were combined with cloud-amount dependendent statistics for relative humidity, the temperature retrieval statistics were almost exactly the same as they were when overall statistics were used for both variables, and the relative humidity statistics were essentially the same as they were when cloud-amount-dependent statistics were used for both variables. It seems reasonable that the relationship between the temperature profile and cloud amount should be much less stable (and hence less valuable as a predictor) than the relationship between relative humidity and cloud amount.

7. COMPARISON OF RETRIEVALS WITH/WITHOUT LIMB CORRECTION

An alternative to producing retrievals directly from cloudy slant-path radiances is to use limb-corrected radiances which have gone through a previous cloud-clearing step. Minimum-variance simultaneous retrievals of temperature and mixing ratio have been produced by Fleming et.al. (1986,1988) using this approach. If these approximations are not used, the cost in computer time or storage goes up substantially. This cost must be offset against improvements in performance if such a scheme is to be used operationally.

Estimation of cloud-cleared radiances is a difficult task, particularly in terms of quality control, so that estimating the effect of bypassing this step is also difficult. However, the limb-correction scheme in the International TOVS Processing Package is easy to apply and has not been modified in some years. Consequently, it was quite straightforward to test the effect of using limb-corrected radiances instead of slant-path radiances in the NLOE scheme described above. Aside from changing the slant-path radiative transfer calculations to a vertical path, the only changes which were made were to recalculate the empirical radiative transfer model corrections (brightness temperature biases) using limb-corrected rather than slant-path radiances, and to change the "measurement error" matrix S_m to one calculated from vertical-path forward calculations. (Exactly the same set of collocated measurements was used to calculate S_m for limb-corrected and non-limb-corrected observations. There was a slight increase in (observed minus forward model) variance for lower peaking HIRS channels and for MSU

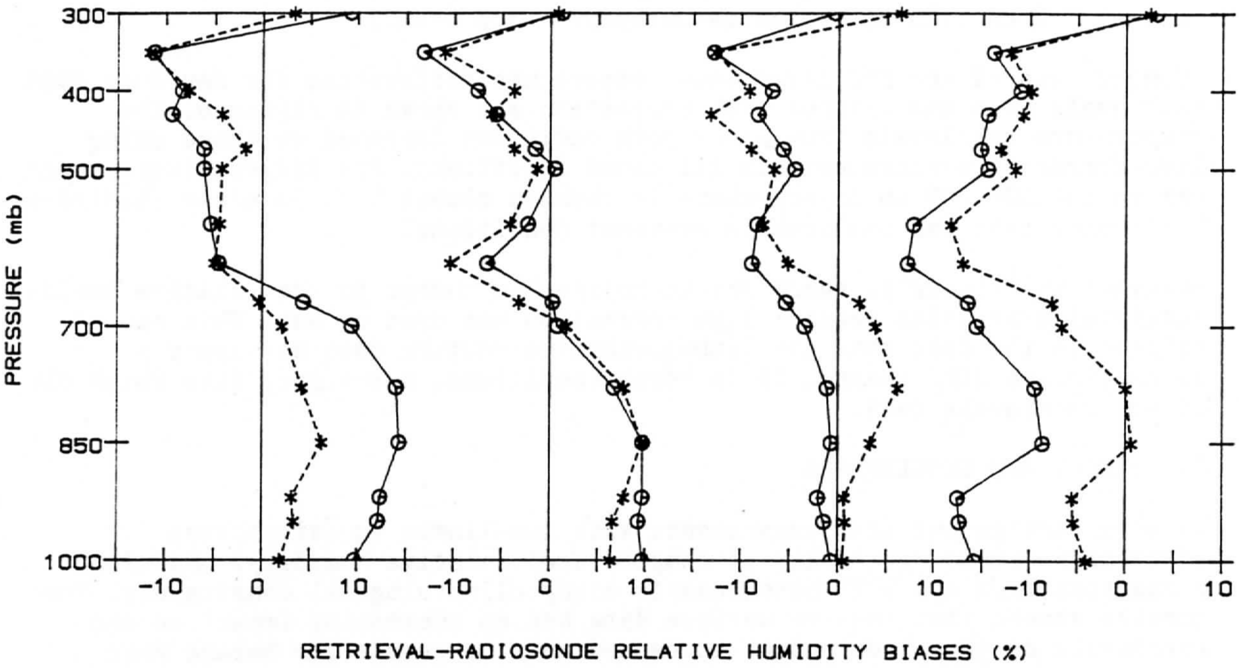

Figure 5. Biases in relative humidity retrievals using constant statistical constraints (solid lines) and using cloud-amount-dependent constraints (dashed lines). From left to right: 97 clear cases, 118 scattered cloud cases, 154 broken cases, 115 overcast cases.

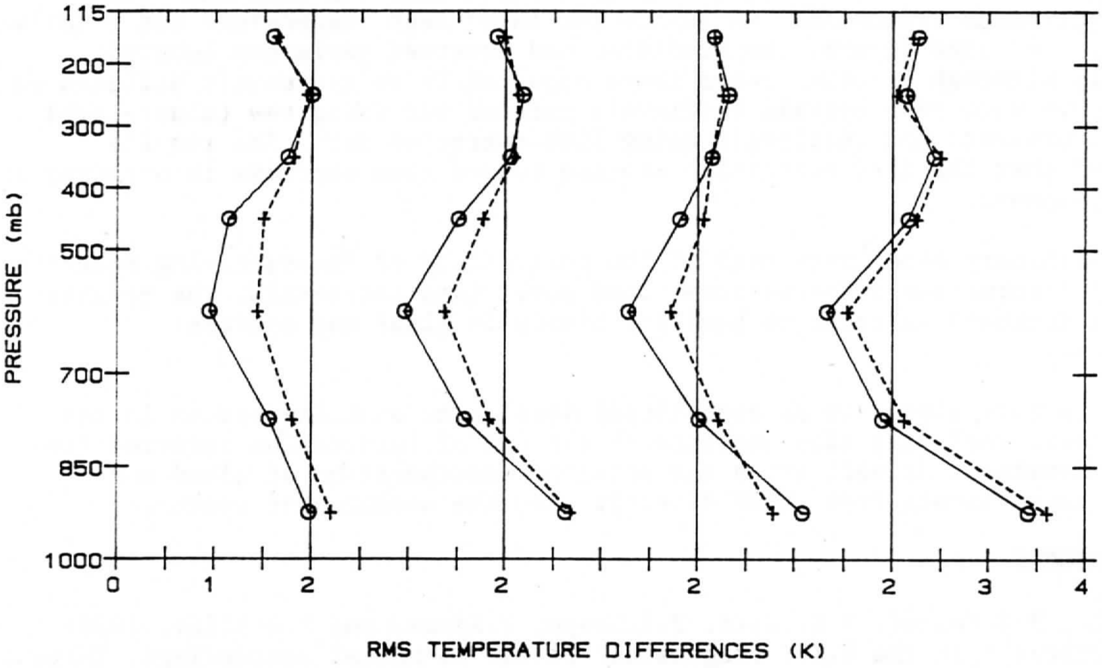

Figure 6. RMS temperature differences between radiosondes and: NLOE retrievals from slant-path radiances (solid lines); NLOE retrievals from limb-corrected radiances (dashed lines). From left to right, 99 clear cases, 106 scattered cloud cases, 127 broken cases, 151 overcast cases.

channel 2 when limb-corrected measurements were used.)

Comparisons of the RMS layer mean temperature differences for May-June 1984 retrievals with and without limb correction are shown in figure 6. The temperature retrievals from slant-path radiances improved on those using limb-corrected measurements in all cloud conditions. The largest improvement was in the 500-700 mb layer, where it reached almost 0.5K in clear conditions. The improvement was smallest in overcast conditions.

Somewhat surprisingly, there was no noticeable change in the relative humidity retrieval statistics whether limb correction was used or not. This may be related to the fact that the limb-correction routine does not apply a correction to HIRS channel 11 in "dry" conditions, a category into which many of our retrievals fell.

8. SUMMARY AND CONCLUSIONS

We have carried out some experiments with non-linear (quasi)optimal estimation (NLOE) retrievals of temperature, relative humidity, and cloud parameters from raw TOVS measurements using climatological constraints. The results showed that in-situ surface data had an increasing impact on the retrievals as the cloud amount increased and the retrievals became more dependent on microwave measurements. The amount of lapse rate information in the retrievals dropped off sharply with increasing cloud when surface data was not used. Comparisons with statistical retrievals using locally generated regression coefficients indicated that the NLOE retrievals were more robust in cloudy and unusual situations. However, this result may depend strongly on the quality of the cloud-clearing scheme used in the statistical retrievals. The retrieval error variance predicted by the NLOE method was compared with (retrieval minus radiosonde) variances for layer mean temperature and relative humidity. For some layers, the predicted and observed variances behaved similarly although in other cases there appeared to be systematic differences. Comparisons were made between retrievals carried out using raw (slant-path) TOVS measurements and retrievals using limb-corrected data. The results indicated that the limb correction process caused some decrease in accuracy in the troposphere.

Some preliminary tests were made of the possibility of incorporating relative humidity information inferred from cloud cover into retrievals. The results showed a decrease in relative humidity biases in clear and overcast conditions.

We hope to move closer to an operational local area sounding system in the coming year. Work will also continue on the use of information inferred from cloud parameters, as well as on the possible incorporation of cloud and surface measurements from AVHRR directly into the measurement vector.

9. REFERENCES

Eyre,J.R., R.W.Pescod, P.D.Watts, P.E.Lloyd, W.Adams, and R.J.Allam, 1986: TOVS retrievals in the U.K.: Progess and Plans. Technical Proceedings, Third International TOVS Study Conference (ITSC-3), Madison, Wisconsin, 13-19 August 1986, pp. 60-91. CIMSS,1986.

Eyre,J.R., 1987a: Inversion of cloudy TOVS radiances by non-linear optimal estimation. Draft version, U.K. Met. Office 19 Branch Memo.

______,1987b: On systematic errors in satellite sounding products and their climatological mean values. Q.J.R.Meteorol.Soc. **113**, pp.279-292.

Fleming,H.E., M.D.Goldberg, and D.S.Crosby, 1986: Minimum variance simultaneous retrieval of temperature and water vapor from satellite radiance methods. Preprint Volume, Second Conference on Satellite Meteorology/Remote Sensing and Applications, Williamsburg, Virginia, 13-16 May 1986, pp.20-23. American Meteorological Society.

______,1988: Operational implementation of the minimum-variance simultaneous retrieval method. Preprint Volume, Third Conference on Satellite Meteorology and Oceanography, Anaheim, California, 1-5 February 1988, pp.16-19. American Meteorological Society.

Huang,H.-L.A.,and W.L.Smith, 1986: An extension of the simultaneous TOVS retrieval algorithm - The inclusion of cloud parameters. ITSC-3, pp.118-130.

McMillin,L.M., and C.Dean, 1982: Evaluation of a new operational technique for producing clear radiances. J. Appl. Meteor. **21**, pp.1005-1014.

Rodgers,C.D., 1976: Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. Geophys. Space Phys. **14**, pp.609-624.

Smith,W.L. and C.M.R.Platt, 1978: Comparison of satellite-deduced cloud heights with indications from radiosonde and ground-based laser measurements. J.Appl. Meteor. **17**, pp.1796-1802.

Smith,W.L., H.M.Woolf, C.M.Hayden, and A.J.Schreiner, 1985: The simultaneous retrieval TOVS export package. ITSC-2, Igls, Austria, 18-22 February 1985, pp.224-253. CIMSS,1985.

Steenbergen,J.D., B.T.Greaves, and T.-C. Yip, 1986: Simultaneous retrieval of temperature and relative humidity using empirical orthogonal functions. ITSC-3, pp.259-275.

______,1987: Simultaneous physical retrieval of temperature, relative humidity, and cloud from TOVS measurements using statistical constraints. Preprint Volume, Second Workshop on Operational Meteorology, Halifax, Nova Scotia, 14-16 October 1987. Atmospheric Environment Service/Canadian Meteorological and Oceanographic Society.

Twomey,S., 1977: Introduction to the mathematics of inversion in remote sensing and indirect measurements. Elsevier Scientific, pp.139-144.

The Technical Proceedings of
The Fourth International TOVS Study Conference

Igls, Austria

March 16-22, 1988

Edited by

W. P. Menzel

Cooperative Institute for Meteorological Satellite Studies
Space Science and Engineering Center
University of Wisconsin
1225 West Dayton Street
Madison, Wisconsin 53706
(608) 262-0544

October 1988