THE ANALYSIS OF HIGH RESOLUTION SATELLITE DATA IN THE MET OFFICE

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1. INTRODUCTION

This paper describes current research into methods of using high resolution local area soundings, (LASS data), in the Met Office analysis -forecasting system.

Section 2 outlines the present LASS system, some of its weaknesses and way of attacking them.

Work on improving the use of such soundings in the NWP analysis is concentrated into three areas:

- The use of the better background in the retrieval process (Section 3).
- The usefulness to the user of knowing which first guess has been used (Section 4).
- The use of the retrieved satellite data within a 4 dimensional assimilation scheme (Section 5).

2. THE CURRENT LASS SYSTEM

The LASS system uses data from the TOVS instruments aboard the TIROS N series of polar orbiting satellites. The raw radiance information, covering the North Atlantic and West European areas, is picked up directly by a receiving station at Lasham and relayed to the 'HERMES' data processing facility at Bracknell. There, the data is decoded and then preprocessed to correct for such things as the presence of cloud and the angle of view of the satellite. The final stage consists of a purely statistical inversion, which produces temperature and humidity profiles on standard pressure levels at a maximum resolution of 80 km.

The inversion step takes the form,

$$(x_a - x) = D\,(y_o - y) \qquad (1)$$

The predictive matrix D is calculated by performing a multiple linear regression on the eigenvector coefficients of covariance matrices from radiosonde profile and collocated radiance observations. x_a is the retrieved profile, x is the mean of the radiosonde profiles, y_o is the observed radiance, and y is the mean of collocated radiance observations.

LASS data has been assimilated into the Met Office's coarse mesh model since September 1984. In addition, a 'fine mesh' assimilation scheme has recently become operational, allowing the data to be analysed at its full resolution. The results from case studies designed to measure the impact of LASS data on both models have in general been disappointing, with significant biases appearing at low levels and near the tropopause (Adams 1984, Bell and Hammon 1985). These may either be associated with cloud clearing problems, or, more fundamentally, the implicit use in the retrieval process of a poor climatological first guess. This second possibility is discussed in more detail in section 3.

To calculate the regression coefficients for the statistical method, a suitable sample of soundings and collocated radiances is required. The sample chosen needs to be large enough to prevent the coefficients from being noisy and unreliable. It must also however be meteorologically similar to the soundings to be processed, which limits its size.

One approach to this problem is to attempt to stratify soundings objectively by air mass type, and to generate coefficients for each type.

Another approach recently introduced into operational practice, is to use our knowledge of the radiative transfer equations to calculate synthetic coefficients; the physical-statistical retrieval method. Given an appropriate sample of profiles (eg from radiosondes; collocated radiances are not needed), with mean x and covariance matrix C, the non-linear radiative transfer equation K_n is used to calculate theoretical radiances, and their variations with variations in the original profiles. This enables a linear matrix K of the partial derivatives of K_n to be calculated. The minimum variance estimate of the retrieved profile x_a from an observed profile y_o with observational error E is then calculated as a correction to a background $x_b = x$

$$x_a = x_b + (KC)^T(KCK^T + E)^{-1} (y_o - K_n(x_b)) \qquad (2)$$

(Rodgers 1976). The error covariance S of the retrieval x_a can be shown to be

$$S = C - (KC)^T (KCK^T + E)^{-1} KC \qquad (3)$$

(Note that these equations are identical to those used in objective analysis by multivariate optimal interpolation).

More information on research into TOVS retrievals is given by Eyre et al (1985).

3. THE USE OF A BETTER FIRST GUESS

The use of a first-guess which is closer to the truth than climatology, such as a model forecast, has a number of advantages:-

(i) A good background can be used in the pre-processing stages to correct the radiances for a non-zero angle of view. The errors generated by the current regression relation tend to be air mass related and horizontally correlated.

(ii) In quality control, it can be used to help detect gross errors, for example in the low level temperatures due to cloud clearing problems.

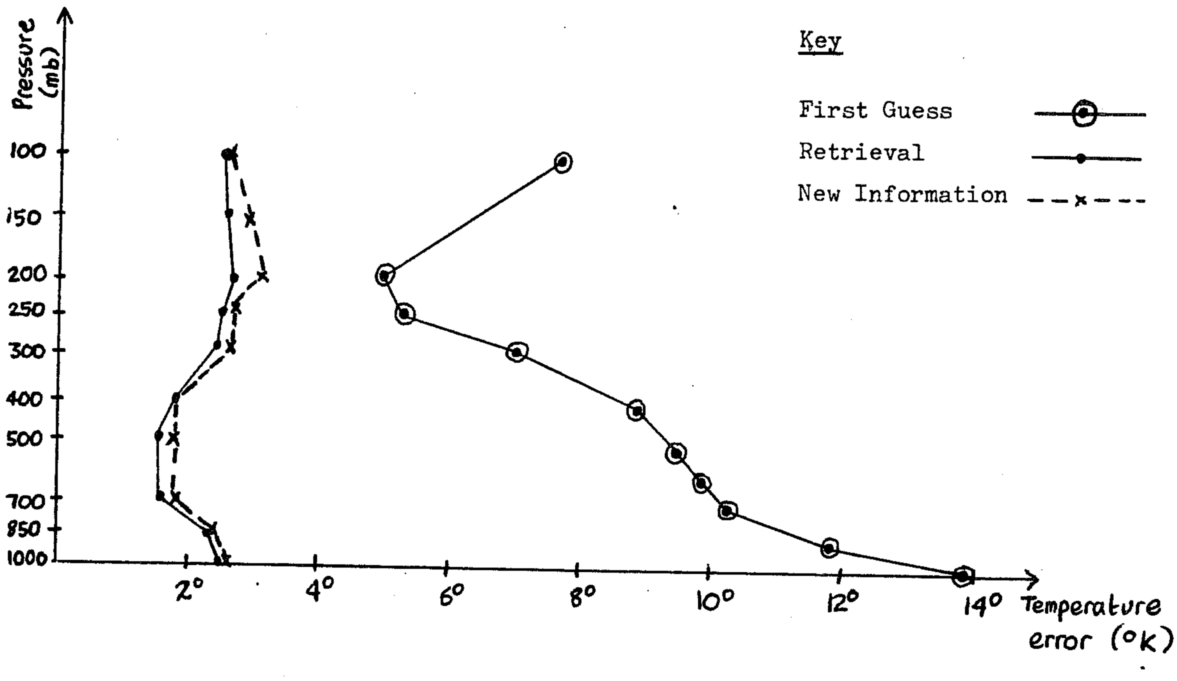
(iii) In the retrieval process itself, smaller adjustments need to be made to the first guess and so the use of the linear models is easier to justify.

(iv) Any classification of soundings into air mass type can be done according to an accurate first guess; a short period forecast in the Northern Hemisphere very seldom gets the air mass wrong. The alternative classification according to the observed radiances, might in some cases fail to distinguish important features not well resolved by the radiances such as the height of the tropopause and the presence of inversions and fronts.

(v) The use of a more accurate first guess also has a direct impact on the rms retrieval error, since information from the first guess carries through to the retrieval in (2). Figure 1 illustrates this. The top panel shows the square root of variances for a sample of radiosonde soundings and the retrieval errors calculated using (3). The lower panel shows corresponding curves for a 12 hour forecast. Also shown are estimates for the errors in the 'new information', defined as that component of the retrieval uncorrelated with the first guess, (discussed further in section 4). This effect in the latter case is not as large as might at first be expected, since the vertical correlation of errors in a more accurate forecast first guess will be less than those in a climatological one. Note that the analysis used for Figure 1 was linear; it does not include effects (i) to (iv) above which are non-linear or dealing with non-Gaussian error distributions.

FIRST GUESS, RETRIEVAL AND NEW INFORMATION ERRORS

a) Climatological first guess



b) Model forecast first guess

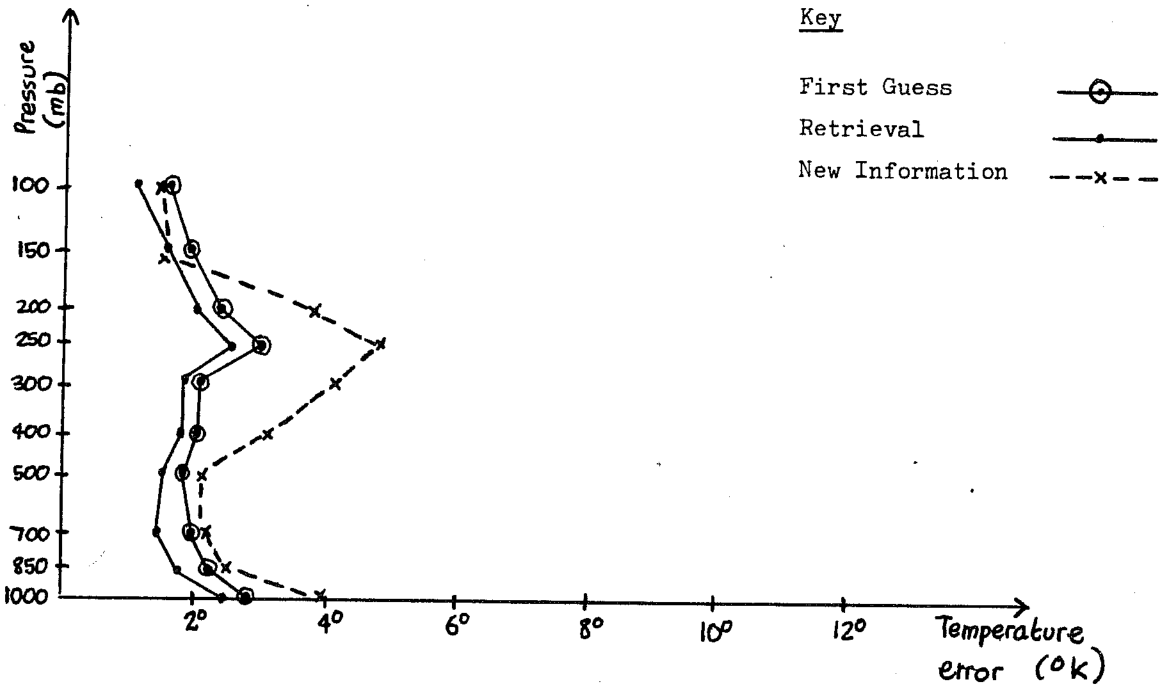


Figure 1

Which of these advantages is most important depends on the use to be made of the retrievals. For direct uses, which require the rms retrieval errors to be as small as possible, probably (v) is most important. On the other hand improvements in rms retrieval error due to (v) are of no use to an objective analysis scheme which has already available the same first guess information, since the essentially linear carry-through of first guess information to the retrieval can be done in the analysis. In this case the non-linear non-Gaussian effects of advantages (i) to (iv) are most important.

As shown in Figure 1, greater accuracy in the first guess leads to more background information and hence less new information being carried through to the retrieval. This makes it harder to use the retrievals correctly in an objective analysis scheme which does not have available the same first guess. This was a major reason for changing some years ago to statistical retrieval methods using a climatological first guess for soundings for international exchange.

4. KNOWLEDGE OF WHICH FIRST GUESS HAS BEEN USED

The product of any retrieval process is likely to retain many properties of the first guess. Purely statistical methods implicitly contain a climatological first guess from the learning sample of radiosondes which is on average further from the truth than a model forecast background. The use of the latter is therefore more desirable, for the reasons given in Section 3.

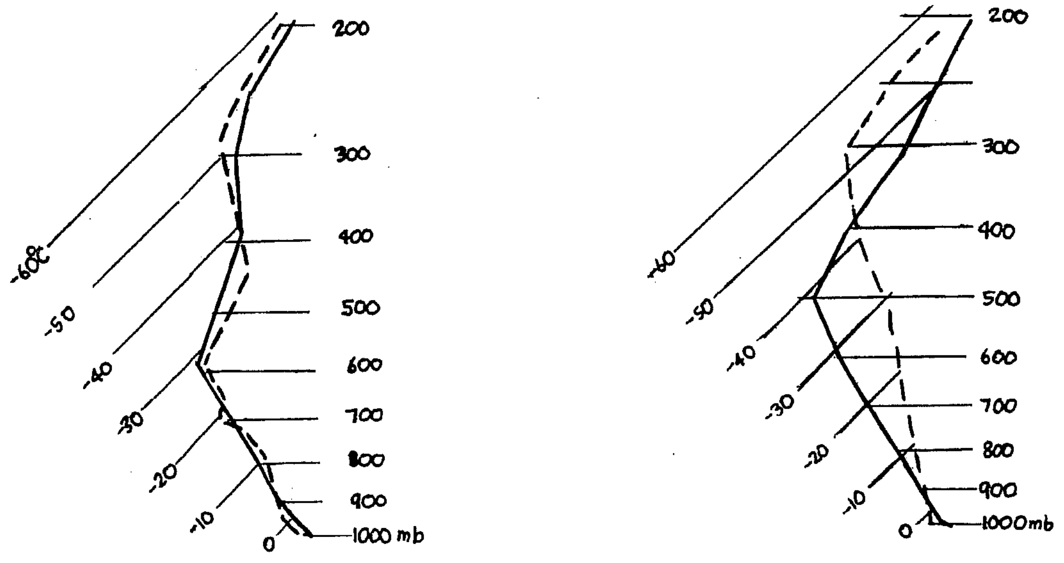
The information from the first guess which most influences the retrieved profile concerns features not well resolved by the radiance data, such as the tropopause height. If an inappropriate first guess is used then the retrieved profile can actually contain erroneous information. An extreme example of this is shown in Figure 2. In this case in some areas the true tropopause was extremely low, yet all the retrieved profiles had tropopauses near the climatological normal (Adams 1984). Attempts to use these retrieved profiles in an analysis could actually degrade it. If information about the first guess is available to the user (not presently the case), then since the equations are basically linear, (apart from the influence of the radiative transfer model K_n), the information from the first guess can be replaced by a different background. If we use (2) to find what retrieval x_a' would have been returned by the method given a different background x_b' (with the same error statistics) we get

$$x_a' = x_a + x_b' - x_b + (KC)^T (KCK^T + E)^{-1} K(x_b - x_b') \qquad (4)$$

Thus although we are advocating, for the reasons set out in Section 3, the use of the best first guess available it is nevertheless possible to correct a retrieval made using an inferior first guess as long as that first guess is available to the user of the retrieval.

A simpler two-stage approximation to (4) can be made. Firstly we rederive (2) with the additional constraint that at each level the retrieval error should be uncorrelated with the background error. This forces the retrieval for each level to take no information from the

CASE STUDY 2.3.84 SATELLITE TEMPERATURE RETRIEVAL COMPARED TO UK MODEL ANALYSIS / FORECAST.



(a) (b)

Tφ diagrams showing :-

(a) Solid line. Operational analysis valid at 12Z 2nd March 1984 at Crawley.
Dashed line. Radiosonde sounding from Crawley (smoothed, as used in the analysis)

(b) Solid line. $2\frac{1}{2}$ hour forecast from the analysis shown in (a).
Dashed line. Satellite temperature retrieval near Crawley, made using a statistical method with climatological first-guess.

Figure 2

background at that level. This gives a less accurate retrieval which can then be recombined with a new background in an analysis routine. This is equivalent to the super-observation formation of Lorenc (1981). The first stage amplifies the corrections made using the radiances to the background so that

$$x_a^* - x_b = (I + D)\ (x_a - x_b) \qquad (5a)$$

where D is a diagonal matrix consisting of the diagonal elements of S divided by the corresponding elements of C:

$$d_{ii} = S_{ii}/C_{ii} \qquad (5b)$$

The estimated error of the constrained retrieval is correspondingly amplified

$$S_{ii}^* = C_{ii}S_{ii}/(C_{ii} - S_{ii}) \qquad (5c)$$

so that when the retrieval is then used in a statistical objective analysis the effect is the same. This is an approximation to (4) in that it ignores off-diagonal terms.

In principle then, both the adjustment (4) and superob/re-analysis (5) methods can be used to replace 'poor' first guess information with good information.

The application of the techniques described in equations 4 and 5 to one case where the first guess used in the retrieval process contained the wrong tropopause height is shown in Appendix 1 and figures 3-5. Both methods were successful in removing much of the incorrect vertical structure.

5. INTEGRATION OF RADIANCE INVERSION AND ANALYSIS

The inversion problem for satellite radiances should be seen as only a part of the much greater analysis problem for NWP. This too can be posed as a non-linear inverse problem. Ideally all the data in 4 dimensions should be processed together with background information, and constraints on balance and on consistency with the prognostic equations, to find the atmospheric evolution nearest in some sense to the data. Because of non-linearities, and non-Gaussian error distributions (ie the possibility of gross errors in the data), this should not be split into distinct steps. However of course in practice it has to be because of the volume of data and the complexity of numerical prediction models. The assimilation scheme being developed at the Met Office splits the problem into several steps, in some cases on different computers, and within each step approximations to the ideal 'optimal' analysis equations are made:-

(i) The quality control of data is largely distinct from its actual assimilation, and performed as early as possible in the processing of the data, before the removal of redundant information which is useful for quality control but not for analysis of good data. This principle is particularly relevant to satellite temperature retrievals, since algorithms to decide that cloud contamination is so great that only microwave radiances should be used, are similar in character to quality control. These steps are done on a dedicated VAX computer, with access to all the basic radiance data and to the forecast background.

(ii) The time dimension is dealt with separately in a continuous forward assimilation, using a high resolution (75 km) forecast model with state of the art parametrizations of physical processes. For this high space resolution a corresponding high time resolution is desirable for the use of asynoptic satellite data; the continuous assimilation scheme allows this.

(iii) The 3-dimensional space analysis problem is split into a vertical step followed by a horizontal step, similarly to the method of Rutherford (1976). In the vertical step all soundings and single level observations are processed to give increments of model variables at all model levels. These are then analysed horizontally to model grid points. If both steps are done using OI, care must be taken not to use the model background information twice. This can be done by constraining the vertical step to take no information from the background, leading to larger increments with higher estimated rms errors but no less new information than those from the standard OI equations. Within this split analysis method the vertical OI step for radiance data is identical to the linearised physical statistical retrieval (2) and the constraint on not using the background is identical to (5). Thus within the split vertical-horizontal framework we can claim to be integrating the analysis and inversion of radiance data, without compromising the detailed processing and non-linearities allowed for in a conventional inversion method. The actual problem of inverting satellite radiances to give a temperature profile is much more complex than is apparent from (2). Declouding, zenith angle correction, and matching the field of view of different radiometers must be done. The radiative transfer model K_n has errors, both systematic and random, due to inexact physical equations and to insufficient resolution of the forecast first guess, particularly in the stratosphere and mesosphere. These must be corrected or allowed for, as must drift in the calibration of the satellite instruments. In our split scheme these problems continue to be dealt with by the LASS system.

(iv) The horizontal analysis step is approximated by a successive correction method, each iteration being at successive timesteps of the forecast model. Thus the successive correction method, which can be tuned to give similar results to univariate OI, is integrated with a repeated insertion method which is designed to avoid the excitation of unbalanced high frequency modes. Hydrostatic and geostrophic coupling of the increments from the univariate analyses also help to maintain balance.

6. CONCLUDING REMARKS

This paper has described current research within the Met Office into improving the analysis of high resolution satellite temperature soundings. The main features are

(i) Use of a forecast first guess for a physical statistical retrieval.

(ii) Knowledge of the first guess and statistics used for the retrieval in the analysis.

(iii) By means of (i) and (ii), integration of the retrieval into a self-consistent approximation to the total analysis problem.

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APPENDIX 1

An Experiment To Test The Effectiveness Of the Linear Adjustment And Superob/Re-analysis Methods In Removing Poor First-Guess Information.

Formulation of Experiment

1) Define 'true' profile xt.

2)Simulate a radiance observation by applying a radiative transfer model to xt. (See Fig.3)

3)Define a'poor'background xb which has an incorrect tropopause height. (See Fig.3)

4)Define a 'better' background xb' ,obtained by adding noise from a Gaussian distribution with standard deviation $C_{ii}^{\frac{1}{2}}$ at level i .(Nb. This method assumes zero inter-level forecast error correlations).

5)Calculate simulated retrievals using 'poor' and 'better' backgrounds. (Eqn.2,Figures 4 and 5)

6)Modify retrieval obtained using poor first-guess by applying the linear adjustment and superob/re-analysis methods .(Eqns.4 and 5,Figs.4 and 5). (The re-analysis is in the form of 1D level by level OI).

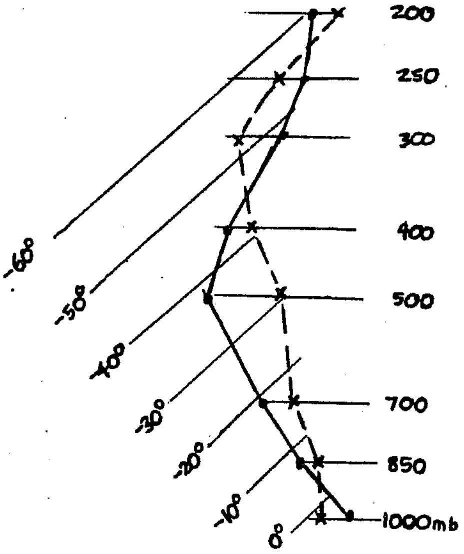
Experimental Conclusions

Figures 4 and 5 demonstrate that both the adjustment and superob/re-analysis methods were effective in removing much of the poor first-guess information.

The linear adjustment method,which unlike the superob/re-analysis method, takes account of the first-guess inter-level correlation structure in the vertical,appeared subjectively to produce a profile more similar in structure to the retrieval made using the better background.

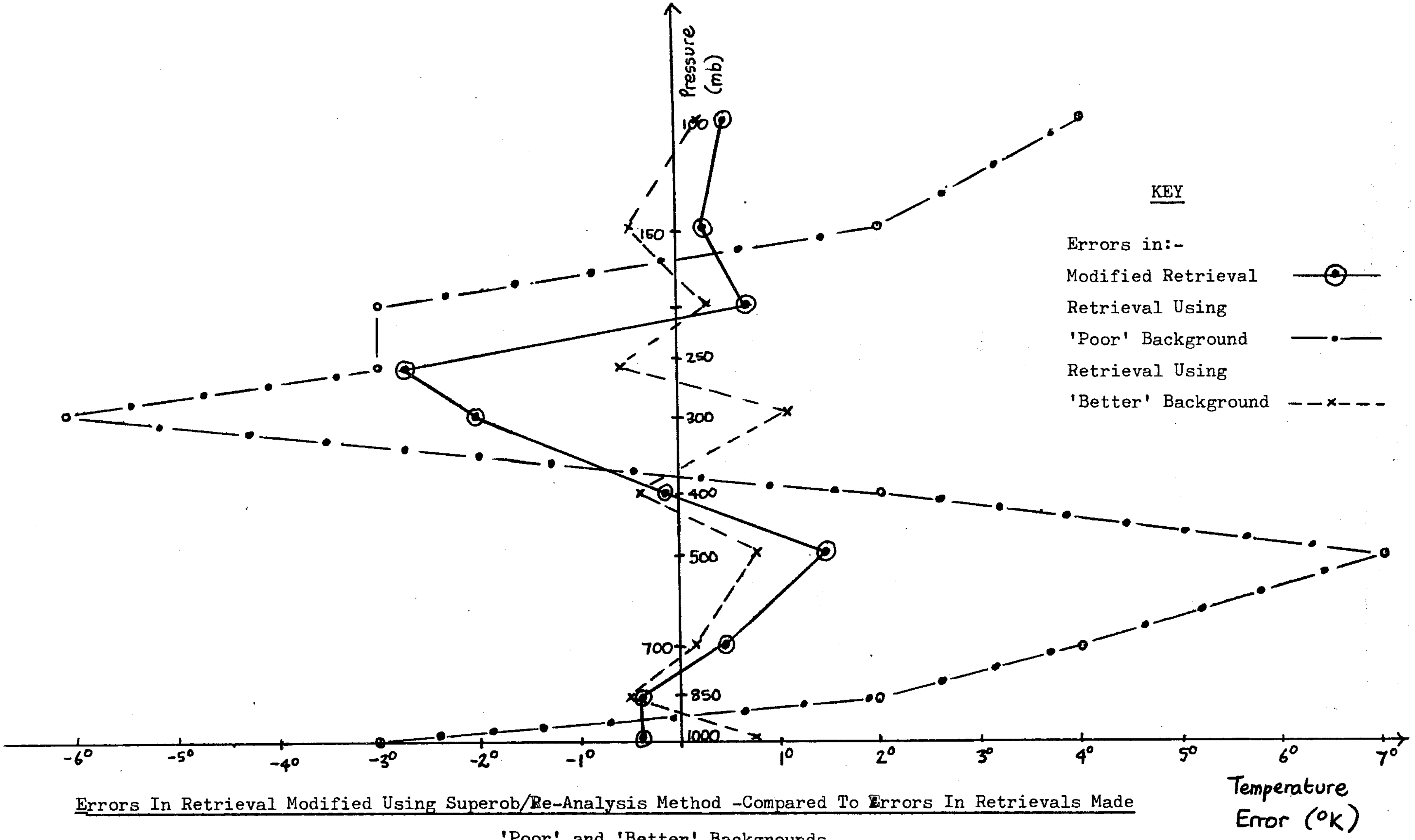
EXPERIMENT TO TEST THE EFFECTIVENESS OF THE SUPEROB/RE-ANALYSIS AND LINEAR ADJUSTMENT METHODS IN REMOVING POOR FIRST-GUESS INFORMATION.

Test Profiles



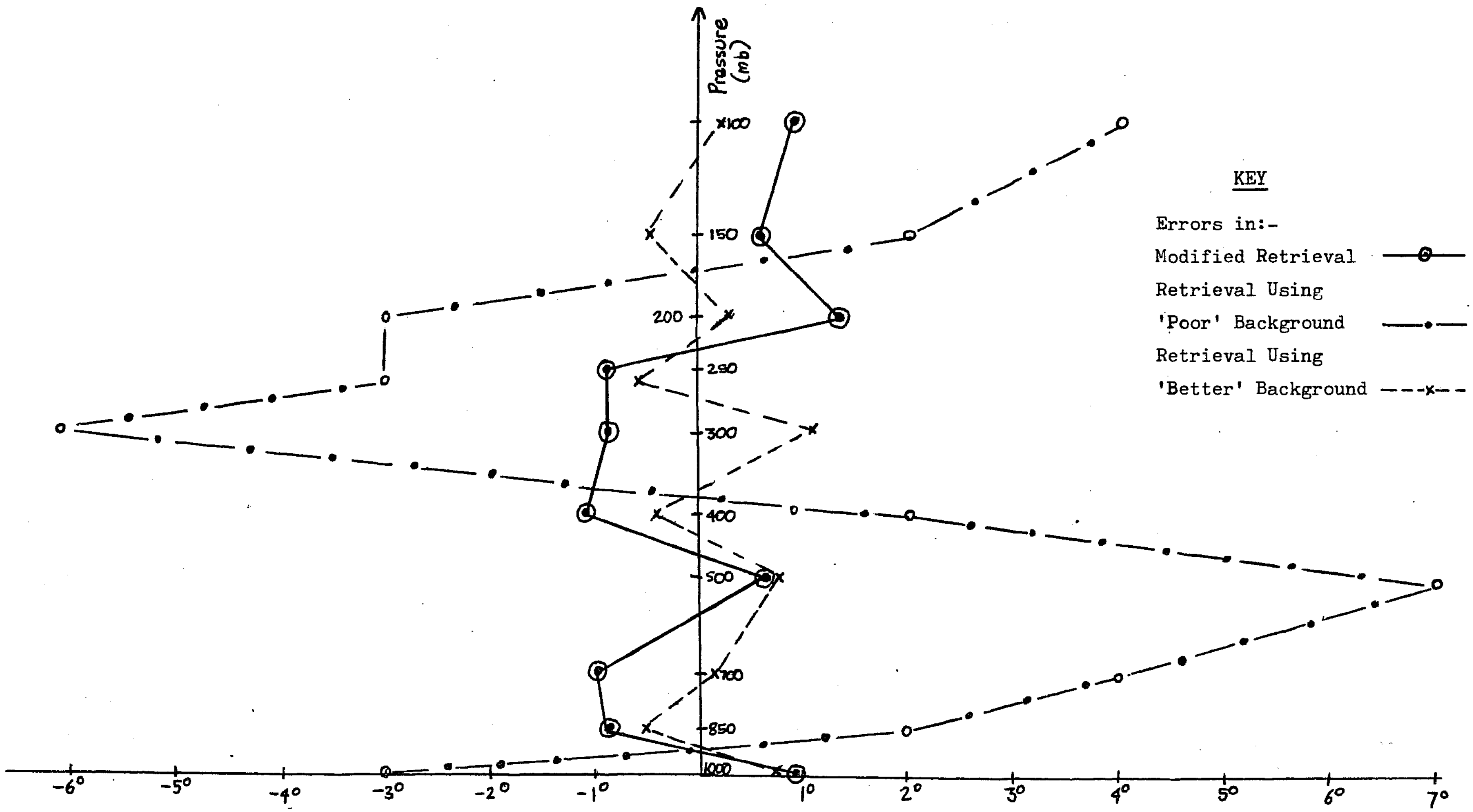
TØ diagram showing :-
Solid line xt :'True profile'
Dashed line xb :'Poor'retrieval background (incorrect tropopause height)

Figure 3



Errors In Retrieval Modified Using Superob/Re-Analysis Method -Compared To Errors In Retrievals Made 'Poor' and 'Better' Backgrounds

Figure 4



Errors In Retrieval Modified Using Linear Adjustment Method-Compared To Errors In Retrievals Made Using 'Poor' and 'Better' Backgrounds

Figure 5