Forecast skill of the ECMWF model using targeted observations during FASTEX

By A. MONTANI¹*, A. J. THORPE¹, R. BUIZZA² and P. UNDÉN²

¹University of Reading, UK
²ECMWF, UK

(Received 9 October 1998; revised 11 March 1999)

SUMMARY

The impact of targeted observations on forecast accuracy is investigated for five case-studies of cyclogenesis during the Fronts and Atlantic Storm-Track EXperiment (FASTEX). Calculations of localized singular vectors (SVs) have been made using the European Centre for Medium-Range Weather Forecasts (ECMWF) forecasting model to find the sensitive regions for each case-study. Two sets of analyses have been prepared: a ‘control’ set consisting of analyses in which all the FASTEX data have been removed from the operational analysis, and a ‘perturbed’ set obtained by adding to the control the data from the dropsondes deployed in regions highlighted as sensitive by SVs. Analysis and forecast differences have been compared with the structure of the SVs as they evolve during the forecast. Model integrations, starting from the two different analyses, have been performed. The impact of the dropsonde data on the forecast skill has been assessed on the basis of both subjective and objective scores. Re-runs of the model from perturbed analyses almost always give better objective scores than those starting from the control analyses. The impact is more evident if the verification area coincides with the regions over which the SVs have been optimized. In this case, short-range prediction errors (up to day 2) are reduced on average by 15%, with a maximum error reduction of about 37%.

KEYWORDS: Adaptive observations  Forecast errors  Singular vectors

1. INTRODUCTION

The problem of forecasting storms as they approach the western sides of continents is particularly difficult: the predictability of these cyclones is highly limited by the fact that they are initiated and develop in data-sparse areas in the middle of the oceanic storm tracks, and little information is available about the actual state of the atmosphere in those regions. Upstream observations of the precursors of these cyclones would be of great help to understand and better forecast this kind of cyclogenesis, by providing more accurate initial conditions to forecast models. For this reason, the Fronts and Atlantic Storm-Track EXperiment (FASTEX) during January and February 1997 used targeted observations made by research aircraft in the west and mid-Atlantic, to improve the description and predictability of cyclones, as well as the parametrization of physical processes in numerical weather prediction (NWP) models (Joly et al. 1997, 1999; Snyder 1996; Clough et al. 1998).

Attention is focussed on weather systems evolving between initial time $t_i$ and final time $t_f$, being located at $t_f$ over a verification region $\Sigma_f$. Extra-observations are taken in flow-dependent geographical target regions $\Sigma_i$ at $t_i$ to improve the forecast verifying at $t_f$ over $\Sigma_f$. In order to achieve this goal, targeted observations should be taken in those areas (referred to as sensitive regions) where analysis errors are likely to be large and to grow rapidly with time. Therefore, one of the main FASTEX scientific objectives is to provide a test for different ‘adaptive’ observational strategies, designed to indicate those regions where dropsonde data would have a crucial impact on the forecast of cyclone development. Different strategies were used during FASTEX to determine where adaptive observations should be made. Among them, the sensitivity vectors (Rabier et al. 1996; Gelaro et al. 1997), the Ensemble Transform Technique (Bishop and Toth 1996) and potential-vorticity maps (Hoskins et al. 1985; Davis and Emanuel 1991).

* Corresponding author, present address: ARPA-SMR, Viale Silvani 6, 40122 Bologna, Italy.
This paper concentrates only on targeting adaptive observations using the singular vector (SV) technique (Buizza and Montani, 1999): the dominant SVs of the integral forward propagator of a nonlinear dynamical system are used to predict \( \Sigma_t \). Attention is focussed on the impact of the data from those dropsondes, deployed in regions highlighted as sensitive by SVs, on the forecast accuracy inside \( \Sigma_f \). SVs provide estimates of the time evolution of initial errors during the forecast (Lacarra and Talagrand 1988; Farrell 1990); they identify the fastest growing perturbations (according to a given norm) during a finite time interval and are used operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF) to construct the initial perturbations of the Ensemble Prediction System (Buizza et al. 1993; Buizza and Palmer 1995; Molteni et al. 1996). A large cause of prediction error is related to that portion of analysis errors which project onto the growing phase space direction; the dominant SVs project along this direction. Following experiments (Buizza et al. 1997) which prove that forecast error can be reduced by perturbing the initial conditions with SV-generated perturbations, Montani et al. (1996) and Buizza and Montani (1999) show that only few SVs, calculated to maximize growth inside \( \Sigma_f \), are needed to define \( \Sigma_t \). ECMWF SVs were used in real time, among other products, to target extra observations during FASTEX, and the impact of the observations on forecast accuracy is evaluated for five case-studies of cyclogenesis during February 1997. The impact of the dropsondes was assessed using the ECMWF 3-dimensional variational (3D-Var) data assimilation system as it was operational during FASTEX (Integrated Forecasting System cycle 15R8; see Courtier et al. 1998).

The methodology of targeting extra observations using SVs is described in section 2. The assimilation and the time evolution of the targeting signal is described in section 3. Results from the case-studies are reported in section 4 and 5. Finally, conclusions are drawn in section 6.

2. METHODOLOGY

The mathematical description of the SV technique, when applied to predictability problems, is well documented in several papers (e.g. Buizza and Palmer 1995; Molteni et al. 1996). In this paper, SVs have been computed at spectral triangular truncation T63, and 19 vertical levels (T63L19), using the total energy norm at both initial and final time (for a discussion about the dependence of SV structure on the choice of norm, see Palmer et al. 1998). The optimization time interval \( \Delta t \) and \( \Sigma_f \) have been adjusted for the different case-studies presented, as explained in following subsections.

(a) Singular-vector configuration

For FASTEX, we produced special operational software to provide targets for the upstream flights. During the two months of the experiment, ECMWF disseminated these special products. These provided daily calculation of targeted SVs with a particular configuration which took into account the alert time necessary to prepare the crew of the aircraft, book the flight space/time and plan the flight track.

After choosing \( \Sigma_f \) (fixed during the experiment and lying between 40°–60°N and 0°–20°W), over which to minimize the forecast error:

- The final time \( t_f \), at which the forecast was required, and also the forecast range (the same as \( \Delta t \)) were defined. In addition to this, the time \( t_l \) at which the additional observations were to be taken (that is, the mid-flight time of an aircraft mission), was defined as \( t_l = t_f - \Delta t \). The research aircraft needed to be alerted a time period \( \Delta t_a \) prior to the nominal time of observation. Hence, the alert time was \( t_a = t_l - \Delta t_a \).
A high-resolution ECMWF forecast at T213L31 (corresponding to 60 km grid spacing in the horizontal and 31 vertical levels) was run from $t_a$ up to $t_f$. Targeted SVs (at T63L19 resolution), maximizing total energy at $t_f$ over $\Sigma_i$, were calculated over the last $\Delta t$ hours of the time interval ($t_a$, $t_f$), in order to provide the target region $\Sigma_i$ at observing time $t_i$.

After FASTEX, SVs were re-calculated for a number of case-studies of interest from a predictability point of view (see next section). In particular:

- the verification region was moved from case to case in order to include the minimum in the forecast mean-sea-level pressure (m.s.l.p.) of the cyclone;
- $t_i$ was adjusted, relating it to the mid-flight time in the far-upstream area; $t_f$ was moved to coincide with the time the system was around the British Isles;
- SVs were calculated with a shorter alert time ($\Delta t_a = 24$ h) and also with zero alert time ($\Delta t_a = 0$ h).

As investigated in Buizza and Montani (1999), the information provided by a particular set of SVs depends strongly on the accuracy of the forecast trajectory along which they are calculated. Typically, forecast skill is reduced as the prediction range increases. Therefore, the longer the forecast range, the higher is the risk of SVs indicating erroneous sensitive regions because of, for example, substantially wrong storm trajectories or missed cyclone deepening. In Buizza and Montani (1999), calculations of targeted SVs were carried out with different values for $\Delta t_a$ (0, 24, 48 h) and the sensitivity of the target region location to the alert time was found to be reasonably small, provided $\Delta t_a$ did not exceed 24 h. In this study, ‘no-alert-time’ SVs were chosen to select the dropsondes to be included in the initial conditions of the perturbed reruns.

(b) Post-experiment recalculation

FASTEX data are grouped in 19 Intensive Observation Periods (IOPs) and IOPs 9, 11, 12 and 17 will be discussed. These case-studies were chosen since they exhibited a large forecast error in the verification region and were also targeted by upstream flights. For each case-study, two sets of analyses were prepared:

- a control set consisting of the analysis without any FASTEX data;
- a perturbed set, obtained by adding to the control the data from those dropsondes deployed in the regions highlighted as sensitive by SVs (calculated from forecasts started from the control analyses).

Subsequently, high-resolution reruns of the model (at T213L31), starting from the two different analyses, were performed and the impact of the dropsonde data on the forecast accuracy assessed. The control analyses (and forecasts) were based on a ‘normal’ data coverage upon which to test (in the perturbed analyses and forecasts) the impact of targeted observations.

The impact of a mobile observing system on the routine meteorological observing network with information from fixed locations is currently far from understood. In addition, the extra data provided by the dropsondes have different error characteristics to the normally assimilated data. Therefore, the inclusion of extra data during an assimilation cycle does not guarantee a priori more realistic analyses or more accurate forecast runs. Not all the information provided by the sondes could be incorporated into the analyses; it proved impossible to use the geopotential data, since the height of a dropsonde above the sea surface at the time of its last reading was unknown. Therefore, only pressure, temperature, humidity and wind (speed and direction) were assimilated in the perturbed
analyses at up to 8 pressure levels (depending on the drop altitude) located at 1000, 850, 700, 500, 400, 300, 250 and 200 hPa. For conventional radiosondes, geopotentials are used rather than temperature and surface pressure. Both sets of variables carry the information about the mass field and there is a good deal of redundancy between them. At the time of these recalculations, the 3D-Var data assimilation system was operational at ECMWF. Then, analysis increments were calculated at T63 resolution (that is, about 210 km in grid-point space) and horizontal scales smaller than T63 could not be resolved. Higher-resolution signals from closely spaced dropsondes were damped and averaged at T63 by the data assimilation system. The advantage of a high-resolution T213 model is to provide an accurate model background; then, the observation increments are calculated at high resolution and the remaining, necessary, analysis corrections at T63 are normally smaller than otherwise would be the case.

(c) Definition of the target area using singular vectors

The initial structure of the most amplifying SVs can be used to identify $\Sigma_i$ in which to take extra observations. Consider the first $M$ SVs at $t_i$ and let $T_i(s)$ be the temperature of the $i$-th SV at the grid point $s = (\lambda, \phi, p)$, where $\lambda$ denotes the longitude, $\phi$ the latitude and $p$ the vertical coordinate. Analogous definitions can be used to identify $\xi_i(s)$, the relative vorticity of the $i$-th SV at a particular grid point. Let $s_0 = (\lambda_0, \phi_0, p_0)$ be the location where the first SV has its temperature maximum (either vorticity or potential vorticity could be chosen as well), that is

$$T_1(s_0) \geq T_1(s) \quad \forall s.$$  \hspace{1cm} (1)

The target area can be identified by the grid points $s$ where the temperature perturbation, for any SV, is larger than a fraction of $T_1(s_0)$. After some experimentation, it was found that an appropriate fraction is about 0.6: this ensures that a significant number of grid points are included in $\Sigma_i$ and, therefore, provides a reasonable geographical extension of the target region. This means:

$$s \in \Sigma_i \text{ if and only if } T_i(s) \geq 0.6 \left( \frac{\sigma_1}{\sigma_i} \right) T_1(s_0), \quad \forall i = 1, \ldots, M.$$  \hspace{1cm} (2)

The weights $\sigma_1/\sigma_i$ are introduced to take into account the fact that SVs of different rank grow with different amplification factors ($\sigma_1, \sigma_2, \ldots$), the first one growing the fastest. As shown previously (Buizza et al. 1993), temperature is good for providing information about SVs at initial time, since about 70% of SVs’ total energy is in potential rather than in kinetic form. Therefore, temperature targets were used to select those dropsondes which were deployed in sensitive regions and which, then, were used to prepare the perturbed reruns.

3. ASSIMILATION AND EVOLUTION OF THE TARGETING SIGNAL

(a) Assimilation of the dropsonde data

In order to test the extent to which the data from a particular dropsonde can locally influence the analysis, vertical profiles of the control analysis, of the perturbed analysis (which incorporates those dropsondes deployed in regions highlighted as sensitive by SVs) and of the raw data from a dropsonde, were considered at initial time. This should show the ability of the system to assimilate at a particular point the extra information provided by targeted observations. The example presented in Fig. 1 shows vertical profiles of the differences in temperature (left panel) and zonal wind (right panel), both
valid at 1800 UTC 17 February 1997, at 43.6°N, 42.1°W, which coincides with the location of one of the dropsondes.

The vertical profile of the temperature differences between the analysis with no-FASTEX data and the dropsonde (dotted profile) indicates that the analysis has temperature values significantly lower (up to 5 K) than those of the dropsonde in the lower troposphere, while differences are less marked above 600 hPa. The differences between the perturbed analysis and the dropsonde (solid profile) are smaller, indicating a closer agreement between the new analysis and that including the dropsonde data, although not all the information provided seems to have been used. Since the analysis process is a compromise between the background field and the various observations, we expect the analysis not to fit perfectly the observations used. It can be seen that the dropsonde data have been partially filtered by the analysis. Similar remarks can be made for the zonal wind component. The dropsonde measures weaker winds in the middle–upper troposphere than the control analysis, the highest difference between the control analysis and the dropsonde being about 10 m s⁻¹ (dotted profile in the right-hand panel of Fig. 1). The vertical profile of the difference between the perturbed analysis and the dropsonde data shows smaller differences, especially in the upper troposphere where the new analysis best reproduces the dropsonde signal. On the other hand, we noticed that the 850 hPa wind measured by the dropsonde is about 50% larger than in the unperturbed analysis (the difference showing a peak of −6 m s⁻¹). Because of the sharp vertical structure, the data assimilation process seems to give too little weight to the low-level part of the sounding. The above results show some dependence on the time of the dropsonde sounding. As the time difference between the dropsonde deployment and the analysis increases, a lesser impact of the dropsonde data on the perturbed analysis is evident. Therefore, the data assimilation system can incorporate local ‘non-standard’ measurements in the perturbed analyses, providing a more accurate representation of the atmosphere. It would be interesting to test the ability of more optimal data assimilation schemes (like 4-D Var) to assimilate the extra information provided by the FASTEX soundings.

(b) Time evolution of the signal

Before comparing the relative accuracy of the control and perturbed reruns, it is important to discuss a few issues concerning SV targeting. A necessary condition for
any targeting technique to be useful is that the signal, initially created in the analysis by
the dropsonde data, travels from the target to the verification area. Based on the working
hypothesis that the perturbed analysis is the best representation of the actual state of the
atmosphere, the differences between the two analyses can be considered a reasonable
estimate of the analysis error. Therefore, it is interesting to study the structure of these
analysis differences and investigate how they evolve through the forecast. Also, the
differences between the control and the perturbed forecasts provide information about
the evolution of the targeting signal, and can be compared to the evolving structure of
the SV (calculated at intermediate times between $t_i$ and $t_f$) and to the weather system
under investigation. This enables one to understand interaction mechanisms between the
basic state and perturbation fields. For this reason, analysis and forecast differences have
been calculated at $t_i$ and, then, every 6 hours until $t_f$. These fields have been compared
to the 6-hourly linear evolutions of the SVs used to define the sensitive regions and to
the analysis fields of the system investigated (available every 6 h).

Here, typical results are presented for the cyclone that developed between 1800 UTC
17 and 1200 UTC 19 February (hereafter $t_i$ and $t_f$, respectively). This case-study (IOP17)
has been chosen because the system is easily identifiable throughout its evolution and a
link between basic state and SV fields can be easily established. Very similar results are
found for the other FASTEX case-studies we examined. The first three rows in Fig. 2
show vertical cross-sections: of the fastest growing SV plotted in terms of temperature
(first row); of the analysis and forecast differences between the control and the perturbed
reuns plotted in terms of temperature (second row); and of the basic state plotted in
terms of relative vorticity (third row). In successive columns, the panels represent the
fields at $t_i$, $t_i + 24$ h, and $t_f$ ($t_f + 42$ h). The direction of the cross-sections changes with
time, but at a fixed instant it is the same for all quantities*. The fourth row (Fig. 2)
shows vertical profiles of $U$, the basic state zonal wind (at $t_i$, $t_i + 24$ hours, $t_f$) at the
point where the SV peaks.

At $t_i$, the zonal cross-sections for the SV show a very marked westward tilt with
height; the disturbance peaks in the middle and lower troposphere and is composed of
elongated filaments of positive and negative anomalies. At the same time, the analysis
differences (control minus perturbed analysis) show two regions of negative and positive
anomalies evident in the lower and upper troposphere, respectively. Most of the structure
is limited to the areas where the dropsondes were deployed, that is along the flight
track of the research aircraft (shown in Fig. 3). The main peak in analysis difference
(2.5 degC at about 700 hPa) approximately coincides with the peak in SV structure, a
secondary maximum being evident in the boundary layer at about 43°N, 40°W. The
first panel of the third row shows that the basic state is characterized by a region
of intense upper-level vorticity 12 degrees of longitude upstream of the SV. At low-
levels, in the location of the analysis error and the SV maximum, a weak anticyclonic
circulation is evident in a region north of the surface cyclone (the region of positive
relative vorticity corresponding to the centre of the storm is not captured by this
cross-section). The zonal wind, plotted where the SV (and the analysis differences) peaks,
indicates easterlies in the lower troposphere and an intense westerly component in the
middle and upper troposphere, peaking at tropopause level. Consequently, the upper
portions of the targeting signal and of the SV will be advected eastwards faster than its
lower portion, thus producing a change in the vertical structure of these fields.

* All the plotted fields are shown on 19 model levels. In the case of the SVs, they are all the levels available at
the end of SV calculations; for the other fields, the 19 levels chosen are a subset of the 31 operationally available
for basic state quantities. Thus, although the y-axis labels of the first row are different from the others, the levels
plotted in each panel are always the same.
Figure 2. Vertical cross-sections: of the first SV (plotted in terms of temperature, first row); of the differences between the control and the perturbed rerun (plotted in terms of temperature, second row); of the basic state relative vorticity (third row); and the vertical profile of the basic state zonal wind (U, fourth row). The fields are plotted in the first column at initial time (t₁: 1800 UTC 17 February 1997); in the second column after 24 h; and in the third column after 42 h (t₂: 1200 UTC 19 February 1997). The directions of the cross-sections are: from 43°N, 70°W to 43°N, 30°W (t₁); from 35°N, 45°W to 60°N, 15°W (t₁ + 24 h), from 50°N, 20°W to 70°N, 10°E (t₂). The vertical profile of U is reported at 43°N, 55°W (t₁), at 48°N, 29°W (t₁ + 24 h), and at 55°N, 12°W (t₂). Contour intervals for the SV are: 0.025 degC (t₁), 0.05 degC (t₁ + 24 h), 0.1 degC (t₂). Contour intervals are: for the temperature differences, 1 degC; for the basic state relative vorticity, 6 × 10⁻⁵ s⁻¹; for U, 10 m s⁻¹. The y-axes in all panels are model levels.

The structure of the SV, plotted after 24 and 42 h of linear evolution, indicates that the disturbance grows in amplitude (the contour interval at t₂ is four times the one used at t₁) and it becomes less tilted until it is nearly vertically stacked at optimization time inside the verification region (note that SVs have by definition arbitrary sign, and care must be taken in comparing the sign of the SV fields with the other fields in Fig. 2). The different advection speeds at lower and upper levels is also evident during and at the end of the evolution of the perturbation, as represented by the second and third panels in the last row of Fig. 2. As the differences between the control and the perturbed reruns do not initially show any vertical tilt, the advection by the zonal wind acts in such a way that the forecast differences are tilted eastwards. The 24 h differences indicate that the low-level structure is located approximately where the SV peaks (at about 47°N, 30°W). But, at this time, part of the signal has already arrived at the verification region (50–65°N, 0–20°W), as shown by the upper-level maximum at 57°N, 19°W. Very similar
Figure 3. Observation summary for Intensive Observation Period (IOP) 17 (from Clough et al. 1998). Low 41 is the designation of the intense cyclone that developed in this IOP. Areas within shaded boundaries are: the far-upstream area (west Atlantic); the near-upstream area (mid-Atlantic); and the mesoscale sampling area (east Atlantic). Six flight tracks of research aircraft are shown, labelled: G-IV (flight 1); Lear Jet, G-IV (flight 2); UK C-130, P3 and G-IV (flight 3). Locations of ships (ship symbols) and sites where radiosondes are released at 6-hourly or more frequent intervals (balloon symbols) are also shown.

Remarks can be made for the 42 h prediction differences: the temperature maximum has grown to about 4.5 degC at 700 hPa, well inside the verification area (at 58°N, 8°W) and slightly above the SV’s peak. The eastward tilt with height is more marked, and a significant fraction of the targeting signal is located more than 10 degrees downstream of the verification area and out of the region plotted in the last panel of the second row. The time-evolving structure of the basic state relative vorticity indicates an intense cyclonic circulation in the lower troposphere, extending up to 500 hPa. At $t_s$, in addition to the low-level maximum, an anticyclonic circulation is evident in the upper troposphere, and two more regions of upper-level positive vorticity are located upstream and downstream of the surface cyclone. During the evolution of the system, both the forecast differences and the SV are about 300 km upstream of the cyclone, although the gap is closed as the system travels towards the verification area.

Therefore, the upper-level structure of the forecast error is always downstream of the SV, while in the lower troposphere (below 700 hPa) the two fields travel approximately together. Both fields peak to the west of the targeted system at intermediate times during the cyclone evolution. The vertical structures of the two quantities change with time as if they were ‘pivoting’ around the levels between 700 and 850 hPa. The signal of the dropsondes gets to the verification area before both the SV and the cyclone, because of the intense zonal wind which advects the upper-level portion of the forecast differences. In conclusion, the signal in forecast difference does travel from the target to the verification region (as does the propagating SV), initially un tilted and, then, tilting eastwards. In the next sections, the impact of such a signal on the performance of the perturbed forecast will be assessed.
4. Case study: IOP17 (dropsondes from the G-IV flight)

In this section, IOP17 (with the dropsonde data from the research aircraft G-IV) will be presented in detail, since this is widely considered to be the best example of an Atlantic storm during FASTEX. The other four case-studies are discussed in the next section. Basic information about the different case-studies investigated is presented in Table 1.

IOP17 had the lowest pressure (953 hPa) recorded during the experiment. It was also characterized by a very active cold front crossing the British Isles causing some severe weather (72 kt gust in South-East England, 6 mm of rain in 6 min in Reading). A brief description of the life cycle of this system starts at around 1200 UTC 17 February 1997. At that time, the low-level circulation in the North Atlantic is dominated by an intense westerly flow with a large-scale low located between Iceland and Greenland. A small low-pressure system, already with a developed structure, is evident southwest of Newfoundland (m.s.l.p. 1015 hPa at 37°N 63°W). The frontal zone is very elongated from west to east, and both the front and the rear of the system seem to be alternative regions of incipient development. At upper levels, the flow is highly zonal with confluence just south of Newfoundland. Twelve hours later, the system has moved north-eastwards (1005 hPa at 40°N 52°W) with maxima of 700 hPa vertical velocity and low-level relative vorticity appearing just ahead of the low (not shown). From now on, the system travels more quickly north-eastwards, deepening, especially once it enters the FASTEX MSA, located around the British Isles. Between 1200 UTC 18 February and 1200 UTC the following day, the pressure minimum drops from 988 to 953 hPa, indicating explosive cyclogenesis. The system had minimum pressure at 59°N 13°W, and a double cloud head with a well pronounced dry intrusion is evident in the mature phase of the cyclone life. Figure 3 shows that six flights targeted the system at different stages of its life cycle. In particular, two upstream flights (by G-IV and Learjet) were performed and two sets of dropsondes (at two different times) deployed in the initiation region of the cyclone. Therefore, two perturbed forecasts were run for this IOP and the impact of each set of extra observations will be analysed separately in the next subsections. As shown by the track in Fig. 3 (labelled 'G-IV (flight 1)'), the G-IV performed a flight in the initiation region of the cyclone between 1500 and 2030 UTC 17 February (take-off and landing in St. John's, Newfoundland; mid-flight time at 1800 UTC), deploying 22 dropsondes. In order to decide which dropsondes to include, SVs were calculated with \( \Delta t = 42 \text{ h} \), between \( t_1 \) at 1800 UTC 17 February and \( t_f \) at 1200 UTC 19 February; \( \Sigma_f \) extends from 50 to 65°N and from 0 to 20°W.

Figure 4 indicates the sensitive regions relative to the fastest-growing perturbations as in (2), in the format similar to that provided during the experiment. A different symbol (circle for SV1, triangle for SV2, '+' for SV3 and '×' for SV4) is plotted depending on which SV is responsible for indicating a particular subregion within \( \Sigma_f \). The figure shows a slight misplacement between the sensitive region and the G-IV flight...
Figure 4. IOP17 (G-IV flight): sensitive regions plotted in temperature, as in Eq. (2), according to the first 4 SVs, valid at 1800 UTC 17 February. The circles (triangles) show the target region $\Sigma_i$ as for SV1 (SV2). See text for further details.

track (from Fig. 3). In particular, two out of the five legs of the flight (and the relative dropsondes deployed) seem to be located too far to the east. Nevertheless, a plot of the 700 hPa temperature structure of SV1 (not shown) indicates a relatively intense signal also to the east, and not only to the south of Newfoundland. For this reason, the data from all the 22 dropsondes have been included to prepare the new perturbed analysis in the 1800 UTC analysis cycle of 17 February. The main target, just south of Newfoundland, corresponds to a region of intense baroclinicity. In that area, a marked meridional gradient in 700 hPa temperature characterizes the flow. The location of $\Sigma_i$ is slightly downstream of a 700 hPa trough (not shown), where warm air is being advected by the horizontal wind, upstream of the right-entrance region of the 250 hPa jet.

Figure 4 gives the SVs' amplification factors and the 3D location (longitude, latitude and altitude) of the temperature maximum for each SV. Since the growth rates of the first two SVs are much higher than the others, information related only to SV1 and SV2 contributes, in practice, to the definition of $\Sigma_i$. In addition, the values found for the altitude of the targets are between 3 and 4 km; this confirms the importance of the mid-lower troposphere as a favourable region for perturbation growth. The real-time SVs, calculated during FASTEX with $\Delta t = 48$ h (not shown), are valid for a mid-flight time at about 1200 UTC 17 February (hence, 6 h before the a posteriori SVs), the verification time being the same for both sets. As could be expected, the real-time SVs indicate a sensitive region located a few hundred kms upstream of that shown in Fig. 4, with the main peak in the lower troposphere at about 40°N, 60°W. It is also worth pointing out that, in this case (as well as in the next one), the verification regions for the two sets of SVs are almost identical.

The importance of low-level structures is also evident in Table 2 which gives, for all the IOPs investigated, the pressure where the total energy of the fastest amplifying SV peaks at initial and final time. At initial time, SV1 has an energy peak at model level 13 or 14 (between 700 and 800 hPa), while at optimization time there is a broader structure, with maxima between about 325 hPa and 850 hPa, depending on the case. At
TABLE 2. APPROXIMATE PRESSURE LEVELS (hPa) OF THE TOTAL ENERGY MAXIMUM OF THE FASTEST GROWING SV AT t₁ AND tᵣ

<table>
<thead>
<tr>
<th>IOP</th>
<th>maximum at t₁</th>
<th>maximum at tᵣ</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>780</td>
<td>850</td>
</tr>
<tr>
<td>11</td>
<td>780</td>
<td>325</td>
</tr>
<tr>
<td>12</td>
<td>780</td>
<td>850</td>
</tr>
<tr>
<td>17 (G-IV)</td>
<td>700</td>
<td>850</td>
</tr>
<tr>
<td>17 (Lear)</td>
<td>700</td>
<td>850</td>
</tr>
</tbody>
</table>

The height of the energy peak is very typical for a SV (Molteni et al. 1996). However, surprisingly the main peak is also often located just above the boundary layer (at about 850 hPa) at tᵣ. This seems to indicate a significant energy growth also at low levels, in addition to the usual picture of upward propagation introduced to explain SV growth (Buizza and Palmer 1995).

Runs from both the control and the perturbed analyses were performed and the skill of the 42 h forecast was tested against the verifying analysis, valid at 1200 UTC 19 February. In all the experiments, it was decided to use the best available analyses, obtained by including all FASTEX extra data available at ECMWF (sounding, data from ships, dropsondes, etc.). The improvement of the perturbed forecast has been assessed on the basis of both subjective comparisons of forecast fields (e.g. m.s.l.p. or low-level vorticity) and objective scores (e.g. root-mean-square errors, hereafter r.m.s.e.).

In Fig. 5, the verifying analysis indicates an m.s.l.p. minimum of 958 hPa at about 58°N 12°W, and an 850 hPa relative vorticity (ξ850) maximum of 3.6 × 10⁻⁴ s⁻¹ just to the west of the cyclone centre. The 42 h control forecast (initialized at 1800 UTC 17 February) clearly underestimates the intensity of the system; the m.s.l.p. forecast error amounts to approximately 11 hPa, the vorticity error being of about 8 × 10⁻⁵ s⁻¹. Also the location of the low centre is significantly displaced to the south-east of the region affected by the strongest winds on the south-western flank of the cyclone. A similar conclusion can be drawn by looking at the control forecast at upper levels (not shown); the system is not predicted to be as deep as it turned out to be. The last column of Fig. 5 shows the benefits gained in the forecast using the dropsondes deployed by the G-IV in regions highlighted as sensitive by SVs. The new forecast performs much better than the control, the m.s.l.p. minimum dropping to 961 hPa and so reducing the prediction error to 4 hPa. In addition to this, the location error is partially reduced, the low centre being moved slightly north-westwards, towards the analysed location. This might be a consequence of erroneous forecasting on scales larger than the cyclone; anyway, these errors cannot be reduced using targeted observations. Also the relative vorticity pattern is more accurate than before, with a forecast error of less than 25% of the initial one. However, it should be noted that both the control and the perturbed forecasts do not represent properly the narrow strip of low-level vorticity evident in the analysis along the cold front of the cyclone.

The higher accuracy of the new forecast is evident also when objective scores are analysed. Figure 6 shows the r.m.s. errors of the 500 hPa geopotential height of the control and perturbed forecasts over Europe (35°–75°N, 12.5°W–42.5°E) and the SV verification region (as in Table 1). The impact is already evident over Europe, but is more marked over the SV verification region, the prediction error being substantially reduced from day 1 of the forecast onwards in the perturbed forecast.

The scores of the control and the perturbed forecasts over the SV optimization region have been calculated at verification time (after 42 hours) and are reported in Table 3 for
Figure 5. Intensive observation period (IOP) 17 (G-IV flight): distributions of mean-sea-level pressure (m.s.l.p.; top panels) and 850 hPa relative vorticity (bottom panels) valid at 1200 UTC 19 February: verifying analysis (left column; m.s.l.p. minimum of 957 hPa), 42 h control forecast (middle column; m.s.l.p. minimum of 968 hPa) and 42 h perturbed forecast (right column; m.s.l.p. minimum of 961 hPa), both forecasts verifying at the same time.

Contour intervals are: 4 hPa (top panels) and $8 \times 10^{-3}$ s$^{-1}$ (bottom panels).

Figure 6. IOP17 (G-IV flight): r.m.s. errors of the 500 hPa geopotential height (in metres) for two different verification areas: Europe (left panel) and the SV verification region (as in Table 1, right panel), comparing the control forecast (marked 'cntl', dashed lines) with the perturbed forecast (marked 'drop', solid lines). All forecasts start at 1800 UTC 17 February 1997. See text for further details.

all the case-studies investigated (errors are reported to two significant figures). The table shows, for this experiment, the 42 h r.m.s. forecast errors in terms of geopotential height surfaces at 500 and 1000 hPa (denoted by Z500 and Z1000, respectively) for the control and the dropsonde-perturbed predictions ('ctrl' and 'drop' in the table). The impact is clear for IOP17 (G-IV flight), the forecast accuracy being increased in the perturbed
TABLE 3. THE Z500 AND Z1000 r.m.s. FORECAST ERRORS (IN METRES) INSIDE THE SVS' VERIFICATION AREAS (AS IN TABLE 1) FOR THE CONTROL AND THE DROPSONDE-PERTURBED T213L31 RUNS (ctrl AND drop, RESPECTIVELY)

<table>
<thead>
<tr>
<th></th>
<th>IOP0</th>
<th>IOP1</th>
<th>IOP2</th>
<th>IOP17, G-IV</th>
<th>IOP17, Lear</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms</td>
<td>ctrl</td>
<td>drop</td>
<td>ctrl</td>
<td>drop</td>
<td>ctrl</td>
</tr>
<tr>
<td>errors (m)</td>
<td>29</td>
<td>28</td>
<td>30</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Z500</td>
<td>40</td>
<td>40</td>
<td>45</td>
<td>38</td>
<td>39</td>
</tr>
</tbody>
</table>

rerun by 14% and 32% at 500 and 1000 hPa, respectively. This improvement is higher than that over Europe, indicating the efficacy of the targeting technique in increasing the quality of a particular forecast range over a specified geographical region.

Figure 6 also shows that the benefits of improving the analysis in the target region extend well beyond the 42 h range, the perturbed forecast performing better up to and beyond day 3. This is consistent with previous studies of SVs and sensitivity studies (Rabier et al. 1996). The differences between the short-range forecasts are less evident, as the verification region differs from the area for which the use of the dropsondes was designed. The impact is less dramatic if scores are considered over the North Atlantic, while there is no improvement at all in the amplitude of the prediction error over the North Pacific (not shown). This is in full agreement with the philosophy of FASTEX, aiming to improve the forecasts locally and not necessarily globally by increasing the observational network only in specific sensitive areas.

Most of these previous remarks still hold for the r.m.s. errors of the 1000 hPa geopotential height. The gain in forecast accuracy over Europe and over the SV verification region is even more marked at 1000 rather than at 500 hPa, especially after forecast day 2, indicating a general benefit gained by the forecast at any level due to a more accurate initialization (reduction of fast-growing analysis errors) in the sensitive areas.

5. OTHER CASE-STUDIES

Four additional case-studies were investigated: IOP17 with the Lear dropsondes, IOP9, IOP11 and IOP12. In the next subsections, the impact of the dropsonde data on forecast accuracy is reported for each set of experiments. For reason of brevity, the synoptic descriptions are omitted (the reader is referred to Montani (1999) for a more detailed discussion of these case-studies).

(a) IOP17 (dropsondes from the Lear flight)

The Lear jet performed a flight in the initiation region of the cyclone, six hours later than the one described before. It took off at 2247 UTC 17 February from Newfoundland, where it landed at 0205 UTC on the following day (mid-flight time: 0000 UTC 18 February; flight marked ‘Lear Jet’ in Fig. 3). The flight investigated the region just south-east of Newfoundland, sampling the northern side of the system (minimum of 1005 hPa at 40°N, 53°W) with 15 dropsondes. The last row of Table 4 and the top left frame of Fig. 7 indicate a good agreement between the flight track and the ‘core’ of the sensitive region for the most amplifying SVs, valid at 0000 UTC 18 February and with the same \( t_f \) and \( \Sigma \) as before (then \( \Delta t = 36 \) h). For this reason, the data from all the dropsondes were used to prepare a new 0000 UTC analysis for the perturbed rerun.

The main target corresponds to a region of high baroclinicity, to the north of the cyclone centre and characterized by strong ascent at 700 hPa. The horizontal and vertical structures of the SVs are very similar to those exhibited before, with the perturbations
amplifying most peaking in the lower troposphere at both initial and final time, as indicated by the values in Table 2. The real-time SVs were calculated for a mid-flight time at 1200 UTC 18 February and peak about 10 degrees to the east in comparison with the actual flight track and the a posteriori SVs.

The comparison (not shown) between the 36 h forecasts (both control and perturbed forecasts start at 0000 UTC 18 February) and the verifying analysis (valid 1200 UTC 19 February) shows that the control prediction error is much smaller than before, at least from a synoptic point of view. As shown before, the 42 h control forecast was quite inaccurate in assessing the intensity and the location of the cyclone. This means that, 6 hours later, the analysis errors were smaller than before and so there is less potential for a predictability improvement. Nevertheless, the 36 h r.m.s. forecast errors inside the

**TABLE 4.** Approximate locations of the most sensitive region, according to Eq. (2), for the investigated case-studies. The amplification factor of the fastest growing SV ($\sigma_1$) is also given.

<table>
<thead>
<tr>
<th>IOP</th>
<th>longitude (W)</th>
<th>latitude (N)</th>
<th>altitude (m)</th>
<th>$\sigma_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>43.1</td>
<td>55.0</td>
<td>2200</td>
<td>7.4</td>
</tr>
<tr>
<td>11</td>
<td>46.0</td>
<td>47.6</td>
<td>2100</td>
<td>10.2</td>
</tr>
<tr>
<td>12</td>
<td>52.5</td>
<td>47.6</td>
<td>2200</td>
<td>12.7</td>
</tr>
<tr>
<td>17 (G-IV)</td>
<td>54.4</td>
<td>43.8</td>
<td>3100</td>
<td>13.2</td>
</tr>
<tr>
<td>17 (Lear)</td>
<td>46.9</td>
<td>47.6</td>
<td>3100</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Figure 7. Sensitive regions, plotted as temperature as in Eq. (2), according to the first 4 SVs, and 700 hPa basic state temperature (thin black lines; contour interval 4 degC) valid at: 0000 UTC 18 February (Intensive Observation Period (IOP) 17—Lear flight, top left panel); 1200 UTC 1 February (IOP9, top right); 1800 UTC 4 February (IOP11, bottom left); and 1200 UTC 8 February (IOP12, bottom right). The circles (triangles) show the target region $\Sigma_i$ as for SV1 (SV2).
SVs' verification region, as reported in Table 3, indicate a marked gain in prediction accuracy for the perturbed rerun at both 500 and 1000 hPa, the error being reduced by 17% and 37% respectively (the highest percentages of all the FASTEX case-studies). On the other hand, little error reduction is evident on a synoptic chart for the perturbed prediction.

(b) IOP9

The low-pressure system investigated during IOP9 is already mature in the far-upstream area. It moves away from the north-east coast of USA, crossing the Atlantic between 1 and 3 February.

The G-IV performed a flight in the developing region of the cyclone on 1 February. It took off from Shannon, Ireland, at 0900 UTC and deployed two sets of dropsondes: the first set was around Greenland, investigating a low-pressure system which was going to verify outside the MSA; the second set was to the north-east of Newfoundland in order to sample the sensitivity regions of the cyclone in question. The aircraft landed in Goose Bay, Canada, at 1530 UTC, after deploying a total of 30 dropsondes. Here, the interest is focussed on the second set of dropsondes. Because of the length of the flight, not all the dropsondes could be assimilated in the 1200 UTC analysis cycle, which can only make use of the data available between 0900 UTC and 1500 UTC. A few dropsondes were deployed after 1500 UTC and were incorporated in the succeeding analysis cycle. In order to maximise the impact of the dropsonde data on the preparation of the perturbed reruns, analyses were cycled in the following way:

- a perturbed 1200 UTC analysis was prepared using the data from the dropsondes deployed between 0900 UTC and 1500 UTC, plus the information provided by the control first-guess forecast run 6 hours before and using the standard observational network without any other FASTEX data;
- a 6 h forecast was run from the 1200 UTC perturbed analysis;
- the 1800 UTC perturbed analysis was obtained by combining this short-range forecast with the data provided by those dropsondes deployed after 1500 UTC plus the standard non-FASTEX observational network;
- the actual reruns (control and perturbed) started at 1800 UTC.

The problem of selecting the dropsondes deployed in the sensitive regions at 1200 UTC and 1800 UTC was tackled by calculating two sets of SVs, one for each of these times. The verification time was kept fixed at 0600 UTC 3 February, as well as the verification region, extending from 52°N to 67°N and from 5°W to 25°W. Then, the two sets of SVs had two different Δt's of 42 and 36 h, respectively. The top right panel of Fig. 7 shows, at 1200 UTC, the locations of the maxima of the fastest growing perturbations plotted in terms of temperature as in Eq. (2). SVs do not indicate a sensitive region of limited geographical extension, within the flight range of a research aircraft. The area highlighted as sensitive is much larger than in the previous case-studies, extending from 50°N to 60°N and from 32°W to 70°W. In order to limit geographically such a large region, the value of the fraction in Eq. (2) has been increased from 0.6 to 0.75. In this way, fewer grid points contribute to define Σi, easing the detection of the crucial regions for cyclone initiation and development. As in the previous case-studies, the main target is in the mid-lower troposphere, in a region characterized by a strong meridional basic state temperature gradient. The most sensitive region is upstream of the upper-level jet maximum and downstream of a maximum in 700 hPa relative vorticity. Table 2 shows that the fastest growing SV has its energy maximum in the lower troposphere at both initial and final time, although a
double-peak structure (not shown) develops in the energy vertical profile at optimization time. The real-time SVs, valid at 1200 UTC 1 February and verifying either 24 or 48 h later, are calculated with a verification region quite different from that used for the a posteriori SVs; hence, the sensitive regions they highlight do not agree with the G-IV flight track. Since most of the dropsondes were deployed before 1500 UTC, more weight was given to the 1200 UTC target. This set of SVs indicates the area to the south and to the south-west of Greenland as being the most sensitive. For this reason, the data from the dropsondes deployed in this region (to the west of 47°W) were included in the 1200 UTC and 1800 UTC assimilation cycles, producing the different initial conditions of the perturbed rerun from the control one. The amplification factor of SV1 is almost halved compared to that of the G-IV flight of IOP17 (see Table 4). This is due to the fact that the IOP9 low is a less intense cyclone than that of IOP17, with no explosive cyclogenesis and less associated severe weather. Also, the IOP9 low is already well-developed at initial time; therefore, the relative growth of SV-like perturbations, in terms of for example drop in m.s.l.p. and wind intensity, is much less than before.

From a predictability viewpoint, the interest is focused on the 36 h forecasts (control and perturbed) initialized at 1800 UTC 1 February and verifying at 0600 UTC 3 February. In the second and third columns of Table 3, the 36 h r.m.s. errors of the perturbed and control forecasts are reported at 500 and 1000 hPa over the SV verification region. No error reduction is shown at the surface, while at 500 hPa the improvement is very limited, the accuracy of the perturbed rerun being only 2% higher than the control. The positive impact of the dropsonde data becomes evident, with lower errors for the perturbed forecast as the forecast range increases. In this case-study, the impact of the dropsonde data was neutral at verification time, the 36 h perturbed and the control reruns performing approximately the same. The positive consequences of the extra information provided at initial time become more and more evident as the forecast range is increased and verification regions located farther downstream are considered.

(c) IOP11

This case consists of a primary cyclone which formed over the east coast of North America and deepened while crossing the Atlantic.

Three upstream flights were performed in order to investigate the initiation region of the cyclone. Here, attention is focused on the flight of the US C-130, which took off at 1120 UTC 4 February and landed at 2100 UTC the same day in St. John’s, Newfoundland, after deploying 19 dropsondes to the south and to the south-east of Newfoundland. As in the previous case-study, the duration of the flight made it necessary to calculate two sets of SVs: the former valid at 1200 UTC (Δt = 42 h), the latter at 1800 UTC 4 February (Δt = 36 h). The verification time was kept fixed at 0600 UTC 6 February, as well as the verification region extending from 50°N to 65°N and from 5°W to 25°W. At both 1200 UTC and 1800 UTC, the most sensitive regions are located at around 700 hPa (the bottom left panel of Fig. 7 shows Σi at 1800 UTC only), corresponding to a meridional temperature gradient at that level and just downstream of a mid-tropospheric trough with a peak in low-level relative vorticity. As in the previous case-studies, the target region is located at the right entrance of the 250 hPa jet maximum. The vertical distribution of total energy of the fastest growing SV (as in Table 2) is very similar to that presented in Buizza and Palmer (1995), with a low-tropospheric maximum at initial time, and a peak located at the troposphere level at optimization time. Only SV1 and SV2 contribute to the definition of Σi, since the amplification factors of the lesser growing perturbations are too small to satisfy the requirements of Eq. (2). Since all the legs of the flight are in good agreement with the target areas identified at 1200 UTC and 1800 UTC, the data
from all the dropsondes has been used to prepare the perturbed reruns. As in the previous case-study, it has been necessary to cycle the 1200 UTC and 1800 UTC analyses, the control and the perturbed forecast actually starting at 1800 UTC 4 February and verifying 36 hours later at 0600 UTC 6 February. There is a very good agreement between the 1200 UTC (a posteriori) SVs and the target indicated by the real-time SVs (not shown), valid at 1200 UTC 4 February ($\Delta t = 48$ h), despite the slight misplacement between the fixed verification region and the a posteriori one (see Table 1).

The results are summarized in Table 3, where the 36 h r.m.s. forecast errors are given for the control and the perturbed forecasts. Inside the SV verification region, the error is reduced by 20% (16%) at 500 (1000) hPa, the improvement being also evident if other verification regions, such as Europe and North Atlantic, are considered. From a synoptic point of view, the perturbed forecast succeeds in producing a better representation of the 500 hPa trough over the British Isles, which was not properly predicted by the control forecast (Anders Persson, personal communication). If m.s.l.p. distributions are considered, the gain in forecast accuracy is still evident. The control forecast underestimates the depth of the cyclone, with an error of about 9 hPa, and is also quite poor in locating the position of the low minimum (just to the north-west of Scotland), misplacing it to the south. If the data from the dropsondes are used, then it turns out that the predictability of both the cyclone depth (error reduced to 6 hPa) and its location are improved.

(d) IOP12

This is probably the most interesting FASTEX case-study from the point of view of predictability, since it was characterized by a massive divergence in forecasts between the various NWP models used during the experiment. In addition, the impact of targeted observations on forecast accuracy proved to be quite controversial and, for this reason, it has been analysed in detail.

The system is a typical example of explosive cyclogenesis, occurring between 8 and 10 February and deepening rapidly as it enters the north-west part of the MSA. The G-IV took off on 8 February at 1000 UTC from Shannon, landing at 1530 UTC in St. John’s, performing a double-mission flight. In addition to deploying 10 dropsondes between 10°W and 30°W (at 53°N) in order to study an already mature system in the MSA, the aircraft used 18 dropsondes west of 42°W (between 48°N and 52°N) to investigate the sensitive regions for IOP12. The data from the second set of dropsondes proved to have a big impact on the predictability of this cyclone. In order to select the dropsondes to be used for the perturbed rerun, SVs were calculated between 1200 UTC 8 February and 0000 UTC 10 February, the verification region extending from 55°N to 68°N and from 12°W to 32°W. Since the last dropsondes were deployed after 1500 UTC, SVs were also calculated to find the sensitive regions at 1800 UTC of the same day (with the same verification time and region as before). Nevertheless, more weight was given to the information provided by the 1200 UTC perturbations, since most of the dropsondes were assimilated in the 1200 UTC cycle.

The bottom right panel of Fig. 7 shows the target area according to the fastest growing perturbations at 1200 UTC. Only the first two SVs determine the target region, since their growth rates are so large. The main SVs peak in the lower troposphere, just below 700 hPa, to the east and to the south-east of Newfoundland (see also the fourth row of Table 4). Energy has a maximum in the lower troposphere at both initial and final time (see Table 2), with a less marked upward propagation of total energy. There is little overlap between the fixed verification region and the one used to calculate the a posteriori SVs (as in Table 1). Despite this, the real-time SVs valid at 1200 UTC
8 February (Δt = 48 h) indicate a sensitive region only a few hundred kms to the south in comparison to that shown in the bottom right panel of the figure. The target region indicated by the a posteriori SVs is located in an area characterized by a tight horizontal temperature gradient at 700 hPa, oriented from the north-west to the south-east. The geopotential height distributions at both 700 and 850 hPa indicate regions of confluent flow just to the south of the sensitive areas. SVs give lesser importance to the surface trough and to the region of relatively strong 600 hPa ascent located to the south of Newfoundland. The upper-level jet is above the target region, and not slightly downstream as in the previous experiment; also, there is no low-level vorticity signal in the vicinity of the target region. The locations of the dropsondes deployed in the second part of the G-IV flight are in good agreement with the regions highlighted as sensitive by the SVs. Therefore, the data from all the 18 dropsondes were assimilated in the 1200 UTC and 1800 UTC analyses (cycled as in the previous case-studies), as well as the control and the perturbed reruns starting at 1800 UTC 8 February. Here, the attention is focussed on the performance of the 30 h forecast, verifying at 0000 UTC 10 February.

Table 3 indicates that at 500 hPa there is a small forecast improvement (about 8%) for the perturbed rerun, but at lower levels the control forecast is clearly more accurate than the perturbed rerun. The errors of the two forecasts start to differ before day 1, and the gap in forecast accuracy increases with time. The figures in Table 3 show higher errors in the verification region for the perturbed rerun, about 11% higher than in the control. If other verification regions are considered, the perturbed rerun performs better than the control at 500 hPa over the North Atlantic from day 1 onwards, while over Europe the two forecasts perform approximately in the same way. At 1000 hPa, the perturbed and the control forecasts have similar errors over the North Atlantic, while the control prediction is clearly best over Europe. Different factors may have contributed to the poorer performance of the perturbed forecast compared with the control; the main ones are listed below.

• The region where the dropsondes were deployed may not correspond to actual sensitive regions. SVs are likely to identify erroneous targets when nonlinearity and diabatic processes play an important role in the determination and evolution of fast-growing perturbations. SVs are calculated assuming purely linear dynamics and neglecting moist processes; these approximations can be inappropriate for describing perturbation growth when explosive cyclogenesis is occurring. In this case-study the system develops very quickly from 1200 UTC 9 February to 0000 UTC the following day, with a deepening rate of about 38 hPa day⁻¹. Hence, a linear model for perturbation growth may be inappropriate and may indicate regions of lesser importance as sensitive for perturbation growth. Nevertheless, extra data in non-sensitive regions should not have a negative impact on forecast accuracy.
  • The quality of dropsonde data may have been poorer than in other cases.
  • The data assimilation scheme may be sub-optimal to such an extent that the extra observations have a negative impact in the preparation of the perturbed analysis.
  • Model errors may have played a major contribution in degrading the quality of the perturbed forecast.
  • The resources currently available limit the horizontal resolution at which SVs can be computed to T63 (equivalent to about 200 km); such a limit could be a reason for inaccurate SV targeting.

It appears that the interaction of these factors acted in such a way to make extra observations detrimental to attempts to improve the forecast.
Figure 8. Scatter plots with all the reruns, showing the 1000 and 500 hPa r.m.s. geopotential height forecast errors (m), comparing errors of the control forecasts ('Without Dropsondes') with perturbed forecasts ('With Dropsondes'). Plots encompass forecast time-periods of 30, 36, 42, 48 h, verifying over the SVs' verification regions (as in Table 1).

(e) **Summary of the results**

In order to have an overall idea of the impact of targeted observations on forecast accuracy, the prediction uncertainties of the control and dropsonde reruns have been summarized in the scatter plot of Fig. 8. The plot shows the 30, 36, 42 and 48 h r.m.s. forecast errors of the two sets of reruns in terms of 500 and 1000 hPa geopotential heights (in metres), verifying over the SV verification regions (changing from case to case according to Table 1).

Since five case-studies, four prediction ranges and two variables are considered, there are in total 40 points in the diagram, each of them corresponding to a pair of control–perturbed forecast errors. The figure shows that very few points are located below the dashed line at 45° and the error reduction is particularly evident for those cases of large prediction errors for the control rerun. On average, the gain in forecast accuracy amounts to about 15%, the highest error reduction being about 37%. Similar remarks can be made if the errors of the control and of the perturbed forecasts are assessed over other verification regions (like Europe and the North Atlantic) and larger time ranges, although the error reduction is less marked (Unden et al. 1997).

6. **Conclusions**

The impact of adaptive observations on forecast accuracy was investigated for the ECMWF data assimilation and forecasting system. Target regions were identified at T63L19 resolution using the analysis as initial conditions (no-alert-time SVs).

A limited number of SVs can detect a reasonably localized target area, whose geographical extension is within the flight range of a research aircraft. The target regions identified by the SVs, are located in the lower troposphere (between 500 and 850 hPa), corresponding to marked horizontal temperature gradients of the basic state and below the right-entrance of the upper-level jet maximum. In almost all the case-studies presented, the target regions indicated by the SVs calculated after the
experiment, are relatively close to those highlighted by the real-time SVs, computed using a 24 h or a 36 h forecast as initial condition. Although the SV energy initially peaks in the lower troposphere, there is a non-negligible downward propagation of energy with time (in addition to upwards), the maximum at optimization time often being located just above the boundary layer (see Table 2). The assimilation and the evolution of the targeting signal has been studied, showing that the data assimilation system operates a filtering on the dropsonde information (for example, in terms of temperature and wind speed) when this is incorporated in the perturbed analysis.

Initial differences between the control and the perturbed analyses (assimilating only those dropsondes deployed in regions highlighted as sensitive by SVs) are vertically stacked at $t_i$, and then propagate from the target to the verification region, growing in amplitude during the evolution. Forecast differences exhibit an increasing eastward tilt with height, as the range increases. This is due to differential advection of the targeting signal at lower and upper levels. Therefore, the portion of the targeting signal travelling in the upper troposphere, reaches the verification region before the targeted system itself. On the other hand, SVs initially tilt westwards with height and they are stacked vertically at optimization time, over the verification region. Hence, in the middle and upper troposphere, the targeting signal is ahead of the evolving SV at intermediate times between $t_i$ and $t_f$. Only below 700 hPa do the two pieces of information travel together, as if both signals were ‘pivoting’ around the levels just above the boundary layer. During the evolution and also at optimization time, the system (plotted in terms of basic state relative vorticity) is slightly downstream of the SV and the forecast difference maximum.

Control and perturbed reruns have been carried out, and the accuracy of the two forecasts assessed on the basis of subjective and objective scores. In the five case-studies examined, the perturbed reruns have lower r.m.s. forecast errors (in terms of geopotential height) than the control ones, the only exception being the surface errors for IOP12, when the dropsonde data have a negative impact on forecast accuracy. Inside the SV verification regions, the errors in the perturbed reruns are reduced on average by 15%, the gain in prediction accuracy being more evident (up to 37%) for cases of larger control forecast errors. In some case-studies, the forecast improvement can also be seen on synoptic weather charts, the perturbed reruns being closer to the verifying analysis in predicting the location and the intensity of the surface low. If the verification region is increased to include either Europe or the North Atlantic, then the positive impact of the extra data in sensitive regions is still evident, although less marked. The forecast-error reductions obtained in the experiments described in this paper are in qualitative agreement with the results obtained by other groups, such as Gelaro et al. (1999) and Langland et al. (1999). Therefore, the results presented in this paper confirm (after Buizza and Montani 1999) the ability of SVs to detect the crucial (sensitive) regions where atmospheric perturbations grow quickly with time and where targeting, if performed, would have a positive impact on reducing prediction errors.

ACKNOWLEDGEMENTS

The authors thank Tim Palmer for helpful discussions on this work. Andrea Montani was supported during this study with a Gassiot Committee studentship award.

REFERENCES


Montani, A., Buizza, R. and Thorpe, A. J.

Palmer, T. N., Gelaro, R., Barkmeijer, J. and Buizza, R.

Rabier, F., Klinker, E., Courtier, P. and Hollingsworth, A.

Snyder, C.

Undén, P., Kelly, G., Le Meur, D. and Isaken, I.


1997 Observing system experiments with the 3D-Var assimilation system. ECMWF Technical Memorandum No. 244, European Centre for Medium-Range Forecasts, Shinfield, Reading, UK