TECHNICAL MEMORANDUM

187

Assimilation of TOVS radiance information through one dimensional variational analysis

J.R. Eyre, G. Kelly, A.P. McNally and E. Andersson

Research Department

July 1992 (SAC paper)

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Assimilation of TOVS radiance information through one-dimensional variational analysis

Document presented to the 20th Session of the Scientific Advisory Committee, 1992

---

1. INTRODUCTION

The TIROS Operational Vertical Sounder (TOVS) on the NOAA series of polar-orbiting satellites measures multi-spectral radiances which are related to the atmosphere's temperature and humidity structure (see *Smith et al.*, 1979). This paper describes a scheme which has been developed for assimilating information from these radiances more directly into the numerical weather prediction (NWP) system at ECMWF. The approach is known as one-dimensional variational analysis or 1DVAR. Extensive testing of the scheme through forecast impact experiments has demonstrated clear and consistent benefits for forecast skill in the northern hemisphere extra-tropics. As a result, the 1DVAR scheme was implemented operationally at ECMWF in June 1992.

Section 2 of the paper presents the background to the development of 1DVAR. It discusses the cause of the problems previously experienced when trying to assimilate satellite sounding products retrieved independently from a NWP system and the reasons for moving towards variational methods for more direct assimilation of the radiance information. Section 3 presents the theory of the 1DVAR approach, and section 4 describes its implementation at ECMWF. Section 5 discusses some aspects of the performance of the 1DVAR scheme, and section 6 presents the results of a series of forecast impact experiments which were conducted during the development and testing of the scheme. Section 7 discusses possible improvements and extensions in its application.

2. BACKGROUND

It is widely recognized that satellite sounding products have a beneficial effect on NWP analyses and forecasts in the southern hemisphere. Indeed they are essential for maintaining the level of forecast skill currently achieved. In the early 1980s, it was also demonstrated that they had, on average, a positive impact when used in data-sparse areas in the northern hemisphere (for example, see *Halem et al.*, 1982; *Bengtsson*, 1985; *Kashiwagi*, 1987). More recently, however, as NWP systems have improved, ECMWF and other major NWP centres have experienced increasing difficulty in demonstrating consistent positive impact on northern hemisphere forecasts from temperature profiles retrieved from satellite sounding data by conventional techniques (for example, see *Andersson et al.*, 1991; *Kelly et al.*, 1991; *Thoss*, 1991).

The main reason for these problems is well understood. It is implicit in the analysis of the inversion problem for satellite sounding data given by *Rodgers* (1976) and has been discussed more recently by *Eyre and Lorenc* (1989). In brief, the problem arises from the rather poor vertical resolution of satellite sounding radiometers. Although the current operational instruments of the TOVS system contain more than 20 spectral channels, their weighting functions are broad and overlapping (see Fig. 1) and they supply fewer independent pieces of information (perhaps 6 or 7). There are components of the atmospheric profiles, namely those representing high-order vertical structure, to which the satellite sounder is blind. The information on these components can be supplied only by prior or "background" information. In a conventional retrieval system the prior information is independent of a NWP system. In the system used operationally by NOAA/NESDIS, it comes from a large library of recent pairs of satellite measurements and collocated radiosonde profiles. Although the methods for using such information are now quite sophisticated and complex, they cannot really compensate for the fundamental "blindness" of the measurements to certain components of the profile, and they often supply information on these components which is less accurate than can be supplied by an NWP system. In such cases, the assimilation of independently retrieved temperature/humidity profiles will tend to degrade rather than improve the accuracy of the NWP model fields.

It is sometimes claimed that this problem could be overcome by taking more care in specifying the error covariance of the satellite products within the assimilating system. However, the errors of retrievals have subtle characteristics (see *Eyre*, 1987). Although they may conform globally to some error covariance, locally their errors tend to appear as biases which are a strong function of the atmospheric state. It is not clear how such error characteristics can adequately be specified in the form of one or more error covariances as used, for example, in an optimal interpolation (OI) analysis.

The solution to this problem is to stop using satellite sounding data in the form of retrieved profiles, as though they were poor-quality radiosonde data, and to start treating them for what they really are — radiance measurements. Météo-France and the UK Meteorological Office (UKMO) adopted these ideas some time ago and have implemented them operationally to a limited extent. At Météo-France a scheme was developed for assimilating TOVS brightness temperatures into a three-dimensional OI analysis. (*Durand and Juvanon du Vachat*, 1985; *Durand*, 1985). Its main limitation is that it approximates the problem as linear and cannot treat properly the nonlinear link between brightness temperatures and NWP model variables. At the UKMO, an equivalent one-dimensional (vertical only) approach was developed in which a forecast profile and its expected error covariance provide the constraints on the inversion (*Eyre et al.*, 1985; *Turner et al.*, 1985). It makes similar approximations of linearity. Experiments with a fully nonlinear one-dimensional scheme have also been performed (*Eyre*, 1989).

At ECMWF, a number of initiatives have been undertaken in order to make more direct use of satellite radiance data within the assimilation system. The UKMO's one-dimensional nonlinear optimal estimation scheme has been imported and an interface to ECMWF's NWP model developed. The scheme has been adapted to run on cloud-cleared TOVS brightness temperatures (rather than on raw TOVS radiances for which it was originally developed). It has been applied for the first time to global data, and this has involved the development of a new radiance monitoring and tuning scheme. In parallel with these activities, the development of a three-dimensional variational analysis (3DVAR) has been a major project at ECMWF (*Pailleux et al.*, 1991). One component of this scheme is the assimilation of global TOVS brightness temperature data (see *Pailleux*, 1990). Much of the development involved for TOVS is common between the 3DVAR and the one-dimensional scheme, including the radiative transfer model and the radiance monitoring/tuning system. Moreover, both approaches are based on the solution of the same variational equation. For these reasons, and to emphasize the link between the two projects, the one-dimensional optimal estimation scheme implemented at ECMWF is known as "one-dimensional variational analysis" or "1DVAR".

3. THEORY

The variational approach to the assimilation of data into an NWP system has been described by a number of authors (e.g. *Lorenc*, 1986). When applied specifically to the assimilation of satellite radiance information it takes the following form: we try to minimize a penalty function $J(x)$ with respect to the atmospheric state x, where $J(x)$ measures the degree of fit to the radiances, to background information and possibly also to other observations and to other physical or dynamical constraints. If the errors involved have Gaussian distributions, then the optimal penalty function can be shown to be a sum of quadratic terms:

$$\begin{aligned} J(x) = {} & (y^m - y\{x\})^T \cdot (O + F)^{-1} \cdot (y^m - y\{x\}) \\ & + (x - x^b)^T \cdot B^{-1} \cdot (x - x^b) \\ & + J_o + J_c \end{aligned} \tag{3.1}$$

where x is a vector containing the atmospheric state, y^m is a vector of measured radiances, $y\{x\}$ is the radiance vector corresponding to the atmospheric state (i.e. involving radiative transfer calculations), O is the expected error covariance of the measured radiances, F is expected error covariance of the "forward operator" $y\{...\}$, x^b is a background profile (e.g. short-range forecast "first guess"), B is its expected error covariance, J_o (optionally) represents the penalty for other observations and J_c (optionally) represents other constraints.

Note that the expression for $J(x)$ is general with respect to the dimension of x: it can be applied to a one-dimensional (vertical) problem analogous to a conventional retrieval, or to a 3-dimensional atmospheric state (e.g. the whole global atmosphere).

There are a number of methods for finding the minimum of such a penalty function. The TOVS 1DVAR scheme uses the method of Newtonian iteration in which the nth estimate of x is updated as follows:

$$x_{n+1} = x_n - \left[\nabla_x^2 J(x)\right]^{-1} \cdot \nabla_x J(x) \tag{3.2}$$

where $^{-1}$ denotes matrix inverse. $\nabla_x J(x)$ is obtained by differentiating eq. 3.1:

$$\nabla_x J(x) = B^{-1} \cdot (x - x^b) - K\{x\}^T \cdot (O+F)^{-1} (y^m - y\{x\}), \tag{3.3}$$

where $K\{x\} = \nabla_x y\{x\}$, and we have omitted terms involving J_o and J_c. The Hessian matrix is obtained by differentiating again:

$$\nabla_x^2 J(x) \approx B^{-1} + K\{x\}^T \cdot (O+F)^{-1} \cdot K\{x\}. \tag{3.4}$$

Note that this is approximate, since terms involving the gradient of $K\{x\}$ have been omitted. These equations can be combined and manipulated to derive the form of the Newtonian iteration given by *Rodgers* (1976)

$$x_{n+1} = x^b + W_n \cdot \left[y^m - y\{x_n\} - K\{x_n\} \cdot (x^b - x_n)\right], \tag{3.5}$$

where $$W_n = B \cdot K\{x_n\}^T \cdot (K\{x_n\} \cdot B \cdot K\{x_n\}^T + O + F)^{-1}. \tag{3.6}$$

The Newtonian method, which has optimal convergence properties, is practicable in the case of the 1DVAR because the state vector x is quite short (about 60 elements) and so the Hessian can be computed and stored.

4. IMPLEMENTATION

4.1 TOVS data

The TOVS brightness temperatures used within the 1DVAR scheme are (at present) the global, cloud-cleared data generated by NOAA/NESDIS and available in Europe in near-real time as part of the "120 km BUFR TOVS" data set. These data have already undergone substantial pre-processing at NESDIS (see *Smith et al.*, 1979) followed by cloud-clearing (*McMillin and Dean,* 1982). The cloud-clearing route is identified with the data and can be either "clear", "partly cloudy" or "cloudy".

4.2 PRESAT

The 1DVAR scheme is implemented as an option within the software framework called PRESAT. PRESAT has been used operationally at ECMWF for pre-processing 120 km BUFR TOVS data since May 1991. Initially it was used to improve the quality control and data selection of TOVS temperature/humidity retrievals received from NESDIS. It was also used to generate differences between measured brightness temperatures and those computed from short-range (nominally 6-hour) forecast profiles, and statistical studies of these quantities have been a necessary prelude to the implementation of 1DVAR (see section 4.5). The 1DVAR scheme was implemented operationally within PRESAT in June 1992 in the configuration described below.

4.3 1DVAR within PRESAT

The 1DVAR scheme follows the method described by *Eyre* (1989). The following changes have been made in order that it can run within the framework of the data assimilation system at ECMWF using the data described in section 4.1.

The state vector x is a vertical atmospheric profile containing the temperature at 40 pressure levels (1000 to 0.1 hPa), the humidity at 15 pressure levels (1000 to 300 hPa, and expressed as natural logarithm of specific humidity), surface air and skin temperatures, and surface pressure. Although allowed for in the scheme, microwave surface emissivity and cloud parameters are effectively excluded from the state vector by setting their background error covariances to zero.

The following TOVS channels are used at present in the 1DVAR (see Fig. 1 for weighting functions): HIRS channels 1-7 and 10-15 and MSU channels 2-4 are used for "clear" and "partly cloudy" soundings; HIRS channels 1-3 and MSU channels 2-4 are used for "cloudy" soundings. The window channels, HIRS channel 8 and MSU channel 1, are excluded mainly because of problems found in the way these channels are pre-processed by NESDIS. The data are used in the form of brightness temperatures (rather than radiances, cf. *Eyre*, 1989).

Brightness temperatures corresponding to the state vector x are computed using the new fast radiative transfer scheme (*Eyre*, 1991). A new feature of this scheme is that the corresponding Jacobian matrix, $K\{x\}$, is now computed exactly using code which is a modified version of the adjoint code. Calculations are performed at nadir with a cloud amount of zero and a microwave surface emissivity of 1.0, in order to simulate the output of the NESDIS pre-processing and cloud-clearing.

The background profile x^b is obtained from the NWP model. Nominally a 6-hour forecast is used: in fact forecast fields at 3-hour intervals are interpolated quadratically in time and bilinearly in space to the location of each TOVS sounding within the "analysis window", which contains all the data between +3 and +9 hours from the previous analysis. The temperatures are interpolated from the NWP model levels (currently 31) to the pressure levels of the radiative transfer scheme (currently, in a linear manner). Above the top of the model (at pressures less than 10 hPa) the profile is extrapolated as described by *Eyre* (1989). The surface pressure and surface air and skin temperatures are obtained from the equivalent NWP model parameters. Over sea-ice, where the model values are currently rather poor, the surface temperatures are taken from the lowest model level. The background profile also provides the initial profile for the minimisation.

The background error covariance matrix, $\boldsymbol{B}$, was originally obtained from the UKMO, where it was generated from statistics of radiosonde-forecast differences (see *Eyre*, 1990). Following the tuning described in section 4.5, the standard deviations were modified to give those in Table 1. The inter-level correlations of error were retained. Recent studies of radiosonde-forecast differences at ECMWF (see section 5) have confirmed that the inter-level correlations derived are very similar to those obtained from the UK studies. The code allows for a spatially-varying value of $\boldsymbol{B}$, but this is not implemented at present.

The measurement error covariance, $\boldsymbol{O} + \boldsymbol{F}$, is at present a fixed diagonal matrix in brightness temperature space corresponding to the standard deviations given in Table 2. These were also obtained as a result of the tuning exercise described in section 4.5.

Following *Eyre* (1989), the iterative minimisation is considered to have converged when the increment is less than 0.4 times the standard deviation of background error at every level. After each iteration, the humidity profile is checked for super-saturation and, if necessary, adjusted. This is a sub-optimal form of physical constraint on the inversion (cf. $\boldsymbol{J_c}$ in eq. 3.1).

4.4 Quality control and data selection

The minimisation proceeds for a maximum of 5 iterations. Any sounding which has not converged by this point is rejected. If the minimisation converges, the "measurement cost" of the solution (i.e. the square root of the first term in eq. 3.1) is calculated separately for each channel. The sounding is rejected if the cost exceeds a threshold in any channel. The threshold is currently set to 10 in HIRS channels 10, 11 and 12, and to 6 in other channels.

A check is made on the difference between measured and forecast brightness temperature in a HIRS window channel. This is important, mainly to detect residual cloud contamination. HIRS channel 8 should be used for this purpose, but at present it is difficult to use because NESDIS apply a water vapour correction to this channel, and the correction has peculiar error characteristics which differ between satellites. At present HIRS channel 10 is used for this purpose; it is not such a clean window but is free from these effects. The data are rejected if measured-minus-forecast brightness temperature is: < -4 K over sea, < -6 K over sea-ice and < -10 K over land.

From the 1DVAR "retrievals" which pass the quality control, a further selection is made to reduce the data density to a spacing of about 250 km. Priority is given to soundings over sea before those over land. Clear, partly cloudy and cloudy soundings are selected preferentially in this order.

4.5 Correcting biases and tuning statistics

There are systematic errors in the brightness temperatures simulated from forecast profiles, arising mainly from errors in the spectroscopic data on which the radiative transfer model is based. There may also be biases in the measurements, resulting mainly from problems in the pre-processing. Together they lead to biases in the differences between measured and forecast brightness temperatures which are comparable with the radiative change corresponding to a typical error in the forecast atmospheric state. Unless these biases are corrected to below this level, it is difficult to use the measured radiances to positive effect in NWP. Moreover, the radiative transfer model biases in some channels are found to be strongly dependent on the atmospheric state, which leads to the requirement for a spatially-varying bias correction.

Using the data base of measured-minus-forecast brightness temperatures constructed by routine running of PRESAT, a scheme has been developed for correcting the relative bias between measured and forecast brightness temperatures. The scheme is described in detail elsewhere (*Eyre*, 1992). It appears to be successful in controlling biases in critical temperature sounding channels to a low level and one which is adequate for successful operation of the 1DVAR. A spatially-varying bias correction is applied to each TOVS brightness temperature departure before it is used in the 1DVAR.

Results from the monitoring of TOVS brightness temperature statistics have been found useful for a number of other purposes. One is the tuning of the error covariances used in the 1DVAR. Once the biases have been removed, the residual variance provides a measure of the sum of the error variances in the measurements, the radiative transfer calculation and the forecast. (Fig. 2 gives an example for MSU channel 2.) The observed residual variance must exceed each component of the error variance, and thus it provides, at the very least, an upper limit on all these error variances. It was found that the values of $\boldsymbol{B}$ and $(\boldsymbol{O} + \boldsymbol{F})$ assumed prior to this work were not consistent with the observed statistics; reductions in the magnitudes of both matrices were required. The known values of the instrument noise provide a lower limit on the magnitude of $(\boldsymbol{O} + \boldsymbol{F})$. Using this and other constraints, ad hoc adjustments have been made to $\boldsymbol{B}$ and $(\boldsymbol{O}+ \boldsymbol{F})$ to make them more consistent with the observed statistics, and to give the values in Tables 1 and 2. So far, only the variances have been tuned; the correlation coefficients have not been changed.

4.6 OI interface

Previous work at ECMWF (*Kelly and Pailleux*, 1988) had shown that NESDIS temperature/humidity retrievals could be assimilated to best effect if used on a limited number of thick layers compatible with the information content of the data. Layer-mean virtual temperatures are presented to the OI analysis on 7 layers: 1000-700, 700-500, 500-300, 300-100, 100-50, 50-30, 30-10 hPa. Layer water vapour contents are presented on the 3 lowest layers. For technical reasons, it has been easiest to use the 1DVAR products within the OI analysis system by integrating the profiles to the same layers and replacing the NESDIS-derived quantity with the 1DVAR equivalent. Since at present the 1DVAR does not use any SSU data, it does not provide significant information in the top layer, 30-10 hPa. Consequently the NESDIS product for this layer is not replaced.

It is possible to think of the 1DVAR as just a different way of performing a conventional "retrieval". However, it is more instructive to regard it as the first stage in the assimilation of radiance data into the NWP fields, in which the radiance information is projected on to a set of vertical levels at each observation point. The second stage, performed by the OI analysis scheme, involves the projection of information on to the analysis variables. A problem which arises in such a 2-stage analysis is the correlation of error between the output of the first stage and the background for the second. This should be allowed for during the second stage. The problem is analogous in principle to the "super-ob" problem described by *Lorenc* (1981).

We have investigated 2 solutions to this problem for 1DVAR output. The first was proposed by *Purser* (1990), who showed that the background-dependence can be removed completely if the "retrieval" is projected into a space of dimension not greater than the number of channels. The formation of layer-mean virtual temperatures on thick layers represents a specific projection of this type. However, Purser's method was found to have noise amplification properties which are too great for this configuration of layers, particularly for the cloudy soundings. We have therefore adopted the method proposed by *Lorenc et al.* (1986) which may be considered as an approximation of Purser's method. By ignoring off-diagonal terms in matrices, it only approximately removes correlated error but is numerically more stable.

The general solution to the super-ob problem is to amplify the observation increments and simultaneously decrease their weights (i.e. increase their estimated errors). Based mainly on theoretical calculations of the error characteristics of 1DVAR output, we have chosen (for the time being) an increment amplifier of 1.5 and a down-weighting factor of 2.0, for each of the 6 layers in which 1DVAR is used.

4.7 Operational configuration

On 23 June 1992 the 1DVAR products were introduced into the operational OI analysis at ECMWF in the following configuration.

a) Northern Hemisphere extra-tropics.
NESDIS products have been removed except for the layer 30-10 hPa. 1DVAR products have replaced NESDIS products in the layers between 100 and 30 hPa. In addition, 1DVAR products have been introduced over the sea for the layers between 1000 and 100 hPa (from which NESDIS products were removed in May 1991).

b) Tropics.
No sounding data are used here, i.e. no change.

c) Southern Hemisphere extra-tropics.
NESDIS products continue to be used above 100 hPa and over the sea below 100 hPa, i.e. no change.

The "tropics" are defined as 20S-20N for clear and partly cloudy soundings and as 30S-30N for cloudy soundings. This choice resulted from earlier experiments on NESDIS retrievals.

The choice of configuration for the 1DVAR was guided by the results of the forecast impact experiments presented and discussed in section 6.

5. 1DVAR PERFORMANCE

The development and testing of the 1DVAR scheme has been performed mainly through the forecast impact studies reported in section 6, and it was on the basis of the positive results obtained that the decision was made to implement 1DVAR operationally. Other aspects of the performance of 1DVAR have been examined to a limited extent only; there is considerable scope for more thorough and systematic investigations, aimed at a re-tuning of the 1DVAR system and its OI interface (see section 7).

A new system developed mainly for this purpose is called COLLOC. It is an extension of the PRESAT concept and runs routinely to provide 3-way collocations between TOVS soundings, NWP model forecasts and radiosondes. It can be run either on NESDIS retrievals or on 1DVAR output to provide data bases for subsequent statistical evaluation. Figs. 3 and 4 give examples of these. They show, for 1DVAR and NESDIS retrievals, the means and standard deviations of the differences between: retrieval and sonde, forecast and sonde, and retrieval and forecast. Interpretation of these statistics is not straightforward, because the NESDIS retrieval is independent of the forecast whereas 1DVAR is not. The fact that the

1DVAR-sonde difference is smaller than the NESDIS-sonde difference is not a measure of their relative utility.

The tendency of the 1DVAR-sonde difference to be slightly greater than forecast-sonde difference is a little worrying. This may be reversed by better tuning (see *Watts and McNally*, 1988) or it may be caused mainly by biases in radiosondes — a known problem, to which solutions are currently being developed. However, there are two reasons why this result may be acceptable. Firstly the individual 1DVAR products have not been smoothed in the horizontal and so may be noisy relative to the forecast. Secondly, all the statistics are by definition from areas near sondes, whereas the impact of the 1DVAR is expected (and is observed) in areas distant from sondes, where the forecast errors will be higher on average.

At this stage it is sufficient to say that the data base generated by COLLOC provides a useful tool for further studies and tuning of 1DVAR performance.

6. FORECAST IMPACT EXPERIMENTS

The 1DVAR scheme has been tested through a series of forecast impact experiments. In each experiment, 1DVAR products have been assimilated into the NWP system for several days. After each day of assimilation, a 10-day forecast has been run and compared with a verifying analysis. Corresponding control forecasts have been run from assimilations without 1DVAR products. In all, over 100 days of assimilation have been completed from 4 different periods.

6.1 May 1991

A series of experiments was run assimilating data over the period 1-15 May 1991 with forecasts from analyses at 12Z from 2-15 May (14 cases). Preliminary experiments (results not shown) led to a number of modifications which were retained for experiments reported here. The inclusion of cloudy soundings was found to be particularly important in the southern hemisphere, otherwise the reduced data coverage had a noticeable effect on forecast skill. The quality of the forecast background over sea-ice was found to be a problem, leading to the strategy reported in section 4.3. It was also found necessary to specify higher background errors in surface temperatures over land and sea-ice than over ocean. The 1DVAR statistics were tuned as described in section 4.5 and the OI analysis weights for 1DVAR products were also modified.

Following these changes, two experiments using 1DVAR products labelled "BAA" and "BBG" were run with the following data configurations:

BAA:	northern hemisphere:	clear and partly cloudy soundings only
	southern hemisphere:	all soundings
	tropics:	no soundings

BBG: northern hemisphere: all soundings
southern hemisphere: all soundings
tropics: clear and partly cloudy soundings

Both experiments were run with the version of the NWP model which was operational in May 1991: resolution T106L19, cycle 38. The controls for these experiments were the operational forecasts, and the operational analyses were used for verification.

The forecast scores expressed as anomaly correlations are shown in Figs. 5-8. For the northern hemisphere as a whole, the average effect of 1DVAR is clearly positive from about day 2 of the forecast (Fig.5). The scatter plots for individual forecasts (Fig.6) are particularly encouraging; at day 3, all but one out of 14 is favourable to the 1DVAR. Over North America (Fig.7a) the impact is strongly positive but over Europe (Fig.7b), for this period, the signal is less clear. The results from the two experiments are very similar but perhaps a little in favour of BAA.

In the southern hemisphere (Fig.8), the results favour the control over 1DVAR and BAA over BBG. Note that in this hemisphere all 1DVAR products are used in both experiments, and so the difference in results probably originates in the tropics.

6.2 December 1991

A set of parallel experiments was run for the period 15-26 December 1991. The results of initial experiments are not shown as they used a set of bias correction coefficients which were subsequently found to produce problems over sea-ice. However, they led to broadly similar conclusions to those obtained from the May experiment. They also suggested that the inclusion of the cloudy soundings had a positive effect in the northern hemisphere in winter when the cloud-cover in mid-latitudes is higher, confirming the results from May in the southern hemisphere.

Based on all these results, it was decided to test a configuration for initial operational implementation in which data were excluded from the tropics and NESDIS products retained in the southern hemisphere (see section 4.7). The problems with 1DVAR in the southern hemisphere appear to be related, at least in part, to data volume and coverage. The sensitivity to adding cloudy soundings has been demonstrated. Also the operational availability of the brightness temperature data (via the 120 km BUFR TOVS data) is significantly lower than that of the NESDIS retrieved products, since the latter are also received reliably as 500 km SATEMs. Moreover the availability to date of the 120 km BUFR TOVS data has been very variable from day to day and often much worse than in the periods chosen for these experiments. It was therefore decided to exclude 1DVAR products from the southern hemisphere, at least until the operational availability of the data improves.

These decisions necessitated a number of technical modifications to the 1DVAR scheme and the OI analysis to permit the use of 1DVAR and NESDIS data simultaneously. When these were completed further experiments was conducted on 7 days of the December period. These used model resolution T106L19, cycle 41; an additional T106L19 assimilation without 1DVAR (labelled "BFO") and subsequent forecasts were run as control. The operational analyses (T213L31) were used for verification.

Some results are shown in Figs. 9 and 10. For the northern hemisphere as a whole (Fig.9), 1DVAR impact was slightly negative at days 3 and 4 but clearly positive beyond day 5. Again, the consistency of scores for individual forecasts (Fig.10) in the medium range is encouraging.

6.3 Pre-operational trials: April-May 1992

Two pre-operational trials were conducted, both using the model at T213L31 for assimilation followed by forecasts at T106L19. Forecasts run at T106L19 from the operational analyses (T213L31) were used as controls (labelled "OPS 106"), and operational analyses provided verification. The first trial was run for the period 7-12 April using model cycle 41, and the second for 15-21 May using cycle 42. 6 days of assimilation followed by 6 10-day forecasts were run in each case.

Results are shown in Figs. 11-14 for the 2 periods combined (12 cases). The impact of the 1DVAR products is strong and favourable. For the northern hemisphere as a whole (Fig.11a), the mean impact is clearly positive from day 3. Also the impact on individual forecasts is consistent at all ranges, with very few negative cases (Fig.12). Over North America (Figs. 11b and 13), the impact is strong and appears at day 2 in the mean scores with some very large improvements, even at day 3. Over Europe (Figs. 11c and 14), the signal is also positive, although the impact tends to emerge later in the forecast, around day 4 or 5. This is consistent with the fact that the largest analysis changes are observed over the Pacific, and so their effect is felt over N America early in the forecast period and over Europe in the forecast period.

Some experimental forecasts were also run from the same analyses at T213L31 and compared with operational forecasts. The impact of the 1DVAR on the forecast skill was not significantly affected by the change in forecast resolutions for the few cases investigated.

7. FUTURE DEVELOPMENTS

The impact on northern hemisphere scores was considered sufficiently clear and consistent to merit early operational implementation of the 1DVAR. However, it is recognized that many aspects of the scheme's performance have not been investigated and there are several areas in which the scheme can be extended and improved.

When real-time availability of data improves, implementation of 1DVAR in the southern hemisphere will be considered. Technical changes at NOAA, Washington DC, should make this possible by the end of 1992. In order to demonstrate positive impact of 1DVAR in the southern hemisphere, it may be necessary to improve the performance over sea-ice, particularly in the winter. At the time of writing, the operational model uses climatological values of surface temperature over sea-ice, and these are often greatly in error. A simple heat balance model has been developed for sea-ice which should improve this aspect of the model "background" and thus assist the performance of the 1DVAR.

There is clear evidence that the humidity information in the 1DVAR products should be beneficial in the tropics, at least in improving the mean analyzed fields (see *Eyre*, 1992). Experiments so far suggest that the inclusion of 1DVAR products in the tropics would have a small adverse effect on forecasts in the extra-tropics. To improve this, a number of aspects deserve attention including the weights given to 1DVAR products in the OI and the specification of the vertical correlation of forecast error.

There is no reason in principle why 1DVAR products should not also be assimilated over land. Positive impact might be expected in data sparse areas.

Now that 1DVAR is running routinely, the COLLOC system is providing a wealth of information to monitor its performance. This will be used to re-tune all the statistical parameters and those in the interface to the OI analysis. When the re-tuning is complete, extension of the scheme to areas other than the northern hemisphere extra-tropical oceans will be considered.

REFERENCES

Andersson E, A Hollingsworth, G Kelly, P Lönnberg, J Pailleux and Z Zhang, 1991. Global observing system experiments on operational statistical retrievals of satellite sounding data. Mon Wea Rev, 119, 1851-1864.

Bengtsson L, 1985. Medium-range weather forecasting at ECMWF. Adv Geophys, 28B, 3-54.

Durand Y, 1985. The use of satellite data in the French high resolution analysis. Proc ECMWF Workshop on "High Resolution Analysis"; Reading; 24-26 June 1985; ECMWF Report, pp.89-127.

Durand Y and R Juvanon du Vachat, 1985. Developments in mesoscale analysis using raw satellite data. Tech Proc 2nd Int TOVS Study Conf; Igls, Austria; 18-22 February 1985; Ed. W P Menzel; Report of CIMSS, University of Wisconsin-Madison, pp.39-57.

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

Eyre J R, 1989. Inversion of cloudy satellite sounding radiances by nonlinear optimal estimation. Q J R Meteorol Soc, 115, 1001-1037.

Eyre J R, 1990. The information content of data from operational satellite sounding systems: a simulation study. Q J R Meteorol Soc, 116, 401-434.

Eyre J R, 1991. A fast radiative transfer model for satellite sounding systems. ECMWF Tech Memo 176.

Eyre J R, 1992. A bias correction scheme for simulated TOVS brightness temperatures. ECMWF Tech Memo 186.

Eyre J R and A C Lorenc, 1989. Direct use of satellite sounding radiances in numerical weather prediction. Meteorol Mag, 118, 13-16.

Eyre J R, P D Watts, J Turner and A C Lorenc, 1985. Research and development on TOVS retrievals in the U.K. Tech Proc 2nd Int TOVS Study Conf; Igls, Austria; 18-22 February 1985; Ed. W P Menzel; Report of CIMSS, University of Wisconsin-Madison, pp.94-100.

Halem J, E Kalnay, W E Baker and R Atlas, 1982. An assessment of the FGGE satellite observing system during SOP-1. Bull Am Meteorol Soc, 63, 407-429.

Kashiwagi K, 1987. On the impact of space-based observing systems in the JMA global forecast/analysis system. J Meteorol Soc Jap, 65, 189-219.

Kelly G, E Andersson, A Hollingsworth, P Lönnberg, J Pailleux and Z Zhang, 1991. Quality control of operational physical retrievals of satellite sounding data. Mon Wea Rev, 119, 1866-1880.

Kelly G and J Pailleux, 1988. Use of satellite sounder data in the ECMWF analysis system. ECMWF Tech Memo 143.

Lorenc A C, 1981. A global three-dimensional multivariate statistical analysis scheme. Mon Weather Rev, 109, 701-721.

Lorenc A C, 1986. Analysis methods for numerical weather prediction. Q J R Meteorol Soc, 112, 1177-1194.

Lorenc A C, W Adams and J R Eyre, 1986. The analysis of high resolution satellite data by the Meteorological Office. Proc ECMWF Workshop on "High Resolution Analysis"; Reading; 24-26 June 1985; ECMWF Report, pp.69-87.

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

Pailleux J, 1990. A global variational assimilation scheme and its application for using TOVS radiances. Preprints WMO Int Symp on "Assimilation of observations in meteorology and oceanography; Clermont-Ferrand; 9-13 July 1990; WMO Report, pp.325-328.

Pailleux J, W Heckley, D Vasiljevic, J-N Thépaut, F Rabier, C Cardinali and E Andersson, 1990. Development of a variational assimilation system. ECMWF Tech Memo 179.

Purser R J, 1990. Vertical aspects of the assimilation of sounding data. Preprints WMO Int Symp on "Assimilation of observations in meteorology and oceanography; Clermont-Ferrand; 9-13 July 1990; WMO Report, pp.501-505.

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

Smith W L, H M Woolf, C M Hayden, D Q Wark and L M McMillin, 1979. The TIROS-N Operational Vertical Sounder. Bull Am Meteorol Soc, 60, 1177-1187.

Thoss A, 1991. Cloud motion winds, validation and impact on numerical weather forecasts. Proc Workshop on "Wind extraction for operational meteorological satellite data"; Washington D C; 17-19 Sept 1991; Eumetsat Report.

Turner J, J R Eyre, D Jerrett and E McCallum, 1985. The HERMES system. Meteorol Mag, 114, 161-173.

Watts P D and A P McNally, 1988. The sensitivity of a minimum variance retrieval scheme to the values of its principal parameters. Tech Proc 4th Int TOVS Study Conf; Igls, Austria; 16-22 March 1988; Ed. W P Menzel; Report of CIMSS, University of Wisconsin-Madison, pp.399-412.

Table 1

Assumed standard deviation of background error.

Pressure (hPa)	Temperature (K)	Ln (specific humidity)
15	1.95	
20	1.66	
30	1.30	
50	0.70	
70	0.64	
100	0.59	
150	0.67	
200	1.01	
250	1.04	
300	0.78	0.74
400	0.68	0.70
500	0.66	0.63
700	0.73	0.63
850	0.88	0.50
950	0.84	0.65
1000	1.09	0.44

Surface air temperature:	sea	1.93 K
	land/ice	4.00 K
Surface skin temperature:	sea	1.57 K
	land/ice	4.50 K
Surface pressure	3.38 hPa	

Table 2

Assumed standard deviation of error in measurements and radiative transfer model.

Channel		Error (K)
HIRS	1	1.17
	2	0.37
	3	0.39
	4	0.25
	5	0.30
	6	0.40
	7	0.61
	10	0.81
	11	1.30
	12	1.50
	13	0.53
	14	0.37
	15	0.29
MSU	2	0.33
	3	0.22
	4	0.28

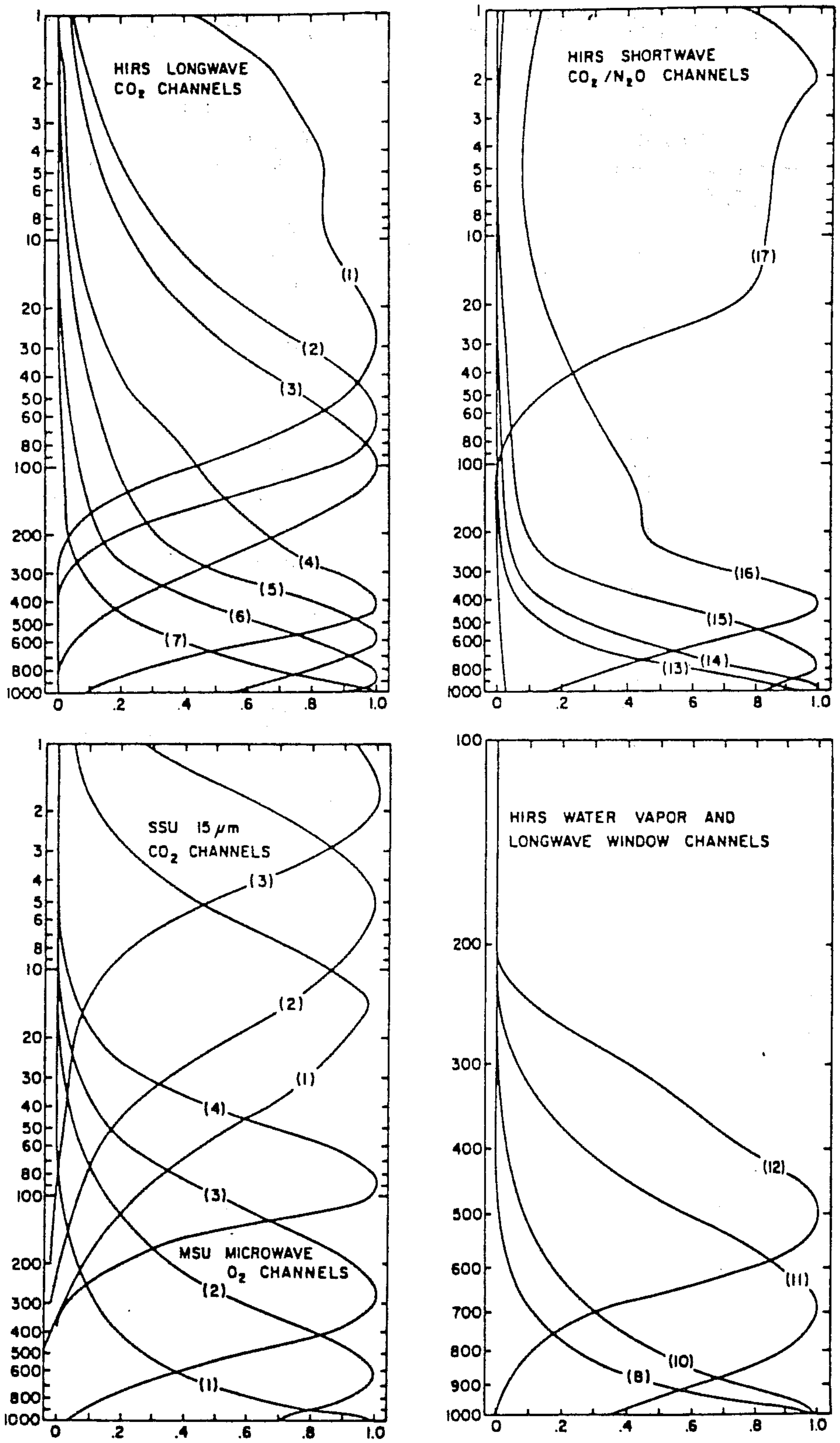

Fig. 1 TOVS weighting functions (taken from *Smith et al.*, 1979).

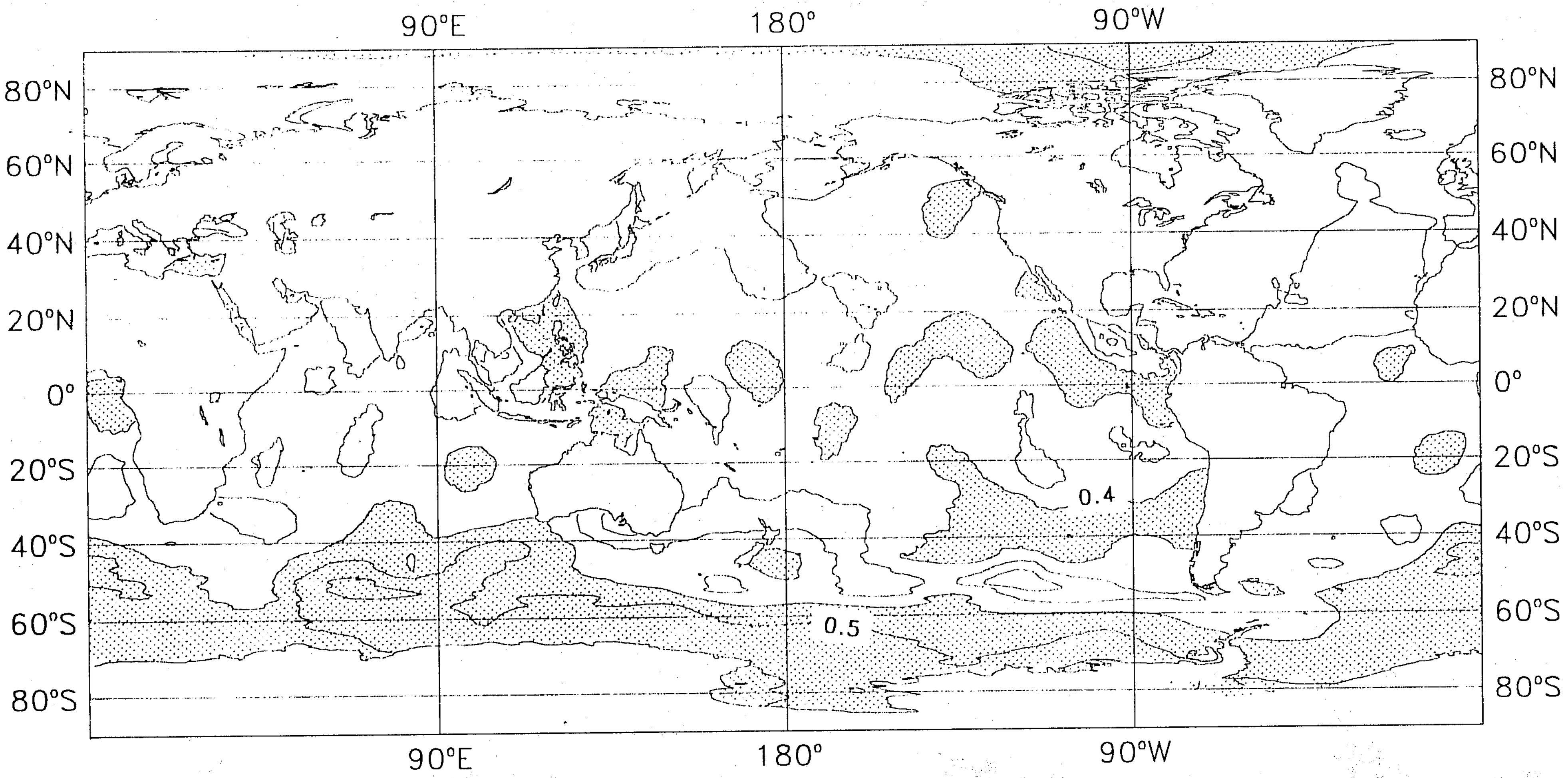

Fig. 2 Local standard deviation of the difference between measured and forecast brightness temperatures (after bias correction). NOAA-11, MSU channel 2, June 1992.

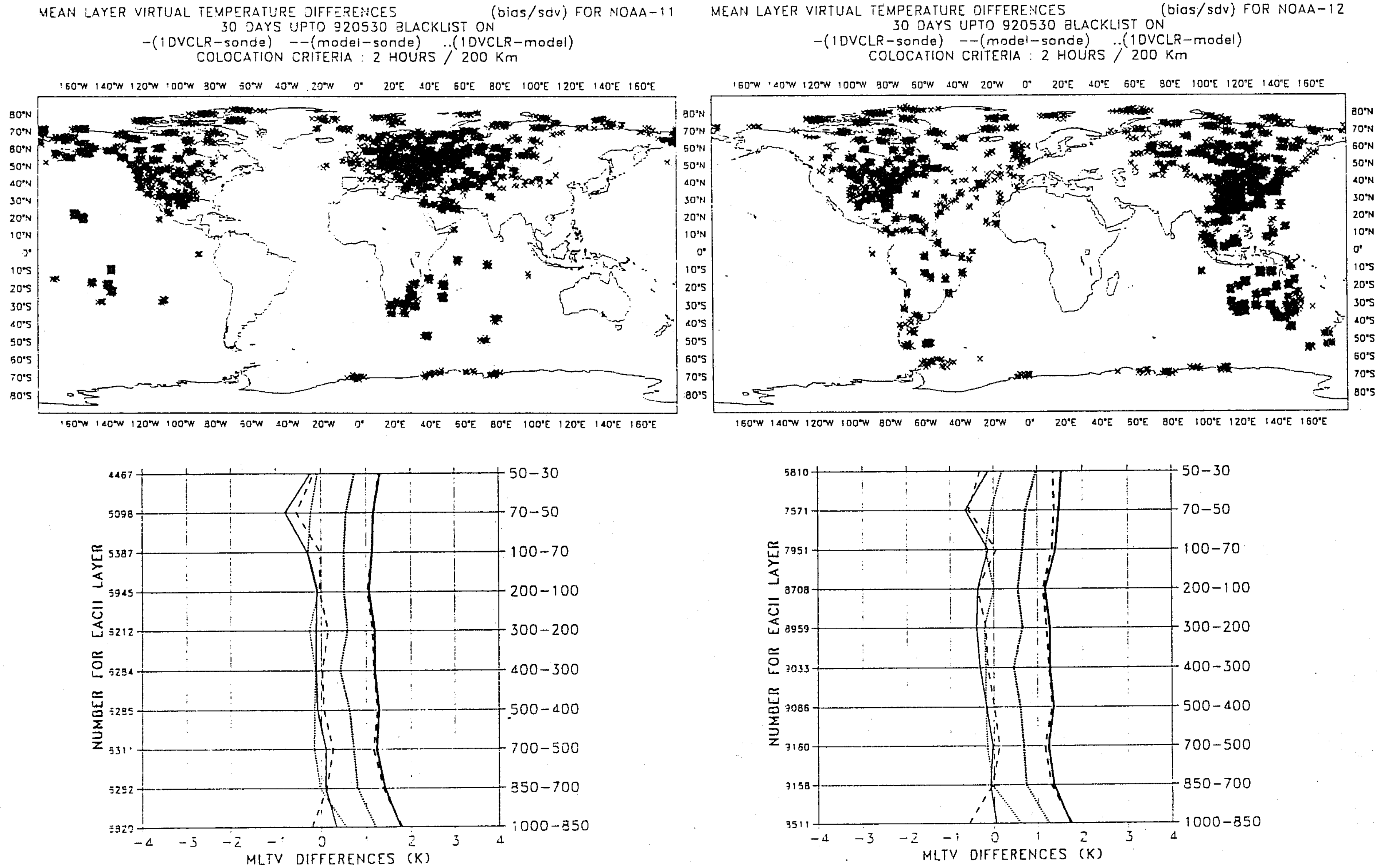

Fig. 3 Example of statistics from COLLOC. Mean and standard deviation of the difference between 1DVAR product and sonde (solid), 1DVAR product and forecast (dashed), and forecast and sonde (dotted). May 1992 for NOAA-11 (left) and NOAA-12 (right).

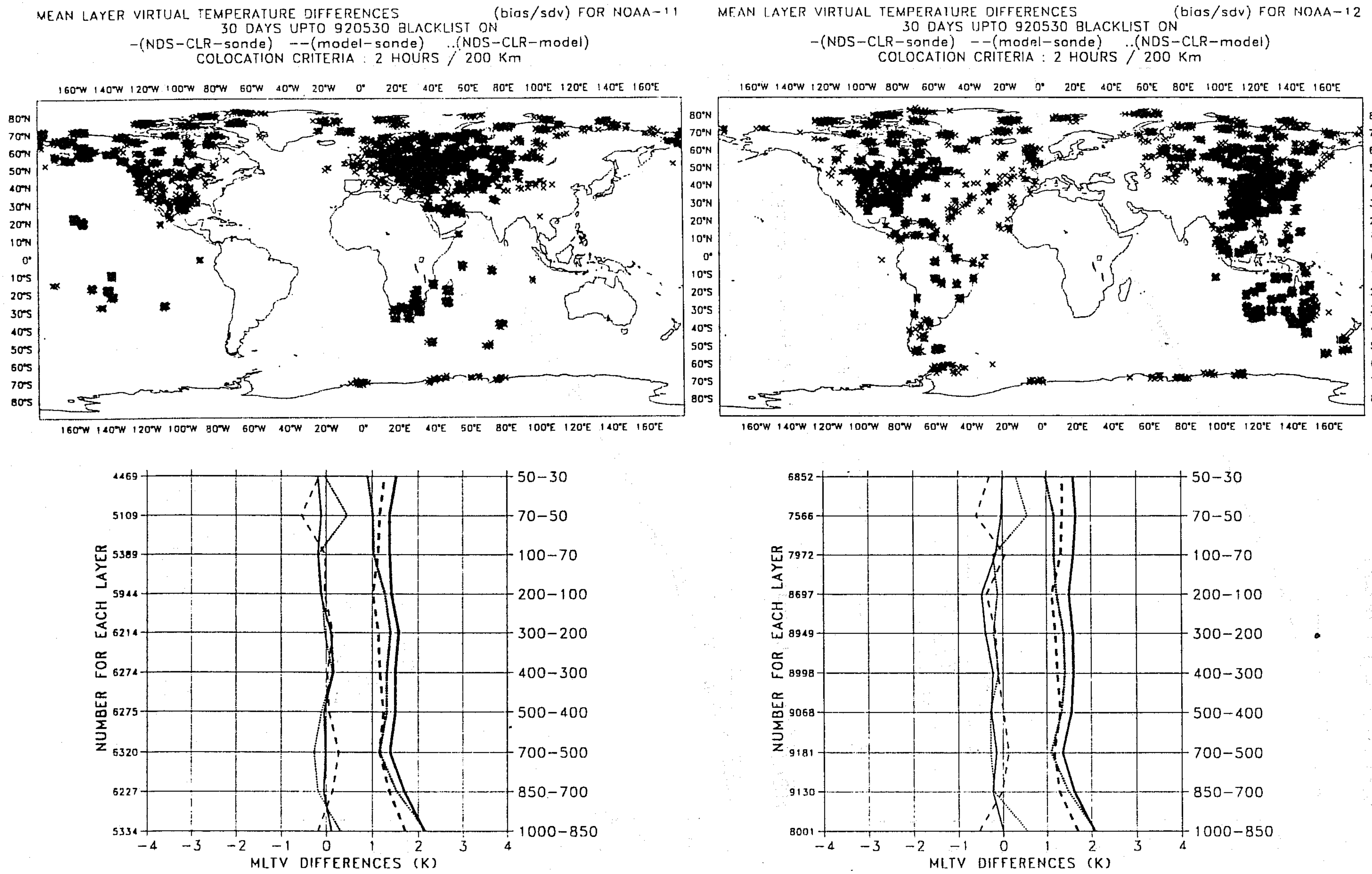

Fig. 4 Example of statistics from COLLOC. Mean and standard deviation of the difference between NESDIS product and sonde (solid), NESDIS product and forecast (dashed), and forecast and sonde (dotted). May 1992 for NOAA-11 (left) and NOAA-12 (right).

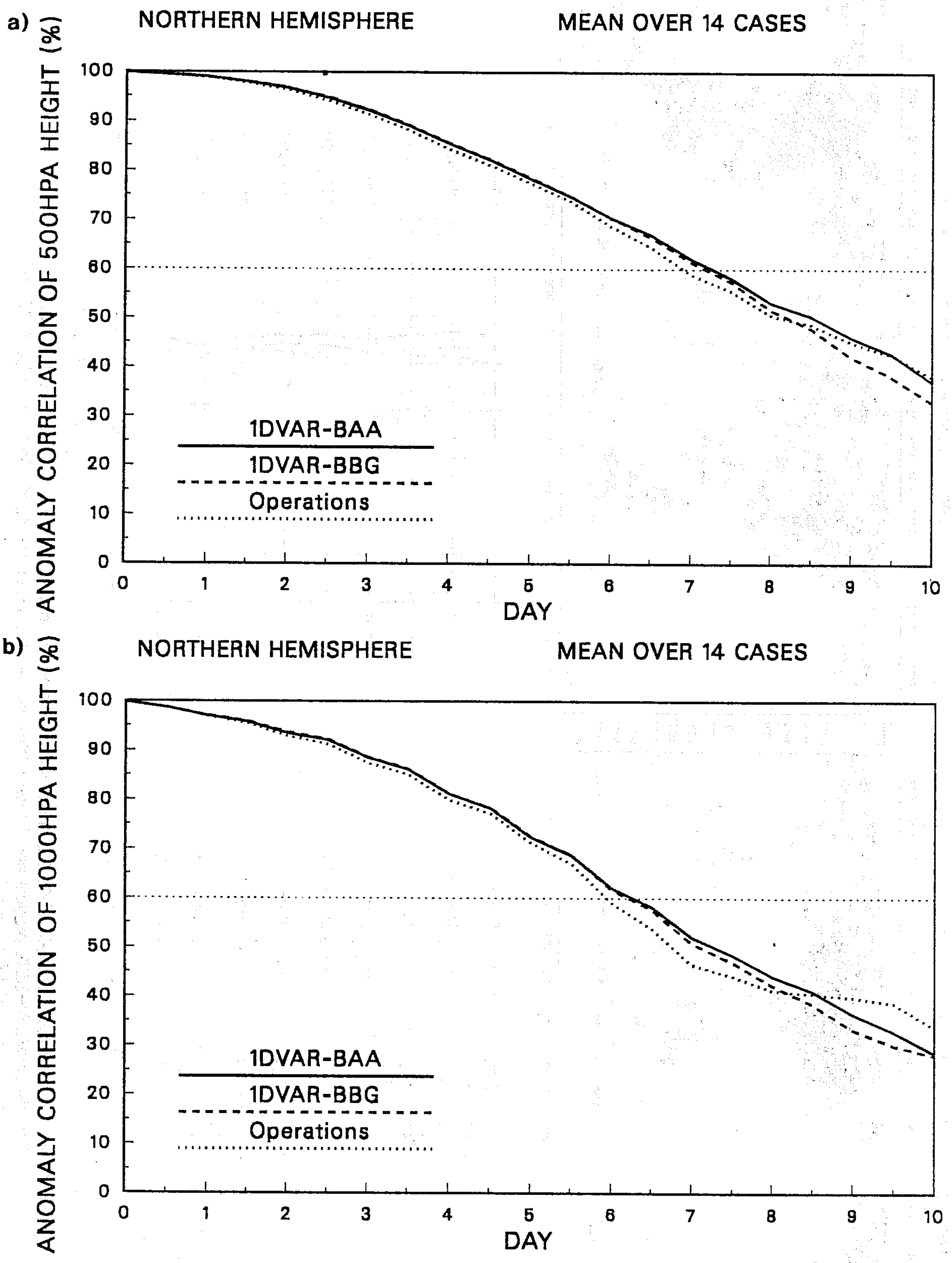

Fig. 5 Results of 1DVAR forecast impact experiments for May 1991.
Mean anomaly correlations for (a) 500 hPa and (b) 1000 hPa height for the northern hemisphere.

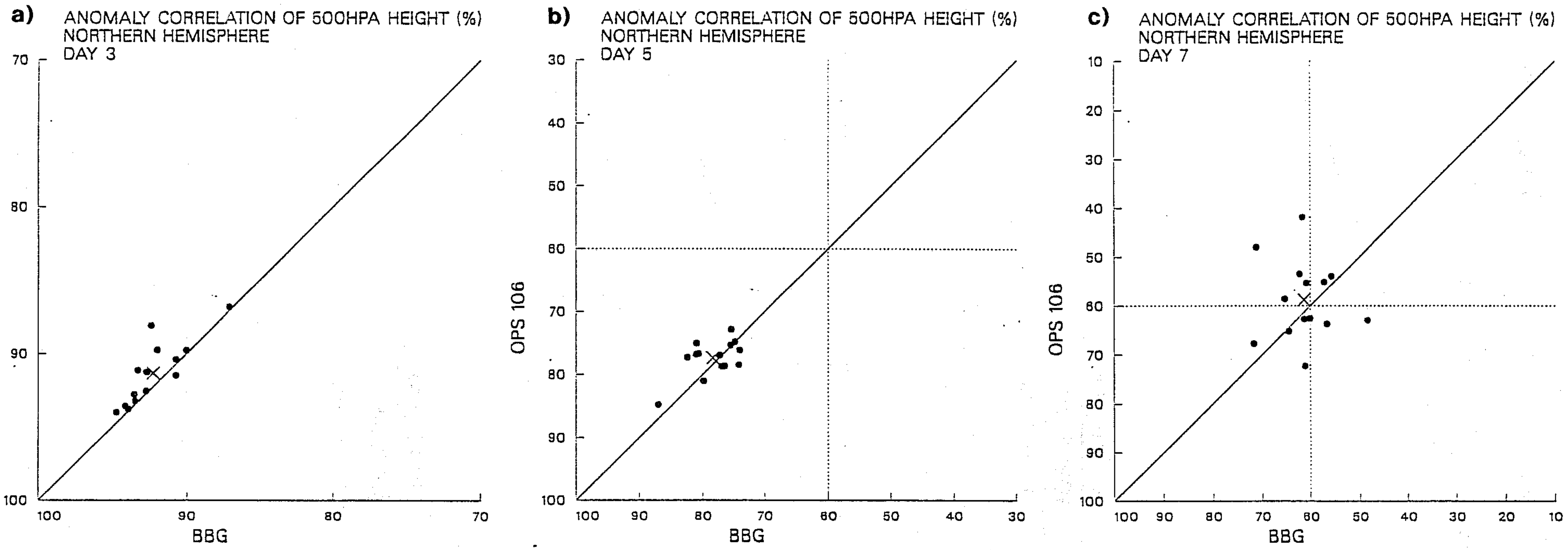

Fig. 6 Results of 1DVAR forecast impact experiments for May 1991.
Anomaly correlations of individual forecasts for 500 hPa height for the northern hemisphere at (a) day 3, (b) day 5 and (c) day 7.

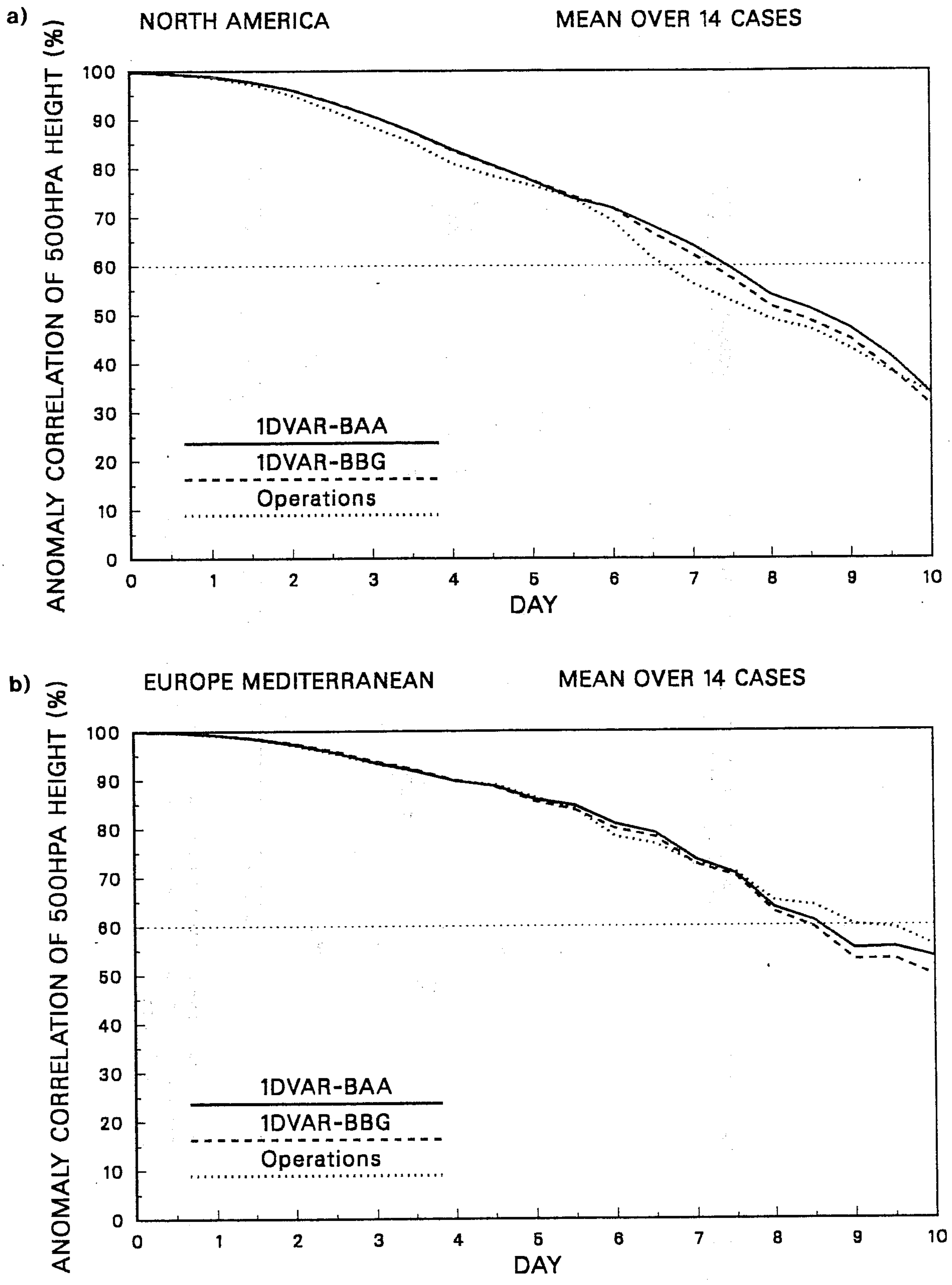

Fig. 7 Results of 1DVAR forecast impact experiments for May 1991.
Mean anomaly correlations for 500 hPa height for (a) North America and (b) Europe and the Mediterranean.

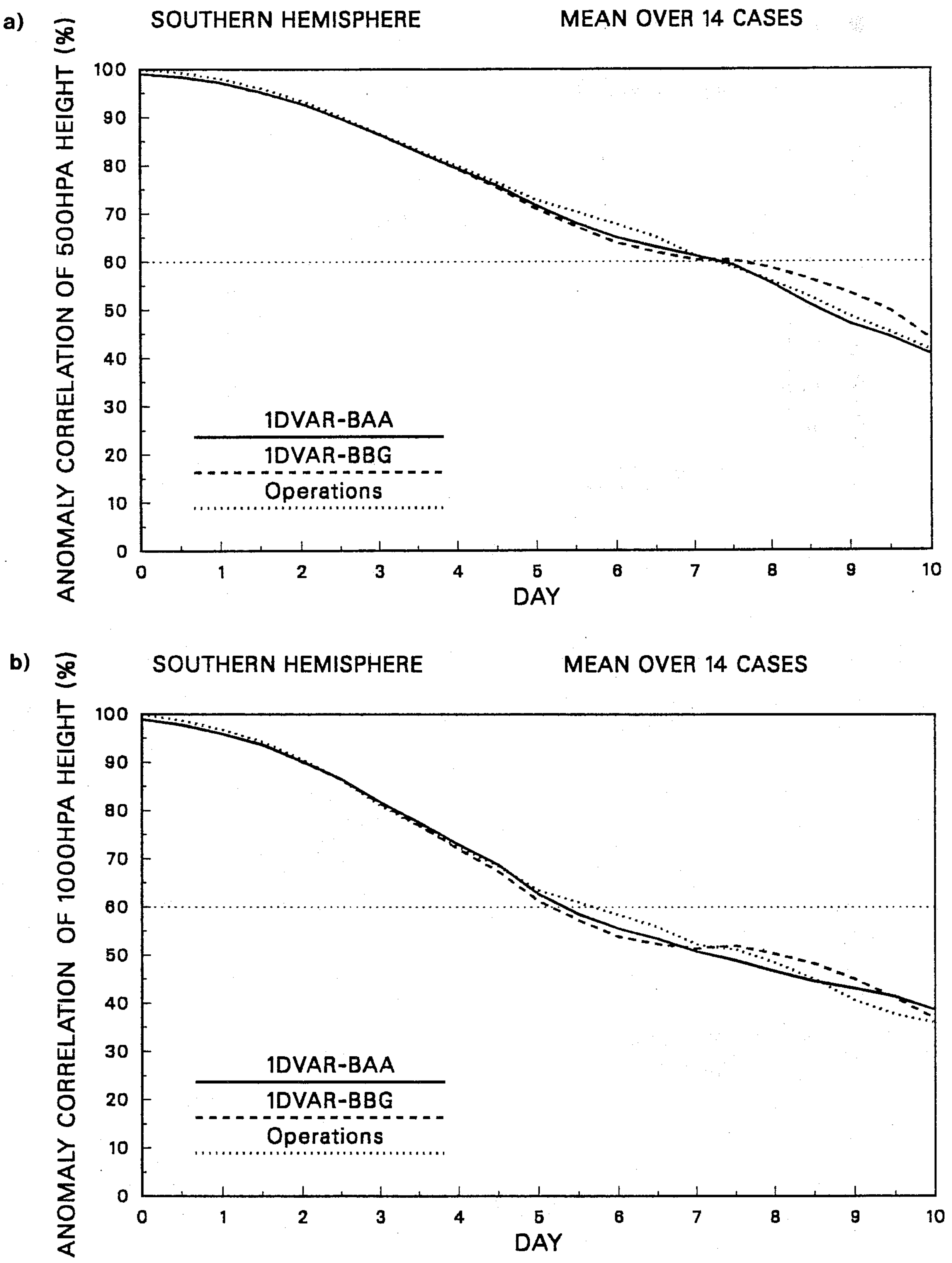

Fig. 8 Results of 1DVAR forecast impact experiments for May 1991.
Mean anomaly correlations for (a) 500 hPa and (b) 1000 hPa height for the southern hemisphere.

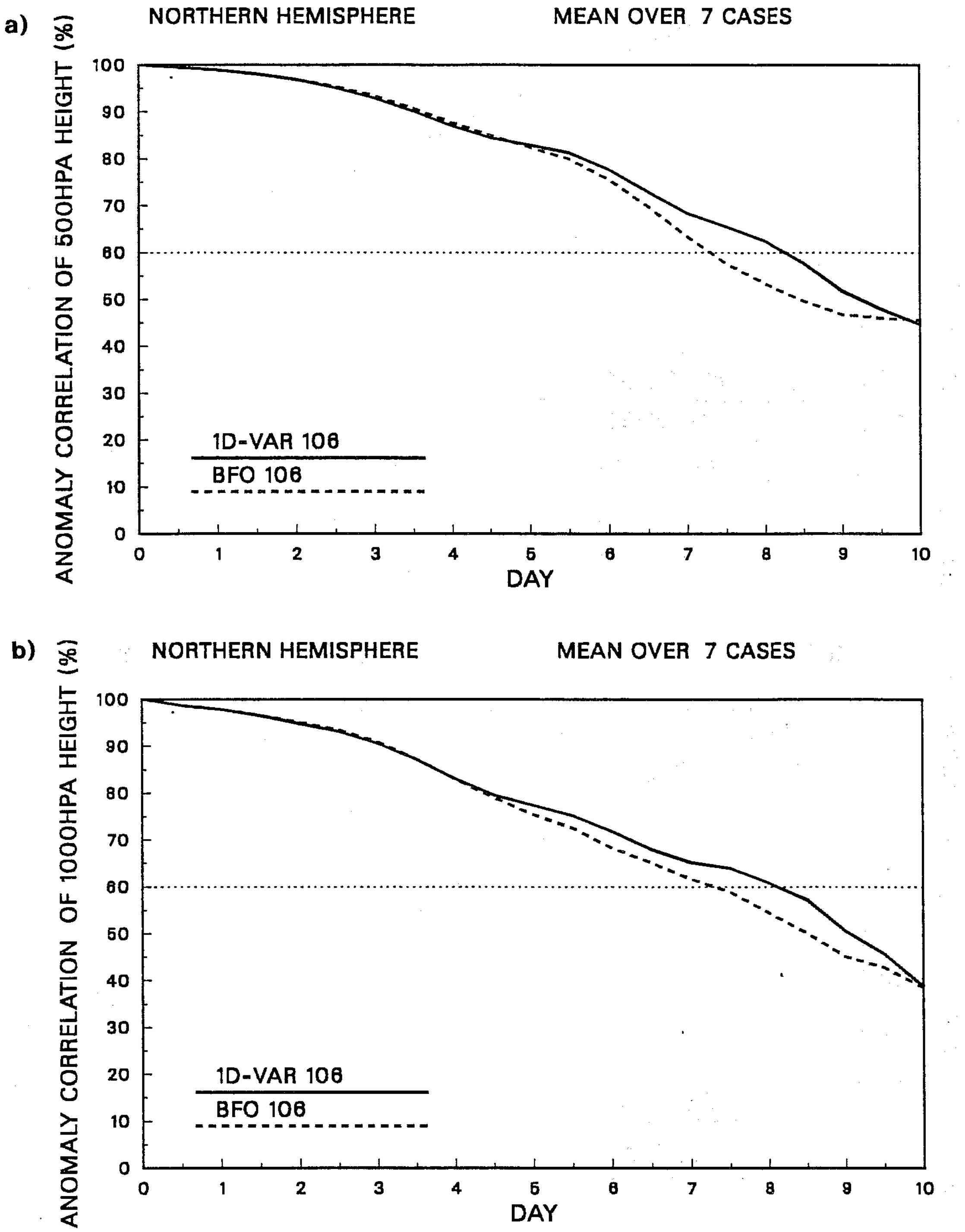

Fig. 9 Results of 1DVAR forecast impact experiments for December 1991.
Mean anomaly correlations for (a) 500 hPa and (b) 1000 hPa height for the northern hemisphere.

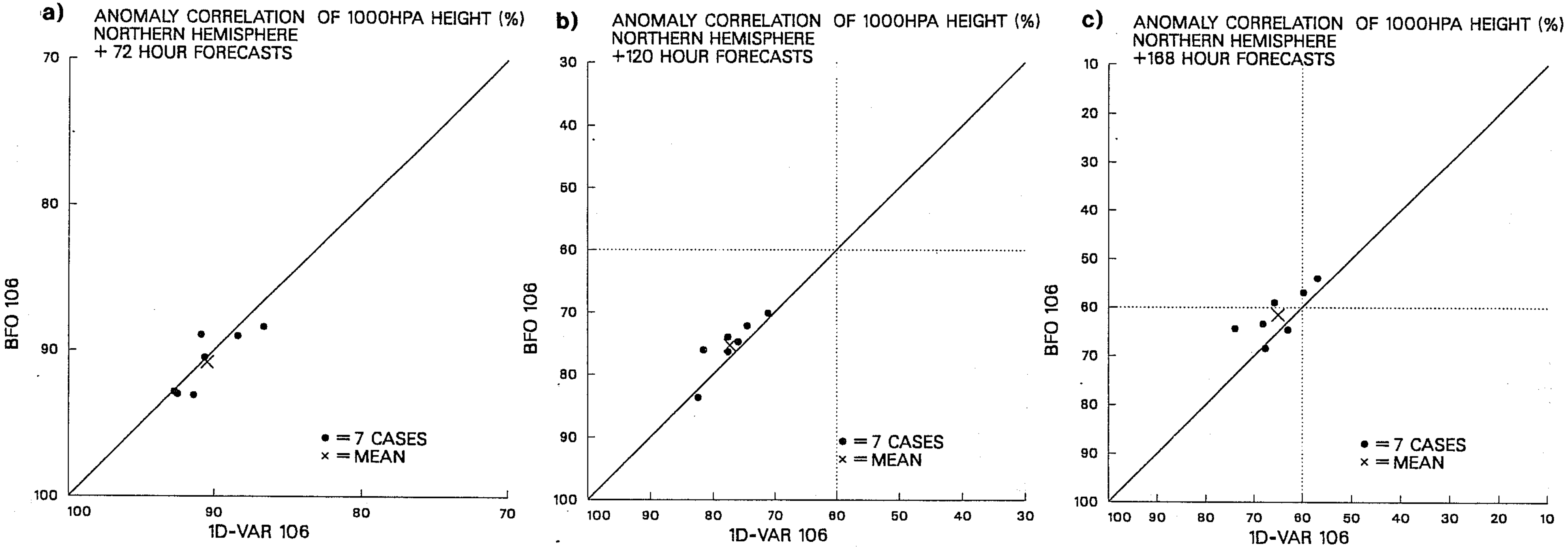

Fig. 10 Results of 1DVAR forecast impact experiments for December 1991.
Anomaly correlations of individual forecasts for 500 hPa height for the northern hemisphere at (a) day 3, (b) day 5 and (c) day 7.

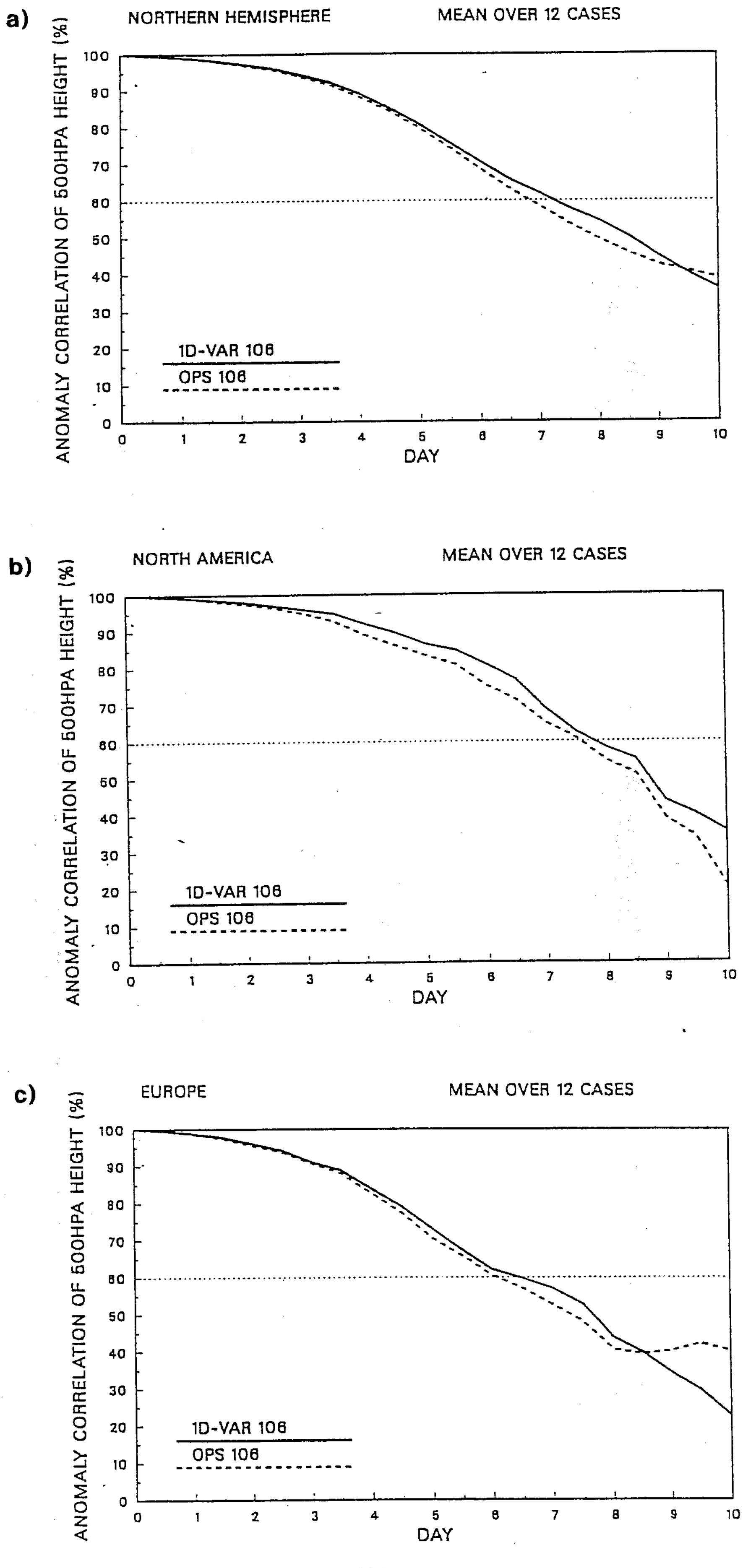

Fig. 11 Results of 1DVAR pre-operational trials in April/May 1992.
Mean anomaly correlations for 500 hPa height for (a) northern hemisphere, (b) North America and (c) Europe and the Mediterranean.

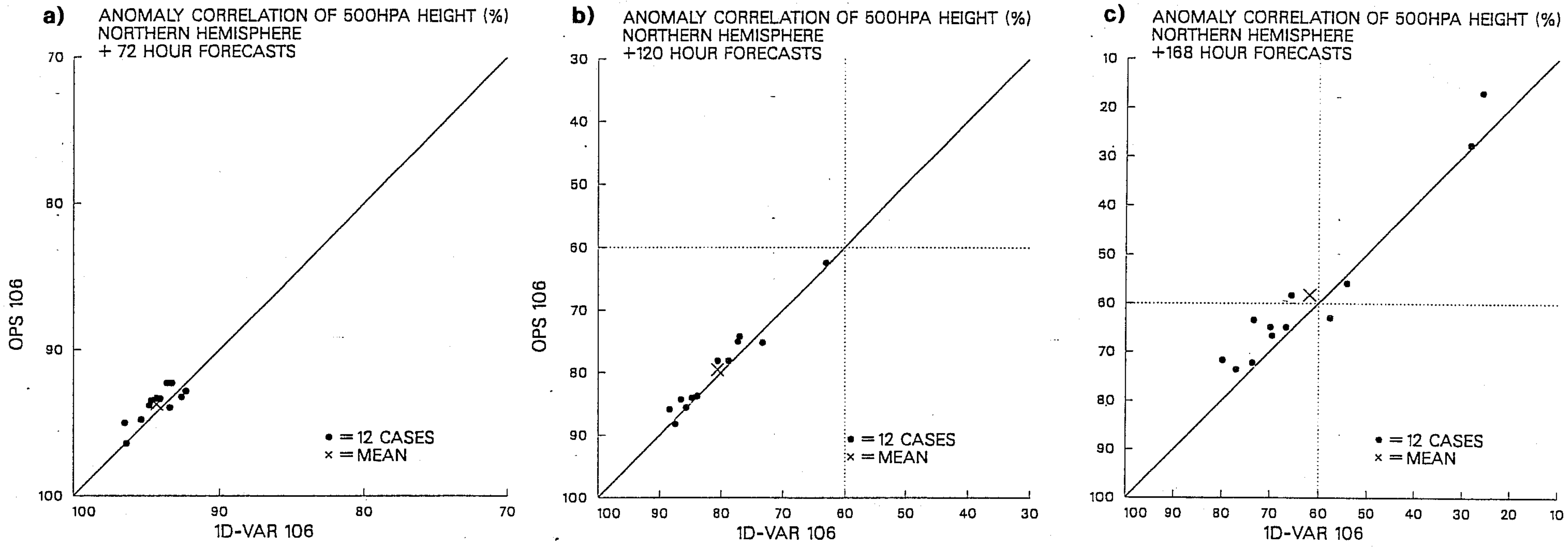

Fig. 12 **Results of 1DVAR pre-operational trials in April/May 1992.**
Anomaly correlations of individual forecasts for 500 hPa height for the northern hemisphere at (a) day 3, (b) day 5 and (c) day 7.

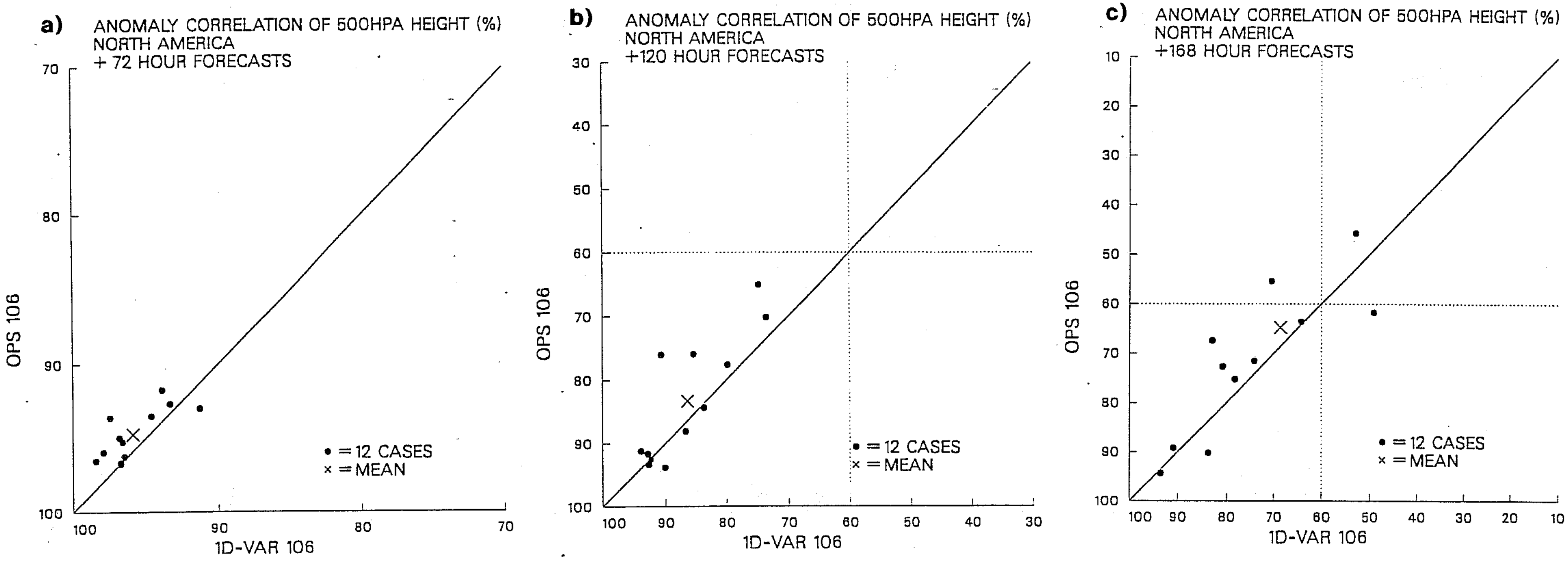

Fig. 13 Results of 1DVAR pre-operational trials in April/May 1992.
Anomaly correlations of individual forecasts for 500 hPa height for North America at (a) day 3, (b) day 5 and (c) day 7.

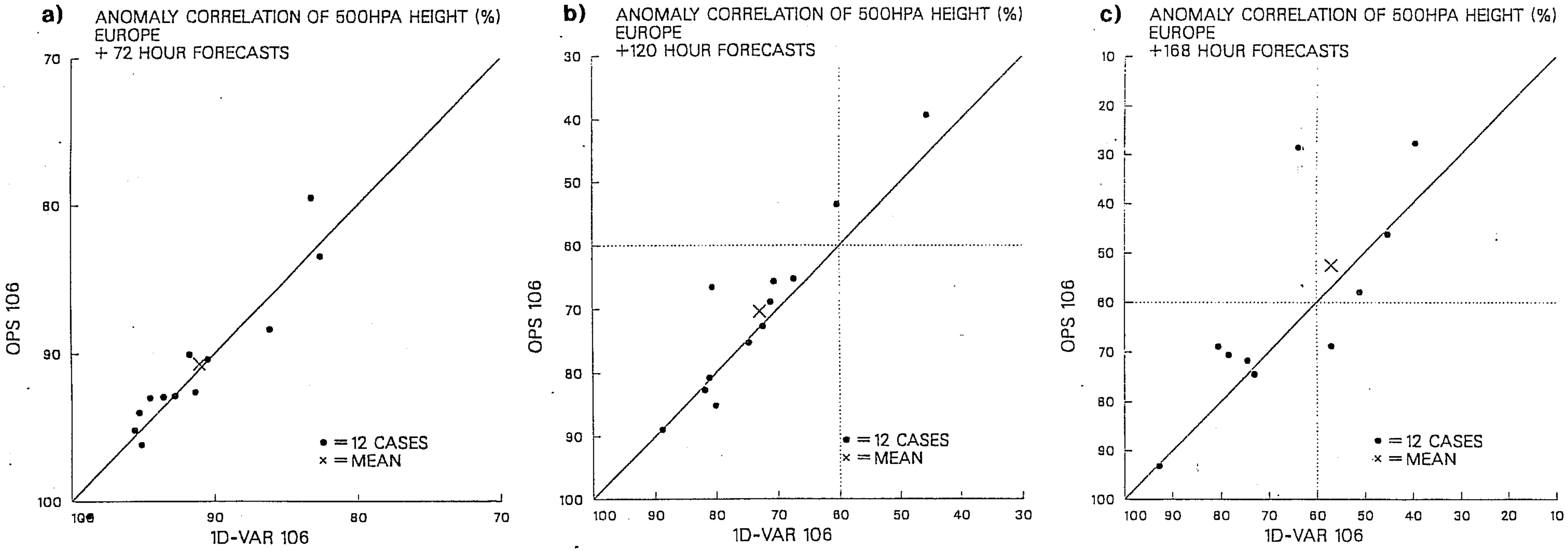

Fig. 14 Results of 1DVAR pre-operational trials in April/May 1992.
Anomaly correlations of individual forecasts for 500 hPa height for Europe and the Mediterranean at (a) day 3, (b) day 5 and (c) day 7.