

Data assimilation by the variational method with results for the Indian region

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सारा — ई. सी. एम. डब्ल्यू. एफ. की प्रचालनात्मक विधि (स्कीम) में जिस ढंग से आँकड़ा संग्रहण की परिवर्तिता पद्धति को उपयोग में लाया गया है, उसके बारे में संक्षेप में यहाँ बताया गया है। उष्णकटिबंधीय चक्रवातों और एशिया की ग्रीष्मकालीन मानसून के संबंध में परिवर्तिता पद्धति (3 डी-वार) के कार्य निष्पादन की जाँच की गई है तथा उसकी तुलना अनुकूलतम अंतर्वेशन (ऑप्टिमम इंटरपोलेशन) स्कीम से की गई है। यह पाया गया कि भूतल के निकट और विशेषकर उष्णकटिबंधीय चक्रवातों की निकटवर्ती तथा अवदाबों की पवनों के विश्लेषण में उल्लेखनीय सुधार हुआ है। बेहतर विश्लेषण के फलस्वरूप ऐसी पद्धतियों के अल्पावधि पूर्वानुमानों (एक से तीन दिन तक) में सुधार हुआ है।

3 डी-वार पद्धति विश्लेषण से ग्रीष्मकालीन मानसून के मामूली से प्रबल होने का पता चलता है, जिससे पश्चिमी घाट और उत्तरी भारत के अधिकांश भागों में अधिक वर्षा का पूर्वानुमान लगाया जाता है। इन दोनों क्षेत्रों में से केवल बाद वाले क्षेत्र के संबंध में प्रेक्षणों से इसकी पुष्टि हुई है। भारत के लिए भू-विभव, पवन और तापमान के पूर्वानुमान के सभी स्तरों में उल्लेखनीय सुधार हुआ है जिसकी हमारे प्रेक्षणों से पुष्टि हुई है। ये परिणाम दो-दो सप्ताह की अवधि के 28 मामलों पर आधारित हैं।

ABSTRACT. The variational method for data assimilation as implemented in the operational scheme at ECMWF is briefly presented. The performance of the variational scheme (3D-Var) with respect to tropical cyclones and the Asian summer monsoon is investigated and compared to the Optimum Interpolation scheme. It is found that the analysis of near-surface winds has improved significantly, particularly in the vicinity of tropical storms and depressions. The better analyses have led to improvements in the short range forecasts (day 1 to day 3) of such systems.

The summer monsoon appears slightly stronger in the 3D-Var analyses, giving enhanced forecast precipitation over the Western Ghats and over large parts of northern India. Only in the latter of these two areas does this verify with observations. The forecasts for India of geopotential, wind and temperature have improved significantly at all forecast ranges, as verified against own analyses. These results are based on 28 cases in two separate 2-week periods.

Key words — Variational assimilation, Objective analysis, Tropical cyclone analysis, Numerical weather prediction, Asian summer monsoon.

1. Introduction

The Indian Ocean is one of the world's major data sparse areas. The uncertainty of forecasts' initial conditions (the analyses) is, therefore, greater there than in many other tropical and subtropical areas. There are intense and extremely important weather events in the Indian Ocean, such as the onset of the Indian monsoon and the occurrence of tropical cyclones, which

in particular require a good specification of the wind field through good quality wind data. The coverage of wind data has recently improved with the availability of observations from the scatterometer instrument of the ERS-1 and ERS-2 satellites. These data indirectly measure the low level wind field over oceans, by measuring the back-scattering of a radar signal reflected by the ocean surface.

This paper gives examples of analysis impact on forecasts for the Indian area by comparison of the results of two different global analysis schemes: the current operational scheme at ECMWF, 3D-Var (Three dimensional variational assimilation), and its predecessor OI (Optimum Interpolation). 3D-Var gives better forecasts for the Indian region than OI did, as will be shown from the objective verification of two 14-day periods in which the two schemes have been run in parallel. The first 14-day period is 24 August to 6 September 1995, *i.e.*, during the Indian Monsoon. The second period is 15-30 January 1996, when tropical depressions formed in the south Indian Ocean.

The three dimensional variational data assimilation scheme has been operational at ECMWF (European Centre for Medium-Range Weather Forecasting) since 30 January 1996. The scheme uses many different types of meteorological observational data and produces global fields of temperature, vorticity, divergence, specific humidity and surface pressure, directly on model levels, for use as initial data in numerical weather prediction. It replaced an Optimum Interpolation scheme which had been providing the initial conditions for ECMWF forecasts since the Centre became operational in 1979. The variational scheme is global in the sense that all vertical levels and all parts of the globe are analysed in a single calculation. This means that all scales from the analysis truncation (currently T63) to the global scale are analysed. There are no artificial boundaries, such as the OI 'analysis-boxes' in the horizontal or in the vertical. This leads to smoother analyses, with less spurious divergence for example.

Another important advantage of the new scheme is that it is more flexible in its use of data. It has been designed to use the TOVS cloud-cleared radiances directly rather than retrieved quantities, such as layer-mean temperatures (Andersson *et al.* 1994). It also makes use of scatterometer wind data (Stoffelen and Anderson 1995, Gaffard *et al.* 1996), which OI did not. This has turned out to be particularly useful in the otherwise data sparse areas such as the Southern Hemisphere oceans and the Indian Ocean. In the Indian Ocean, where there is a lack of good quality cloud motion winds, the addition of scatterometer data has made a real impact on the accuracy of the analysis. Scatterometer data have good spatial resolution and provide, from time to time, accurate measurements of tropical storms. We present a study of analysis and forecast accuracy with respect to tropical cyclones

which has revealed a significant improvement with 3D-Var compared to OI, partly due to the inclusion of scatterometer data. An example of an improved forecast of a tropical depression in the South Indian Ocean is also presented in this paper.

A detailed documentation of the 3D-Var formulation and results is currently being prepared to appear in the literature. This paper gives a brief description of the scheme (section 2) followed by results primarily of relevance to the Indian region. Section 3 describes the experiment setup. In section 4 we present analysis results, with an emphasis on tropical cyclones and in section 5 we focus on the Asian summer monsoon. Forecast verification is presented in section 6. Summary and future outlook are given in section 7.

2. The variational scheme

This section briefly outlines the ECMWF variational analysis scheme. More details can be found in Courtier *et al.* (1993), and in a series of three papers on 3D-Var (Courtier *et al.* 1996, Rabier *et al.* 1996 and Anderson *et al.* 1996) which is currently being prepared. Details on the OI analysis can be found in Lorenc (1981), Shaw *et al.* (1987) and Undén (1989), and the general formulation of OI can be found in Hollingsworth (1987) or Daley (1991).

2.1. General formulation

The variational analysis seeks to minimize a cost function $J(x)$ with respect to the control variable x , which is a representation of the atmospheric state (Talagrand and Courtier 1987). The cost function consists of three terms which measure the degree of mis-fit of x to the observations (J_o), to the background field (J_b) and to the slow manifold (J_c).

$$J(x) = J_o + J_b + J_c \quad (1)$$

$$J_o = [H(x) - y]^T O^{-1} [H(x) - y] \quad (2)$$

$$J_b = (x - x_b)^T B^{-1} (x - x_b) \quad (3)$$

$$J_c = \alpha_g \left| \frac{dG}{dt} \right| \quad (4)$$

where, x_b represents the background field (typically a 6-hour forecast, sometimes called 'first-guess') with the forecast error covariance matrix B . y is the observation vector and O is the covariance matrix

of observation errors, containing both measurement and representativeness errors (Lorenz 1986). H is the ensemble of operators (linear and/or weakly non-linear) transforming the control variable x into the equivalent of each observed quantity. We will call H the 'observation operator', as in Pailleux *et al.* (1991). The J_c term measures the gravity wave tendency with an energy norm (Thépaut and Courtier 1991), with α_g a tuning parameter. J_c is used to reduce the amount of gravity waves in the analysis. It can be shown that for a linear observation operator H , without a J_c term, the variational analysis is theoretically equivalent to the OI analysis (Lorenz 1986).

To reduce the memory and computational cost of 3D-Var an alternative formulation has been described by Courtier *et al.* (1994). Following their formulation the observation increments are computed at high resolution (typically triangular spectral truncation T 213) and the minimisation is performed at a lower resolution (typically T 63).

In a variational scheme, the comparison between model and observation takes place in terms of the observed quantity. Model equivalents of the observed quantities are calculated by applying a specific operator H for each type of observation. The observation operators can be a function of any analysis variables as well as any other model variables, auxiliary parameters and constants. The analysis variables (or 'control variables') will be adjusted by the variational scheme such that the fit between model and data is improved.

2.2. Mass/wind balance

The J_b part of the total cost function is defined in Hecklet *et al.* (1992) and Courtier *et al.* (1993, 1996). Multivariate balance is imposed on the increments by J_b using Hough-mode separation and penalisation of the gravity modes, which provide a mass/wind coupling over the whole globe. It is assumed that approximately 10% of the forecast error variance lies in the gravity wave part of the flow and 90% in the Rossby part. In the separation between Rossby and gravity waves all vertical modes are used. Horizontal modes used are those corresponding to vertical modes 1 through 7. Beyond vertical mode 7 the same set of horizontal modes are used for all higher modes. The control variable x consists of the mass-variable p ,

vorticity, divergence and specific humidity in spectral space, where
$$p = \sum_{i=1}^L RT_i \Delta \ln P_i + RT_r \ln p_s$$

where T is temperature, T_r is the reference temperature = 270° K, and p_s is surface pressure.

The mass/wind balance is gradually relaxed towards the equator, between 30 degrees north and south and the analysis is univariate within five degrees of the equator. This is in accordance with findings reported by Daley (1996) which show that Hough mode balance as well as linear balance are both inappropriate for tropical analysis. The actual tropical mass/wind balance is governed by a mix of dynamical and physical (diabatic) processes, such as latent heat release from convective precipitation.

2.3. Structure functions

The specification of forecast error statistics assumes homogeneous and isotropic correlations with a horizontal variation of the forecast error variances (as in ECMWF OI), but in 3D-Var the formulation does not, however, assume separability between the vertical and horizontal directions. A fully 'non-separable' formulation is used (Rabier *et al.* 1996) based on statistics derived by Rabier and McNally (1993) in a study of differences between 24 and 48 hour forecasts, valid at the same time, a technique proposed by Parrish and Derber (1992). The broadness of the vertical structure functions in 3D-Var depends on the horizontal scale, and the shape of the horizontal correlations depends on vertical level. The vertical correlations are generally sharper (broader) for smaller (larger) horizontal scales. The horizontal correlations are generally broader in the stratosphere than in the troposphere.

A non-separable specification of background errors has three distinct advantages over the traditional separable formulation (Phillips 1986): (i) It allows broader vertical correlations for mass than for wind; (ii) It gives sharper horizontal correlations for temperature than for mass and (iii) It accounts for the broadening of the horizontal scale with increased altitude. These general features of the background errors have been reported in observational studies, such as Hollingsworth and Lönnberg (1986) and Lönnberg and Hollingsworth (1986), but for practical reasons were only partly accounted for in OI analysis schemes.

2.4. Minimisation

The variational formulation allows the analysis problem to be solved globally but not *exactly*. An approximate solution is found through a number of iterations of a minimisation algorithm. The scheme seeks to minimise the cost-function. For each iteration the minimisation requires the calculation of the cost-function and its gradient with respect to the model variables. Given the value of the cost-function and its gradient, the minimisation algorithm finds an updated model state, with a smaller cost-function. The process is iterated until convergence, or until the predefined maximum number of iterations have been reached. We currently allow a maximum of 70 iterations in 3D-Var. The minimisation algorithm used (M1QN3, Gilbert and Lemaréchal 1989) is based on the limited memory quasi-Newton method.

The cost-function consists of just one number (a scalar) but the gradient has the same dimension as the model, in the order of 10^6 . The most efficient way to calculate the gradient is through the application of the *adjoint* technique. The cost of calculating the gradient with the adjoint technique is typically only two to four times the cost of calculating the cost-function.

3. Description of experiments

In this paper we extract results of relevance for the Indian area, from the pre-operational tests of 3D-Var. We present analysis and forecast results from two data assimilation experiments at full operational resolution (T 213) comparing 3D-Var and OI. In these two periods each covers 14 days: 950824 to 950906 and 960116 to 960130. They have been selected here because they were run with exactly the system that later became operational at ECMWF.

The experiments started with identical initial conditions, using the same sets of conventional observational data: radiosondes, synop, buoys, aircraft data, cloud motion winds, pilot winds, and paobs. 3D-Var used TOVS radiances, instead of retrieved thicknesses (Andersson *et al.* 1994, 1996, McNally and Vesperini 1996). In addition, scatterometer data were used in 3D-Var (Gaffard *et al.* 1996) but not in OI.

The forecast model version used in these experiments (internally labelled cy 13r4) includes the prognostic cloud scheme of Tiedke (1993), mean orography and a new parameterisation of subgrid scale orography (Lott and Miller 1996).

4. Analysis results

4.1. Fit to data

Accumulated statistics of rms of observation-minus-analysis (obs-an) show how closely an analysis scheme fits the observed data, whereas observation-minus-background (obs-bg) statistics give an indication of the quality of the background (6-hour forecasts) of the assimilation. Fig. 1 shows profiles of obs-an (dashed) and obs-bg (full lines) for all used Indian and neighbouring radiosonde wind data, within 5° to 25° N and 70° to 90° E, for the 14-day period from 950824-12 to 950906-12 UTC. It appears that OI (Fig. 1b) fits the observed winds much closer than 3D-Var. The OI rms of obs-an is between 1.8 and 2 m/s within the troposphere for both u and v components, whereas the corresponding statistics for 3D-Var are 2 m/s at the lowest levels increasing to approximately 3.5 m/s at 200 hPa.

The obs-bg statistics (full lines in Fig. 1), on the other hand, indicate a comparable forecast performance of the two schemes. Both show an rms of approximately 3 m/s at the lowest levels, increasing to a maximum at the jet-level of about 8 m/s in the u -component and 6 m/s in the v -component. The rms of the 3D-Var obs-bg for the u -component is even slightly better than for OI between 400 and 70 hPa.

We shall see later in this section that the poorer obs-an fit is a consequence of the 3D-Var analyses being smoother than the OI analyses. The obs-bg departures are nevertheless as good as or better than OI, which is a clear indication that the smoother 3D-Var analyses produce an assimilation of similar accuracy to OI. These results could also be interpreted as an indication of excessive noise in the OI analysis, caused by fitting the data too closely, without benefit to the 6-hour forecast quality.

4.2. Structure of analysis increments

Maps of analysis increments (analysis minus background) of wind clearly show that the 3D-Var analyses are, as suspected, smoother than OI. Fig. 2 shows vector wind increments at 850 hPa for 3D-Var in Fig. 2(a) and OI in Fig. 2(b). There are several areas where the OI increments abruptly change magnitude or direction between successive grid points, whereas 3D-Var appears smoother. This characteristic is further emphasised in analysis of increments of divergence (Fig. 2c & d). We can see that OI has

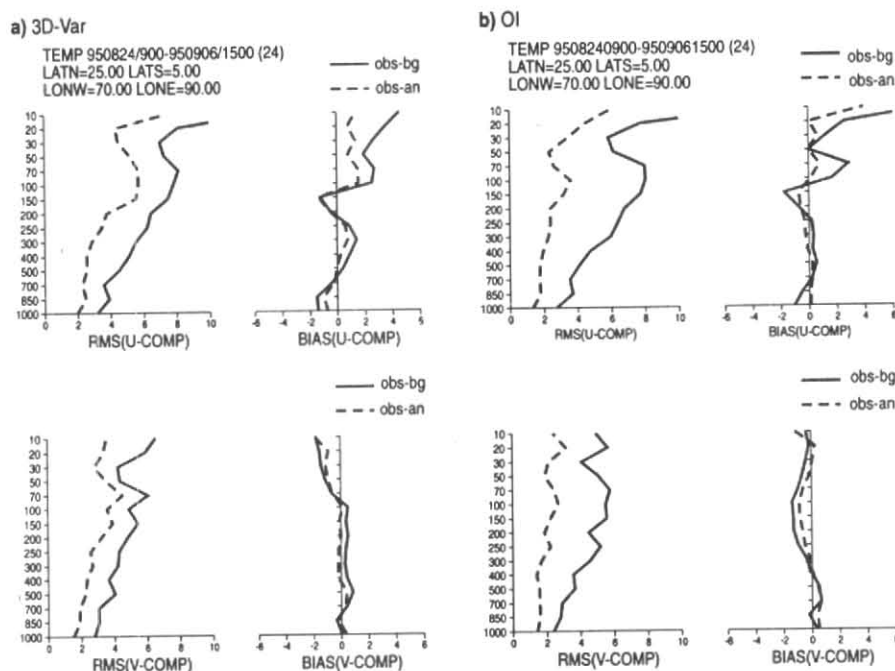


Fig. 1. Rms difference in u and v -components, left hand diagrams, and bias, to the right, of observation-minus-analysis (dashed) and observation-minus-background (full line), for all used radiosonde wind data in the Indian area (within 5° - 25° N and 70° - 90° E), for the 14-day period from 950824-12 to 950906-12 UTC. Fig. 1 (a) shows 3D-Var and (b) shown OI

fitted the wind data along the west coast of India by introducing strong divergence between the wind data, whereas 3D-Var in relation has suppressed the divergence. The OI wind increments are also more divergent/convergent in high orography, such as the Himalayas.

There are several explanations for the different analysis behaviour: (i) The background errors for wind are unrealistically high in OI, and much lower in 3D-Var (Rabier *et al.* 1996), especially between 20° and 30° N; (ii) OI uses sharper vertical correlations in the tropics than in the mid-latitudes, whereas 3D-Var applies the vertical correlations in spectral space, uniformly for the whole globe. This leads to stronger vertical filtering in 3D-Var than in OI, in the tropics and (iii) The OI analysis is performed locally in so called 'analysis boxes', which creates artificial divergence along box edges, and reduces horizontal filtering.

4.3. Near-surface wind and tropical cyclone analysis

Fig. 3 shows an example of an analysis of a tropical cyclone, in this case tropical cyclone Karen in the Caribbean on 31 August 1995. Fig. 3(a) shows the observed scatterometer winds for an orbit

which passes directly over the cyclone position (indicated by a large dot, at 20° N, 52° W). Fig. 2(b) shows the background (six-hour forecast) valid at the same time and Fig. 2(c) shows the 3D-Var analysis. The OI analysis is not shown, but is similar to the background field in this case because few conventional data exist in this area, and ECMWF OI does not use scatterometer wind data. We see that the 3D-Var in using the ERS-1 winds has produced a good analysis of the cyclone. In every ERS-1 location 3D-Var has the choice between two equally probable winds with approximately opposite directions. This very rarely leads to any difficulties; the wind analyses are always horizontally consistent (Gaffard *et al.* 1996).

Our second example is a tropical depression in the Indian Ocean, located just off the south eastern coast of Madagascar, on the 24 January 1996, 1200 UTC. The Tropical Cyclone Centre at La Reunion reported a centre of 1003 hPa and near-gale force winds at 30 knots (15 m/s). The Meteosat visible image is shown in Fig. 4, overlaid with the mean sea level pressure contours of the 48-hour forecasts from the 3D-Var and OI assimilations. We see that the 3D-Var forecast is deeper (1005 hPa) and located in the correct position, which is clearly superior to the operational forecast which has a centre of 1008

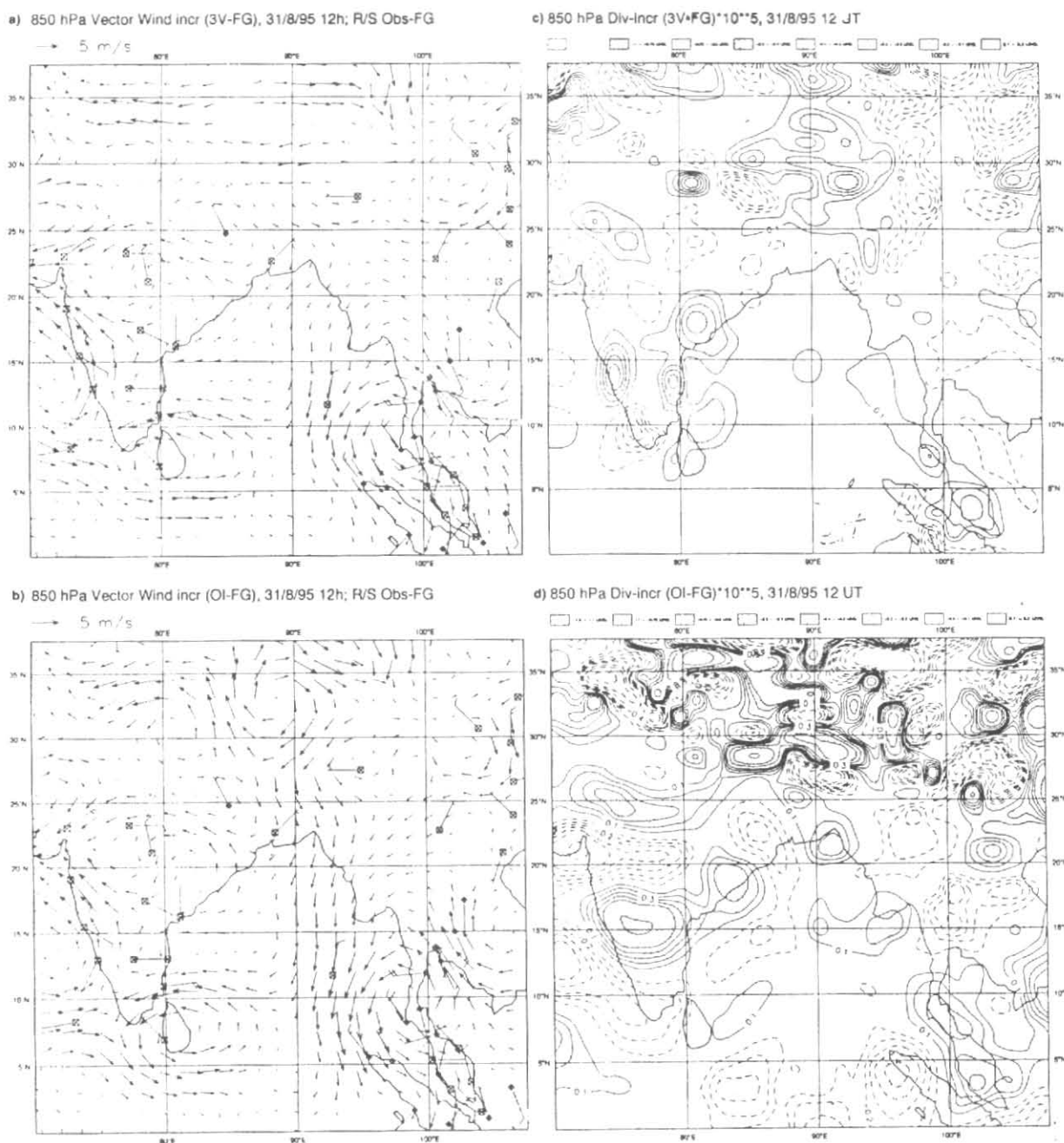


Fig. 2. Vector wind increments at 850 hPa, 31 August 1995, for (a) 3D-Var and (b) OI. Observed minus background wind differences from used radiosonde reports are also shown. Panels (c) and (d) show the corresponding divergence increments

hPa, located too far to the southwest. These forecasts were based on initial data at 22 January 1200 UTC. At 0600 UTC that day an orbit of ERS-1 scatterometer data crossed the area and detected a tropical disturbance - the incipient depression.

We have presented two very striking examples of what appears to be favourable impact from the addition of scatterometer data in 3D-Var. It is

conceivable that other factors also contribute to the improvement, as a more systematic study remains to be made. Nevertheless, over a longer experiment period, using an earlier pre-operational version of 3D-Var, a significant improvement of the definition of the analysed wind field in and around tropical cyclones has been observed. Table 1 shows the result of a subjective study of all reported tropical cyclones (hurricanes, typhoons and tropical storms) in the

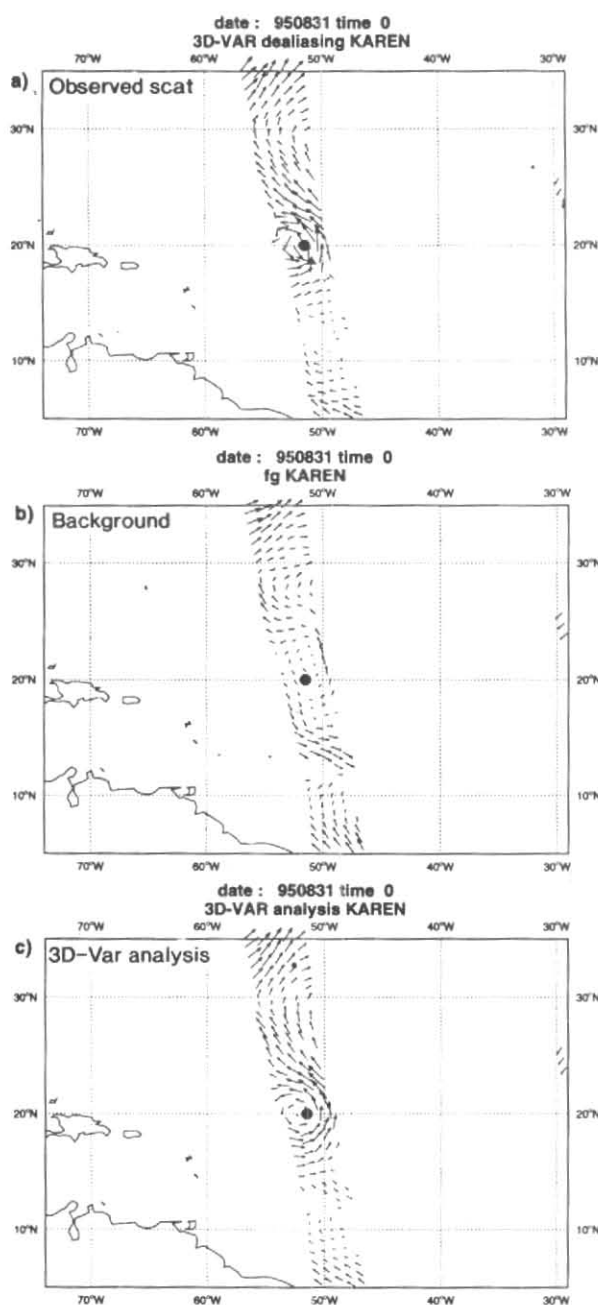


Fig. 3. Tropical cyclone Karen, 31 August 1995. Panel (a) shows the observed scatterometer winds for an orbit which passes directly over the cyclone position (indicated by a large dot, at 20°N, 52°W), (b) shows the background (six-hour forecast) valid at the same time, and (c) shows the 3D-Var analysis, interpolated to observation locations

period between 19950828 and 19950918 comparing the position and intensity of the cyclones in the 3D-Var and OI analyses and forecasts. Most of the cases occurred in the Caribbean or in the western Pacific and South China Sea. In a sample of 65 cyclone analyses 29 were improved, 30 were equal

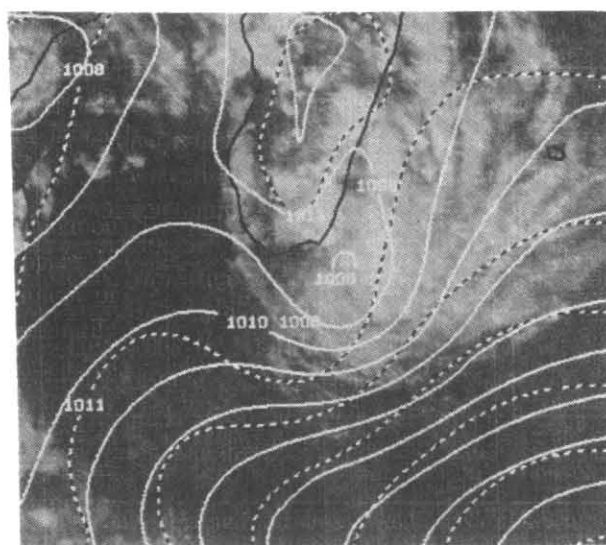


Fig. 4. Part of METEOSAT visible image, 960124 1200 UTC, showing a tropical disturbance to the south-east of Madagascar. The 48-hour forecast 1000 hPa geopotential is countoured light grey for 3D-Var and darker grey for OI

TABLE 1

Subjective study of tropical cyclone position and intensity in analyses and forecasts, comparing 3D-Var with OI. The sample includes all hurricanes, typhoons and tropical storms in the period from 19950828 to 19950918

3D-Var	An	Day 1	Day 3	Day 5	Day 7
Improved	29	23	25	16	12
Neutral	30	32	26	32	18
Worse	6	10	14	12	6

and 6 were worse. The improved analyses led to better forecasts in the short range, day 1 to day 3, as shown in Table 1.

5. Performance during summer monsoon

The performance of the ECMWF model during the Asian summer monsoon was studied by Das *et al.* (1995). They studied the impact of a series of changes to the ECMWF forecast model that became operational in April 1995: a new prognostic cloud scheme; mean orography; a new parameterisation of the subgrid scale orography; and changes to the semi-Lagrangian scheme. The same version of the model (cy 13r4) has been used in these experiments. Das *et al.* (1995) reported an overestimation of rainfall over the Western Ghats and an underestimation of convective rainfall over some inland parts of India. In this section we will

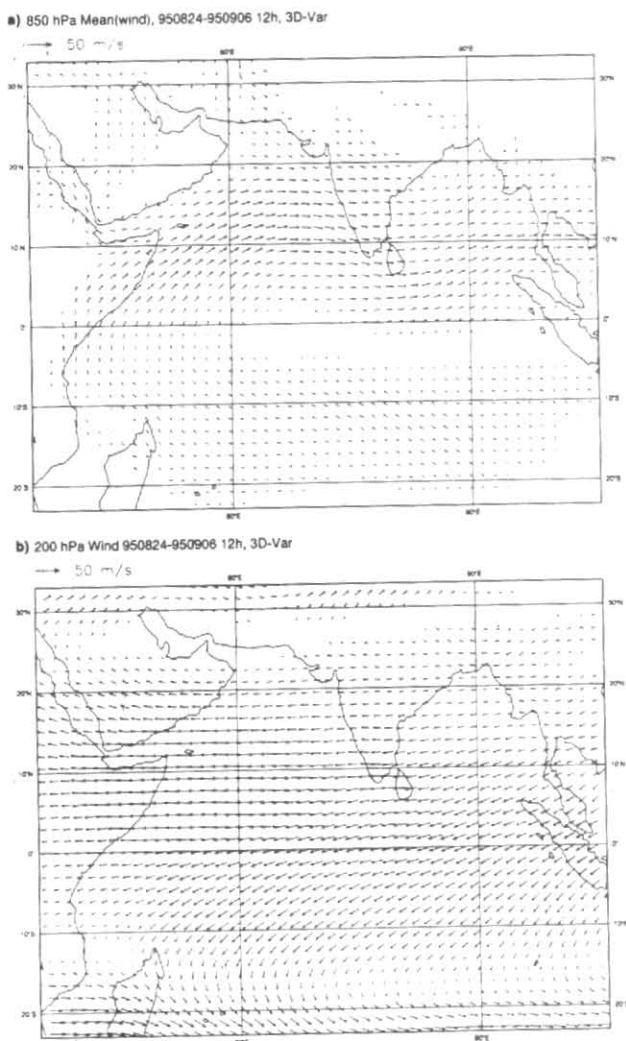


Fig. 5. Fourteen day mean 3D-Var analysed wind, 950824 to 950906, 1200 UTC at (a) 850 hPa and (b) 200 hPa. The unit wind vector as given in the legend is 50 m/s

investigate the impact of the change of analysis scheme on the monsoon circulation and rainfall.

The summer monsoon circulation typically establishes itself in late May, peaks in July and breaks up towards the end of September (Ju and Slingo 1995, Figs. 1 & 2). It is characterized by low level easterlies to the south of the equator and strong westerly winds from Somalia towards India - the Somali Jet. The mean flow at 200 hPa is westerly to the south of the Equator and easterly to the north, *i.e.*, there is a strong vertical wind shear in the region of the Somali Jet.

The mean flow, in the studied two week period (950824 to 950906), at 850 hPa and at 200 hPa is shown in Fig.5, as obtained from the 3D-Var experiment. We can recognize the climatological

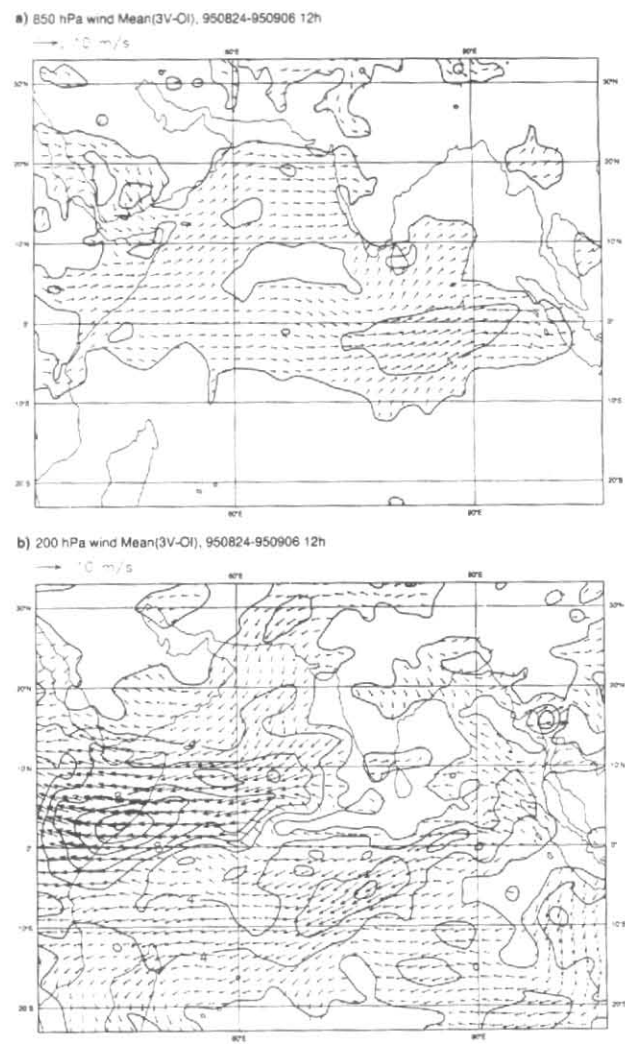


Fig. 6. Like Fig. 5, but showing the mean difference between 3D-Var and OI analysed winds, at (a) 850 hPa and (b) 200 hPa. The unit wind vector as given in the legend is 10 m/s. The magnitude of the vector wind difference is contoured with an interval of 2 m/s

features mentioned above. The difference between 3D-Var and OI is shown in Fig. 6, for both levels. We can see that the monsoon circulation is stronger in 3D-Var. The Somali Jet is upto 2.4 m/s stronger and the easterly flow at 200 hPa is upto approximately 3 m/s stronger. The cross-section along 15°N in the Arabian Sea and across the Indian subcontinent (Fig. 7) confirms the mean strengthening of the flow, and shows an increased upward motion over parts of India. Fig. 6 also shows a weakening by 4 m/s of the low-level easterlies along the equator to the west of Sumatra.

These changes in mean flow are associated with changes in precipitation. The average daily

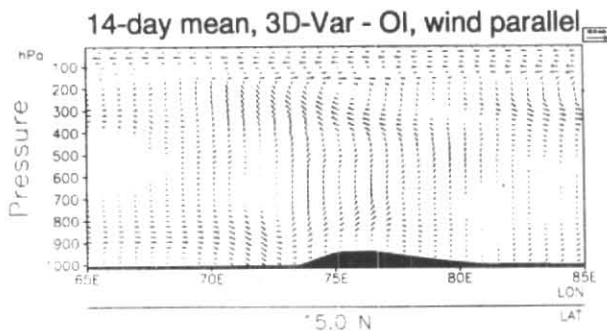


Fig. 7. Fourteen day mean analysed wind difference (3D-Var minus OI) in the cross section along 15°N, dates corresponding to Fig. 5

accumulated large scale plus convective precipitation in the 24 to 48-hour forecasts for the study period is presented in Fig. 8(a) 3D-Var, and Fig. 8(b) OI. The plotted numbers show the difference between forecast and measured precipitation at all stations from which at least 10 reports were received during the 14-day period. We can see that both sets of forecasts share the same tendency to overpredict the rainfall along the Western Ghat and to underpredict the rainfall in many inland areas, reported by Das *et al.* (1995) as being typical of the current ECMWF

forecast model. The main differences between the two rainfall forecasts are : (i) the heavy precipitation along the west coast of India has further intensified in the forecasts from 3D-Var (a negative result), (ii) it extends further northwards (positive), (iii) the underprediction in the lee of the Ghat mountains is unchanged (neutral) and (iv) the precipitation further to the north has increased by approximately 2 mm per day (positive) which at many stations has reduced the error. Another significant change occurs on the slopes of the Himalayas, where forecasts from 3D-Var give much less rain than forecasts from OI, the accuracy of which is, however, impossible to verify due to the lack of observational data in that area.

6. Forecast results

In this section we present the forecast results from two data assimilation experiments at full operational resolution (T213), as described in section 3. The results for the two periods have been averaged together, although they cover two separate seasons. In Fig. 9 we show the average root mean square (rms) of forecast error for both schemes as verified against own analyses. The Indian area is here defined as 5° to 32.5°N and 75° to 102.5° E. Figs. 9 (a) & (b) show forecast

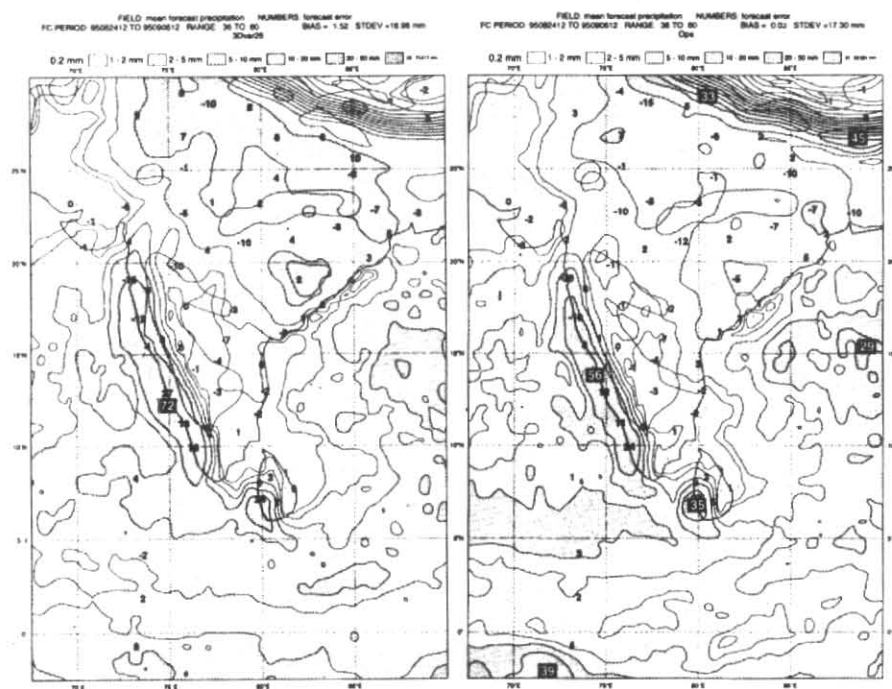


Fig. 8. Average daily precipitation during the second day of forecasts (*i.e.*, 48 minus 24 hour precipitation) from 1200 UTC each day during the 14-day period 950824 to 950906, 1200 UTC. Panel (a) shows 3D-Var and (b) shows OI. Numbers at observation locations indicate mean difference between observed and predicted rainfall, at all stations reporting at least ten of the 14 days. The larger framed numbers indicate local maxima of mean forecast precipitation

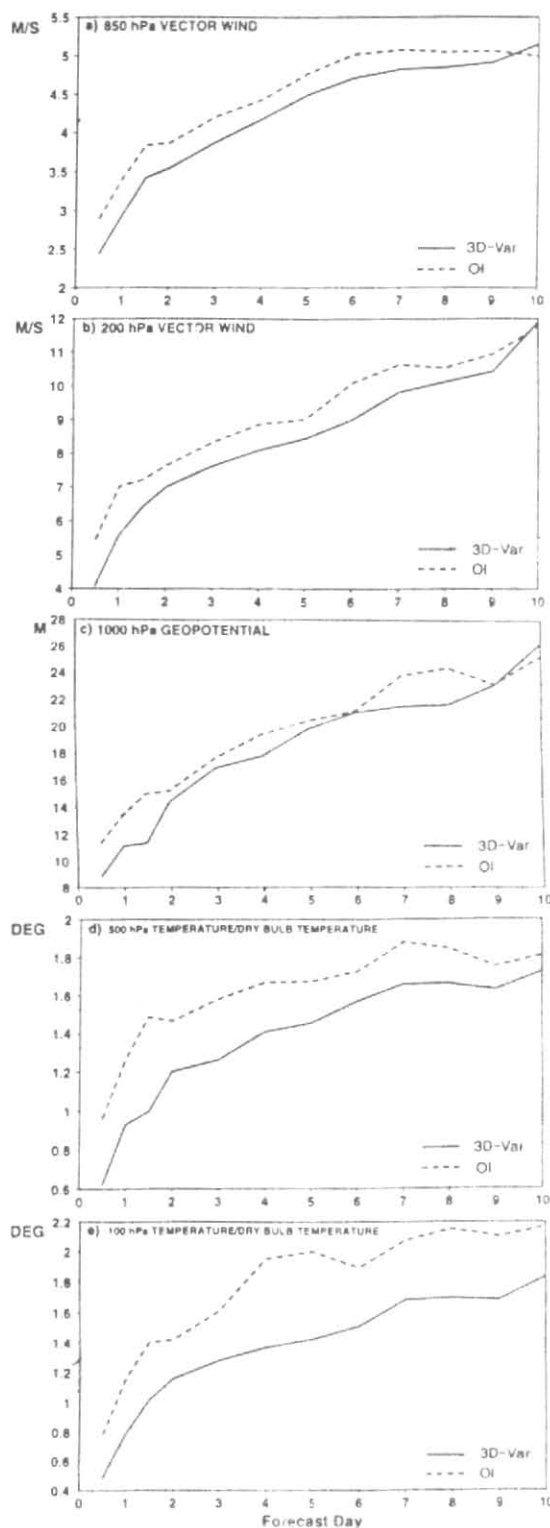


Fig. 9. Objective forecast verification, averaged for the two 14-day periods, i.e., comprising 28 cases in two separate periods. Forecasts have been verified against own analyses. The rms of forecast error is shown for (a) 850 hPa winds, (b) 200 hPa winds, (c) 1000 hPa geopotential, (d) 500 hPa temperature and (e) 100 hPa temperature. 3D-Var is indicated by full line and OI is dashed

verification for wind at 850 and 200 hPa respectively. We see that 3D-Var produces better forecasts for the Indian region, at all forecast ranges than OI. Fig. 9(c) shows 1000 hPa geopotential and Figs. 9(d) & (e) show temperature at 500 and 100 hPa respectively. We can see a very substantial advantage for 3D-Var. Charts of the rms of forecast error show improvements over most parts of India and the Indian Ocean (not shown).

The improvement for the Indian region is much stronger than for other tropical/sub-tropical regions. The verification for the tropical band as a whole (within 20 degrees of the equator) shows a mixed result in the troposphere, with a clear 3D-Var improvement restricted to the stratosphere (Andersson *et al.* 1996). At this stage we can only speculate why the new scheme works particularly well in the Indian region.

The extra-tropical results are outside the scope of this paper. It could just briefly be mentioned that the results of the complete pre-operational tests, comprising 120 days in four separate periods, show an over-all neutral impact for the Northern Hemisphere troposphere and a clear positive impact for 3D-Var in the Southern Hemisphere (Andersson *et al.* 1996).

7. Conclusion

The performance of the three dimensional variational analysis scheme (3D-Var), which became operational at ECMWF in January 1996, has been studied with respect to the Indian region. The study comprises two 14-day periods: one during the summer monsoon and the other during January. Indian forecast accuracy at all ranges has improved with the new scheme. The rms of vector wind forecast error has for example been reduced by 0.5 m/s at both 850 and 200 hPa, in the Indian area.

One case of a tropical depression, located near Madagascar, has been presented. The development and movement of this system was accurately predicted in forecast starting from 3D-Var analyses, less so with OI. A more general study of all occurring tropical storms, typhoons and hurricanes in a three week period has shown that this is not an untypical result. There has been a significant improvement in the quality of near-surface wind analyses over sea, particularly evident in the vicinity of tropical storms. The improvement has also been noted in the quality of wave-height predictions from ECMWF analyses (P Janssen, pers.

comm.). Part of the improvement is thought to be due to the use of scatterometer wind data, although other factors may also contribute.

The change of analysis scheme has also had a noticeable impact on the mean analysed monsoon circulation. The mean wind speed of the Somali Jet is higher by upto 2 m/s in places. This results in a slight increase in precipitation in the 48-hour forecasts for parts of India.

In the introduction it was mentioned that 3D-Var is more readily adaptable to new types of data. Work on the exploration of additional data is continuing. Several new types of satellite data are in the pipeline, and the usage of some existing data could be improved. For example, SSM/I total precipitable water data are currently used experimentally (Phalippou 1996), with the aim of improving the humidity analysis. Another example is the upgrade from TOVS to ATOVS which will provide an improved temperature sounding capability in cloudy conditions from its additional microwave channels. The amount of scatterometer data is likely to increase at least three-fold within the next year with the arrival of data from the NSCAT instrument on the ADEOS satellite and the ASCAT instrument on METOP.

The amount of Cloud Motion Winds (CMW) is also on increase due to enhanced processing techniques. Winds are produced from visible, infra-red and water vapour images. All CMW are currently used as pointwise data at the reported pressure. It is now envisaged that particularly the water vapour winds could better be used as vertically averaged winds with the vertical weighting given by the radiative transmittance function of the imager in question. This would alleviate some of the problems with height assignment of such data. There is unfortunately a gap in the coverage of cloud motion wind data over large parts of the Indian Ocean. This is due to the variable quality of INSAT winds (Thoss 1991), which therefore are not used at ECMWF at present. A reassessment of the INSAT data quality earlier this year, using 1995 data, confirmed that the low and medium winds are still poor, and should not be used for the time being (Tomasi 1996). There have, however, been reports that progress has recently been made in identifying the causes of the quality problems. Furthermore, a new INSAT product based on visible imagery at 0600 UTC is now being received at ECMWF (since August 1996), the quality of which is currently being assessed. Future

improvements in data availability, data quality or analysis methods are likely to be particularly valuable in currently data sparse areas, such as the Indian Ocean.

The coming year will also see increased experimentation with the four-dimensional variational scheme, 4D-Var. The fourth dimension in 4D-Var is time, signifying that the development in time of the atmosphere and of forecast errors will be better accounted for by the use of observations distributed in time over several (upto 24) hours, and by the use of the forecast model itself as a constraint. 4D-Var and 3D-Var share the same program codes and are technically integrated. Experiments to-date have been promising. It has been demonstrated that the structure functions (which are static in 3D-Var) are in 4D-Var modified by the dynamics of the model to reflect the position of fronts and rapidly developing storms for example (Thépaut *et al.* 1993). Experiments so far have been carried out with a very rudimentary physics in the assimilating model. The development of a simplified, but more complete, physics package and its adjoint including processes such as large scale precipitation, convection and gravity wave drag, will further enhance the prospects of 4D-Var, not least in the tropics. It is hoped that data from frequent water vapour images from geostationary satellites will be used in 4D-Var (Kelly *et al.* 1996) and result, through the adjoint of the model dynamics and physics, in additional information not only on humidity, but also on the wind and temperature fields.

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