EXPERIMENTS USING ONE-DIMENSIONAL VARIATIONAL ANALYSIS OF TOVS DATA AT ECMWF

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1. INTRODUCTION TO 1DVAR

1.1 Theory

1DVAR is essentially an interface allowing the assimilation of TOVS radiance information into the ECMWF forecast model. A full discussion of the theoretical aspects of 1DVAR is presented in *Eyre et al* (1993), and only the main points will be reproduced here. The scheme generates products of temperature and humidity from the TOVS radiances by finding the state of the atmosphere X that minimizes a cost function $J(X)$ expressing departures from the measurements in radiance space and departures from the background in profile space. This cost function may be written

$$J(X) = (X-X_b)^T.B^{-1}.(X-X_b) + [\ Y_m-Y(X)\ ]^T.(O+F)^{-1}.[\ Y_m-Y(X)\ ]$$

where B is the error covariance of the background state X_b, O is the error covariance of the measured radiances Y_m and F is the error in the radiative transfer model generating synthetic radiances $Y(X)$ for a profile X. The solution obtained by minimization of the above function is optimal in the sense that departures are inversely weighted by the relevant error covariances. In this way the solution does not draw too close to a poor background or to bad quality radiances data.

The 1DVAR products are then passed to the ECMWF Optimal interpolation scheme (OI) (see *Lorenc*, 1981) where they are combined with all other observations to produce an analysis of the atmospheric state. The background information used in the generation of the 1DVAR products is a short range forecast from the previous analysis interpolated to the observation location and time. It is important to note that it is the same as that used in the subsequent OI analysis.

1.2 Technical Details

Radiance Input: TOVS measurements are extracted from the NESDIS "120km BUFR TOVS" data set containing cloud cleared and limb corrected brightness temperatures. These are classified by NESDIS as either "clear", "partly cloudy" or "cloudy". Depending on the cloud classification, 1DVAR currently uses the following combinations of channels: HIRS 1-7, HIRS 10-15, MSU 2-4 for clear and partly cloudy cases: HIRS 1-3, MSU 2-4 for cloudy cases. Synthetic brightness temperatures corresponding to a profile X are calculated using the fast radiative transfer model described in *Eyre* (1991). The same fast model computes simultaneously elements of the jacobian matrix d(radiance)/d(profile) which is required to compute the gradient of the cost function during the minimisation process. To be consistent with the measured values against which they are compared, brightness temperatures are computed at nadir assuming zero cloud and unit surface emissivity.

Radiance Errors: The combined random error in the pre-processed TOVS measurements and the fast radiative transfer calculations is currently described by diagonal covariance matrix ($\boldsymbol{O}$+$\boldsymbol{F}$). An upper bound for the variance in each channel is provided by statistics of measured minus forecast calculated brightness temperature. Values from these comparisons are reduced in an ad hoc manner to compensate for fact that ($\boldsymbol{O}$+$\boldsymbol{F}$+forecast radiance error) is actually measured. Combined systematic errors in the measurements and radiative transfer model (ie biases) are predicted by an air mass classification (using MSU channels as predictors) and removed accordingly. Details of this procedure are described in *Eyre* (1993).

Background Input: A short range forecast is made from the previous analysis (6 hours previous) and interpolated to the location and time of the satellite sounding. Further interpolation and extrapolation is required to transform from the forecast model levels to a profile specified on the NESDIS standard levels for radiative transfer calculations. This consists of 40 temperatures (0.1 mb-1000 mb) and 15 humidities expressed as log mixing ratio (300 mb-1000 mb). Surface air temperature and humidity values and the surface skin temperature are also obtained from the interpolated model fields.

Background Errors: Random errors in the forecast background profile are described by a full covariance matrix $\boldsymbol{B}$ specifying variances and interlevel correlations for temperature and humidity errors. These values have been determined using coincident radiosonde profiles as "truth" and deviations assigned as "forecast error". Every precaution has been taken to avoid sonde stations of dubious quality and all stations have been bias corrected, but it is inevitable that the so called "forecast error" will contain a possibly significant contribution form radiosonde error.

Quality Control: The TOVS measurements are screened for the presence of residual cloud contamination using a variable threshold test applied to HIRS channel 10. If brightness temperatures calculated from the forecast background are warmer than the measured values by more than 4K over sea, 6K over ice or 10K over land the sounding is rejected. Diagnostics from the minimization of the cost function are also used to quality control the 1DVAR products. If the scheme fails to converge within 5 iterations or converges upon a solution which is in poor agreement with the measured radiances (using predefined thresholds) the sounding is rejected. A further thinning of the data takes place resulting in an approximate spatial resolution of about 250 km. In this process clear soundings are selected in preference to partly cloudy and cloudy measurements; also sea locations are chosen before land.

Interface to OI: Estimates of the atmospheric temperature and humidity profile are generated by 1DVAR on the standard NESDIS levels, but this information is presented only in a reduced form to the OI analysis. The temperature data are specified as 7 mean layer values (1000-700, 700-500, 500-300, 300-100, 100-50, 50-30 mb) and humidity as 3 precipitable water values (1000-700, 700-500, 500-300). The reason for this reduction is two fold: Firstly, it allowed much of the existing OI data structures to be used with a minimum of recoding. Secondly, the problem of correlation between the 1DVAR products and the background is conveniently dealt with in the reduced layer space by a process of amplifying and down-weighting the 1DVAR increments in the OI. It can be shown that this is (approximately) equivalent to performing the 1DVAR minimisation of the cost function in a reduced space subject to an additional constraint that its errors are uncorrelated with those of the background. A full justification of this approach is contained in *Eyre et al* (1993).

2. PERFORMANCE OF 1DVAR

2.1 Quality of Products

The quality of the products generated by 1DVAR has been investigated using coincident radiosonde estimates of the true atmospheric profile. The results for a three month global comparison are shown in Fig 1 together with equivalent statistics for NESDIS TOVS products generated from the same radiance data (*Reale et al*, 1986). It can be seen that the 1DVAR agreement with radiosondes is much better than NESDIS, but this result in itself should not be interpreted as an indication of the relative usefulness of either product. The 1DVAR products originate from a background (6 hr forecast) which will generally be accurate and a good fit to the radiosonde data (prior to any radiance adjustment) and such comparisons will tend to unfairly favour the 1DVAR over NESDIS. However, the radiosonde comparison statistics do illustrate some important points.

The 1DVAR products differ from the forecast background (dotted line) by between 0.5 - 1K standard deviation, showing there is a reasonable level of adjustment of the background by the TOVS radiances. Ideally we would hope that the radiance adjustments would produce products which are closer to the radiosonde truth than the forecast background, but it can be seen that this is not always the case. The 1DVAR may be tuned incorrectly (see *McNally and Watts*, 1988) such that it is performing sub-optimally and producing retrieved profiles which are actually less accurate than the forecast background. That is to say that some or all of the parameters used to calculate the cost function and its gradient ($\boldsymbol{B}$, $\boldsymbol{O}$, or $\boldsymbol{F}$) may be inaccurately specified to some extent. However, radiosonde comparison statistics will tend to be representative of data dense areas where improvement over the forecast background is most difficult, ie where the forecast is expected to be most accurate and a comparable accuracy to the forecast in these areas

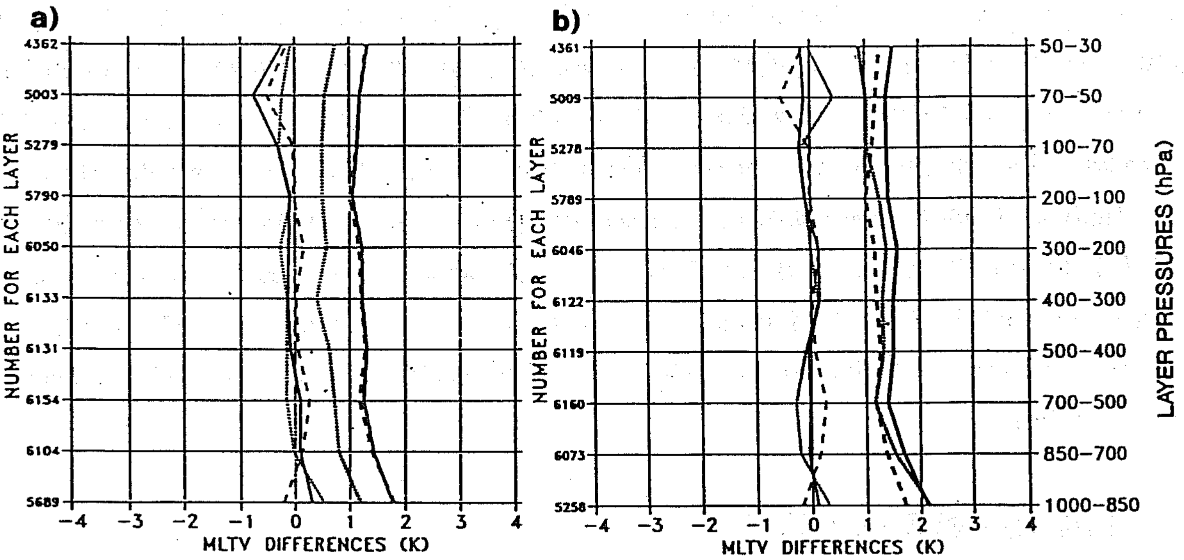

Fig 1 Mean and standard deviation of differences from radiosondes for (a) 1DVAR, (b) NESDIS expressed as mean layer virtual temperatures. Three months of data between August and October 1992 were used. In each cases the solid line is satellite product-sonde, the dashed line is background-sonde and the dotted line are the retrieval-background differences.

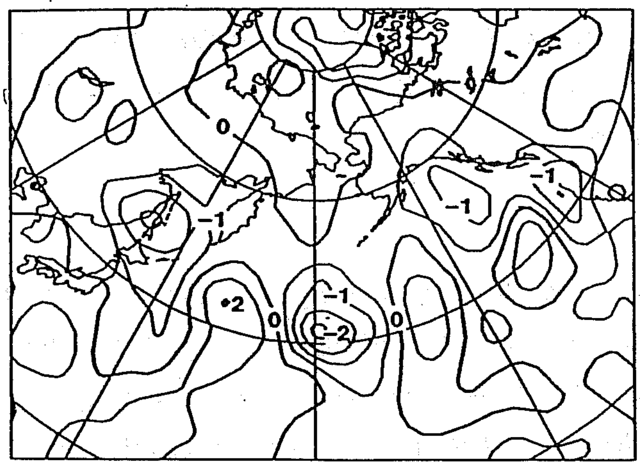

Fig 2 Typical analysis increments caused by the assimilation of 1DVAR in the Northern Hemisphere for the 500 mb height field (Dm).

is still encouraging.

2.2 Impact on the analysis

In the introduction 1DVAR was described as an interface between the radiances and the OI analysis. Thus as a first step it was useful to investigate how well the 1DVAR could convey the TOVS radiance information to the ECMWF analysis and generate appropriate increments in the OI.

Fig 2 shows a typical example of analysis increments obtained using the 1DVAR products. An inspection of the corresponding radiance deviations from the background indicated that, at least in a qualitative sense, the signal in the TOVS radiances is causing appropriate adjustments to the background field in the analysis. As expected (knowing how accurate the short range forecast background is) increments are generally small, but significant in areas such as the mid Pacific. The size of the increments suggest that the weighting scheme applied to the 1DVAR products works reasonably well, and there is no evidence of the sounding products overpowering or conflicting with other observations in conventional data dense areas.

As well as impacting individual analyses, the continued assimilation of 1DVAR products is able to alter the mean state of the forecast model over a period of time. This has been found to be particularly true for humidity. Fig 3a shows differences from measured values of radiances calculated from the short range forecast, averaged over a two week period with no assimilation of 1DVAR products. It can be seen that there are systematic differences suggesting (in this case for HIRS-11) a problem in the mid-tropospheric humidity of the model, most acute in the tropics. A parallel assimilation using the 1DVAR produced adjustments to the mean humidity field shown in Fig 3b, bringing the forecast model into a state which agrees much better with the measured radiances in Fig 3c.

Having demonstrated that the 1DVAR products have sufficient weight to influence significantly the data assimilation process, the quality of the analyses with and without 1DVAR products was investigated. The best measure of a good analysis (apart from it producing good forecasts which will be discussed later) is the degree of fit to observations. It has already been shown that assimilation of 1DVAR products produces a model state which is a better fit to the radiance data which is of course to be expected. However, there is independent evidence to suggest that the 1DVAR is producing better analyses from an improved fit of the model wind field to AIREP wind measurements (Fig 4). This improvement in the model wind field can only originate from a dynamical balance with a more accurate temperature specification in the 1DVAR analysis.

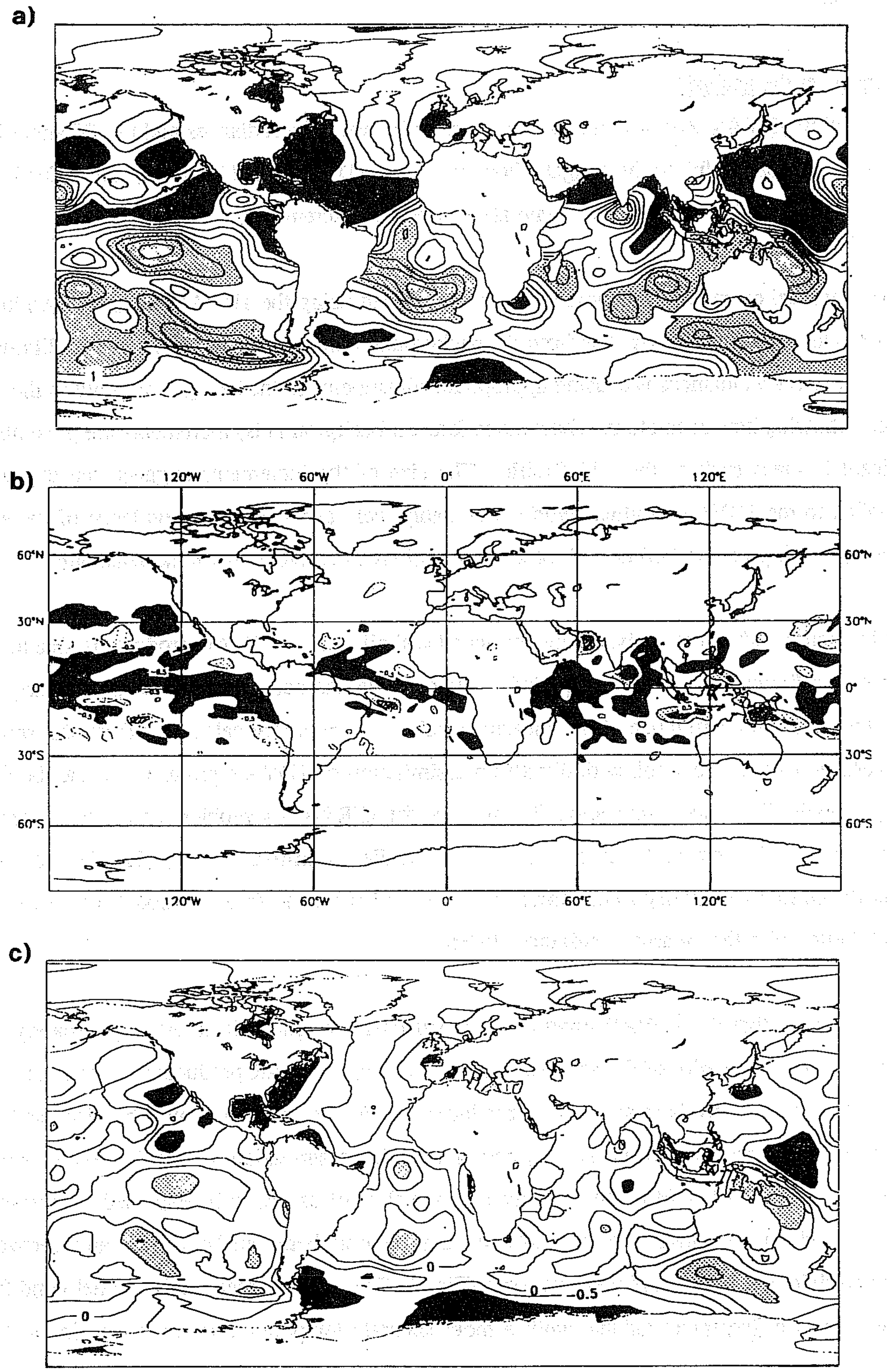

Fig 3 (a) Mean measured-background radiance for HIRS-11 for May 91 cases study without 1DVAR. Dark shading indicates measurements more than 2K cold. (b) Adjustments to the 700 mb specific humidity field by assimilation of 1DVAR products with dark shading indicating a reduction of more than 0.5 g/kg. (c) same as (a) after 1DVAR products have been assimilated.

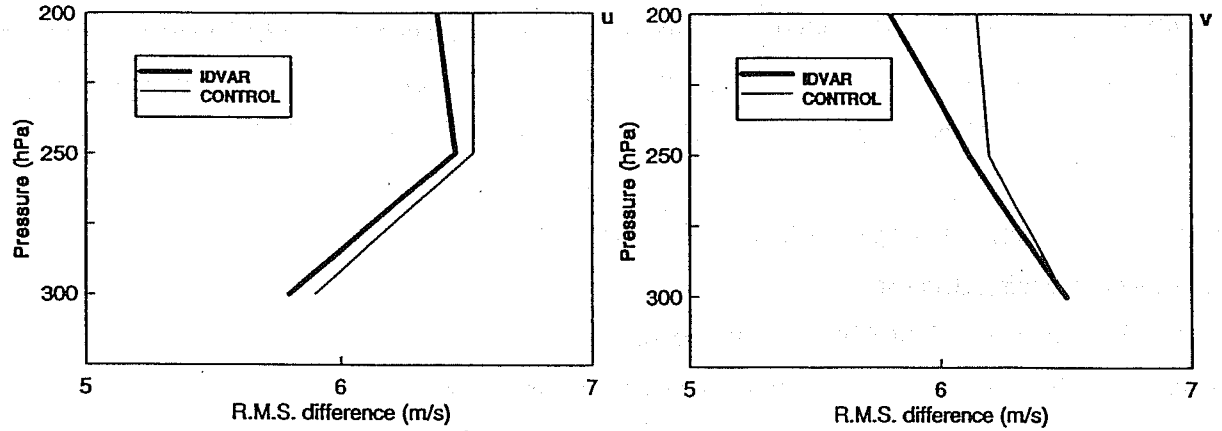

Fig 4 RMS differences from AIREP observations of the model wind U/V components with and without 1DVAR assimilation.

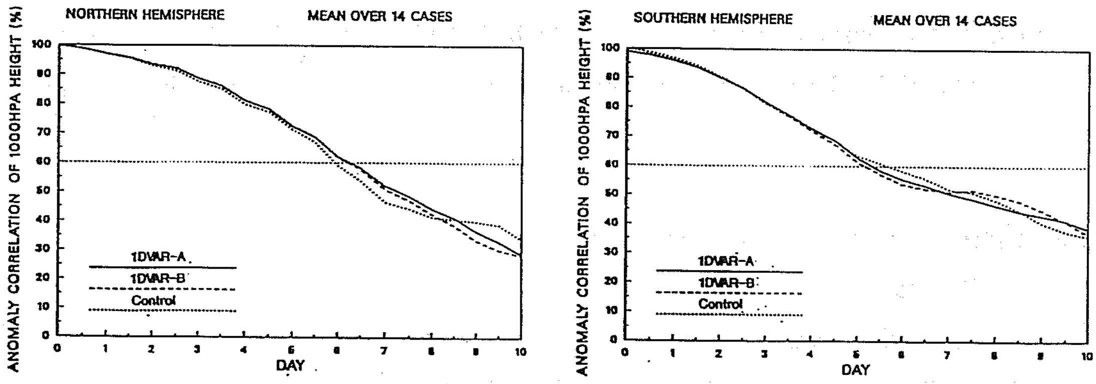

Fig 5 Anomaly correlation statistics for the May 91 case study.

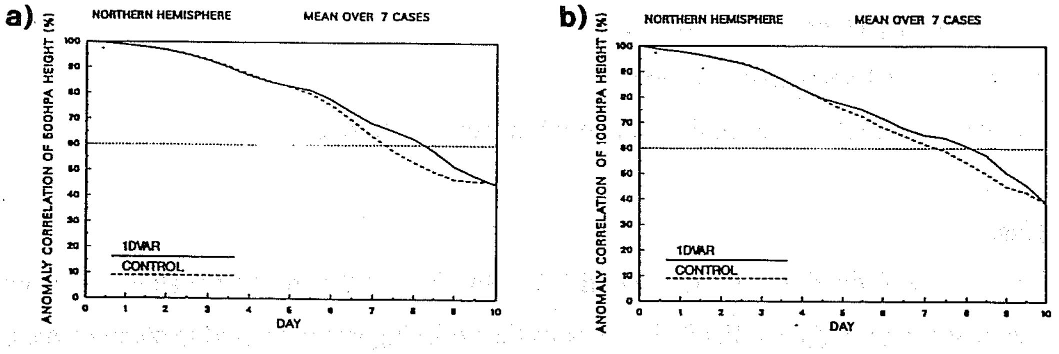

Fig 6 Anomaly correlation statistics for the Dec 91 case study with 1DVAR used only in the NH.

2.3 Impact on Forecast Accuracy

A series of experiments were run to test the performance of the ECMWF data assimilation scheme using 1DVAR in terms of the quality of subsequent forecasts. Before implementation it had be demonstrated that 1DVAR could improve upon the configuration of satellite sounding data that was operational at that time. This was based exclusively upon the use of NESDIS sounding products in the following configuration.

Northern Hemisphere - no tropospheric sounding data used
Tropics - no sounding data used
Southern Hemisphere - all NESDIS data used over sea
Stratosphere (above 100 mb) - all sounding data used outside the tropics

The justification for this configuration was a series of experiments (described in *Thoss et al*, 1991) which clearly demonstrated that while NESDIS TOVS products were useful in the Southern Hemisphere (and crucial to maintain reasonable quality forecasts), no benefit (and indeed some detriment) was obtained by its inclusion in the Northern Hemisphere and Tropics. This configuration, from now on referred to CONTROL provided the control or benchmark against which the impact of 1DVAR was to be tested. Two different experimental 1DVAR configurations were tested as possible candidates for implementation.

1DVAR-A
Northern Hemisphere - clear and partly cloudy data over sea
Tropics - no sounding data
Southern Hemisphere - all soundings over sea
Stratosphere (above 100 mb) - all sounding data used outside the tropics
1DVAR-B
Northern Hemisphere - all soundings over sea
Tropics - clear and partly cloudy soundings over sea
Southern Hemisphere - all soundings over sea
Stratosphere (above 100 mb) - all sounding data used outside the tropics

May 1991 Case

The first experiment performed was for the period 1-14 May 91 and the results are shown as hemispheric skill scores (anomaly correlations) in Fig 5. In all cases the verifying analyses used to compute the anomaly correlation statistics are those of the operational forecast. It is not believed that this choice has any significance beyond the first few days of the forecast and in any case would tend to over penalize the 1DVAR forecasts. For the Northern Hemisphere it can be seen that there a small but clear positive impact of the 1DVAR assimilation on the forecast quality. While it is small, such an improvement sustained over a period as long as two weeks is certainly considered significant.

The distinction between the two different configurations of 1DVAR appears negligible. This suggests that the influence of the extra data in the tropics has little effect until the very extremes of the forecast range, where the effect is slightly negative.

For the Southern Hemisphere the 1DVAR underperforms relative to operations around day 5 or 6 and is otherwise neutral. Again there is little difference between the two 1DVAR assimilations until the extremes of the forecast range. At this range only 1DVAR-B is able to clearly improve over the operational forecast. Further investigations showed this improvement to be due more to the retention of cloudy data in the winter hemisphere that the inclusion of the tropical soundings.

December 1991 Case

The second period tested was 19-26 December 91 chosen primarily to investigate the performance of the 1DVAR forecasts for the Northern Hemisphere winter. The results obtained are not shown since they were very similar to those of the May 91 experiments, suggesting the inclusion of data in the tropics gave little benefit, but 1DVAR-B (using cloudy soundings) was generally superior in the winter hemisphere.

Problems were identified for the Southern Hemisphere due to data availability. At the time, the "120 km BUFR TOVS" data from NESDIS were found to be susceptible to significant loss of part or whole orbits. While in the Northern Hemisphere such drop-outs could be reasonably compensated by conventional data sources, in the Southern Hemisphere (which relies heavily on satellite data) they were found to cause a significant deterioration of the forecasts. The operational scheme had no such problems since it had the facility to merge homogeneously with the very reliable 500 km SATEM sounding products when the high resolution data were missing.

From these results a third configuration of 1DVAR was constructed which omitted all sounding data from the tropics, retained merged NESDIS data in the Southern Hemisphere (ie the same as CONTROL) and only used 1DVAR (including cloudy data) in the Northern Hemisphere. The performance of this configuration relative to the operational control forecasts is shown in Fig 6, again in terms of anomaly correlation statistics. It can be seen that in the Northern Hemisphere there is a significant improvement over the control beyond day 4 and this was adopted as the best 1DVAR configuration at least until the problems of data acquisition could be solved.

April / May 1992 Cases

The combined NESDIS/1DVAR configuration was selected to undergo final testing for operational implementation. Two six day periods were chosen in April and May 1992 for which parallel data assimilation and forecast were performed. The results are combined from the two periods and are shown in Fig 7 for the Northern Hemisphere and two local area verifications. There is a clear positive impact of the new configuration in terms of the anomaly correlation statistics.

Despite the clear improvement in skill scores the result of a subjective evaluation of the new system against operations was found to be somewhat neutral. Some clear cases of synoptic improvement could be demonstrated, but in general they were rare. This was surprising but could be explained by a further investigation of the anomaly correlation statistics. The spectral nature of the ECMWF model allowed the skill scores to be conveniently analyzed at different wavenumber truncations (essentially different horizontal scales) and these are shown in Fig 8. It can be seen that the most significant improvement is obtained in the wavenumber range 4-7 corresponding to scales larger than those considered synoptic. This suggests that the TOVS data in the Northern Hemisphere are improving mostly the large scale features of the forecast and may explain why such clear skill score gains are not accompanied by comparable synoptic improvements.

3. SUMMARY AND FUTURE PLANS

The impact of the 1DVAR was considered sufficiently positive to implement it as part of the operational ECMWF data assimilation scheme on the 26 June 1992. The results of these experiments are important since they are a clear demonstration of the usefulness of TOVS data in NWP for the Northern Hemisphere.

The stability of the 1DVAR scheme has been very encouraging and no long term ill-effects have been experienced to date. However, the TOVS radiances will continue to be monitored on a daily basis together with the quality of the generated products, to detect any problems of model drift or poor tuning in the 1DVAR.

Experiments being performed at present (with full data coverage) suggest that 1DVAR may be successfully extended into the Southern Hemisphere to replace the NESDIS sounding products when the BUFR TOVS data acquisition improves in early 1993.

The impact of TOVS data in the Tropics using 1DVAR is still not fully understood and it is considered safer for the time being to exclude it. There is clearly a substantial amount of information in the radiances to adjust the model tropical humidity field, but it is felt that a more sophisticated specification of particularly $\boldsymbol{B}$ (forecast background error covariance) may be required to successfully use 1DVAR temperature products.

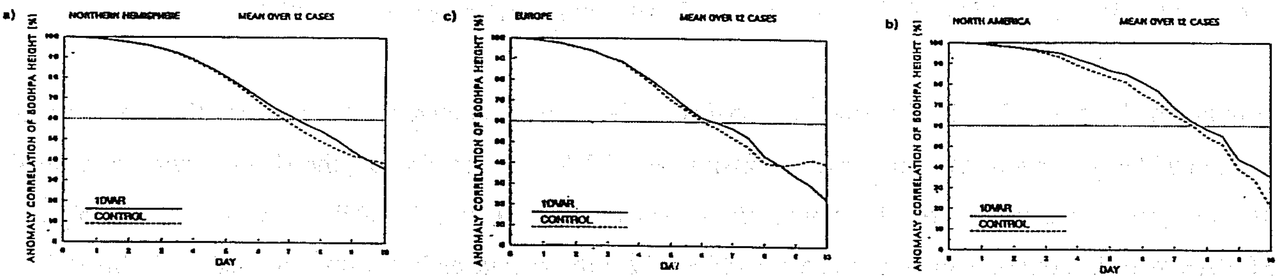

Fig 7 Anomaly correlation statistics for the final testing of 1DVAR in April/May 92.

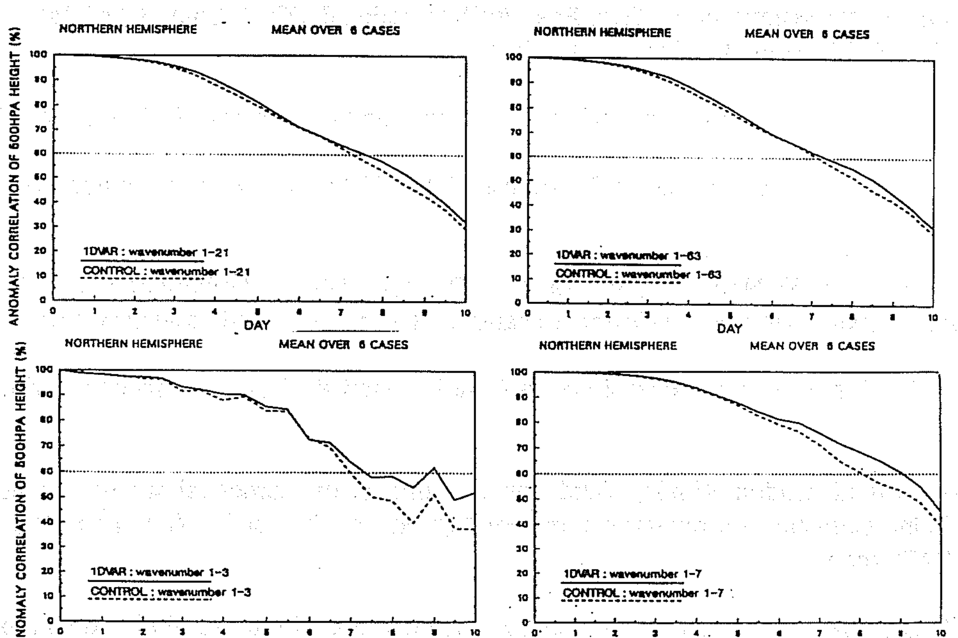

Fig 8 Breakdown by wavenumber of the anomaly correlation statistics for April/May 92 case.

The general problem of correctly specifying forecast background error is still uncertain, although the current matrix $\boldsymbol{B}$ seems to be performing reasonably well in operations for the Northern Hemisphere alone. It is known that the correlation structures implied by $\boldsymbol{B}$ are crucial to the adjustment process, and there is conflicting evidence from a number of past and current studies as to what they should be. A great deal of effort is being directed towards resolving this problem, not only for the 1DVAR scheme, but also for the future extension to the 3DVAR analysis of TOVS radiances (*Anderersson et al*, 1993).

It is planned that the ECMWF operational analysis scheme will be changed from OI to 3DVAR towards the end of 1993. Although the 3DVAR will assimilate TOVS radiance directly, the 1DVAR will be retained as a pre-processing stage to quality control the radiance measurements. It will also be used to supply the 3DVAR with information about parameters which affect the radiances but cannot be analyzed directly for practical reasons (eg the stratosphere above the model extent). These reasons alone justify continued effort into improving and extending the scope of 1DVAR, but it is also hoped that much of the experience gained about problems such as tuning will be directly relevant to the future analysis systems.

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