Targeted observations in FASTEX: Adjoint-based targeting procedures and data impact experiments in IOP17 and IOP18

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SUMMARY

The Fronts and Atlantic Storm-Track EXperiment (FASTEX) provided an opportunity for testing targeted-observing procedures in a real-time framework during January and February 1997. This study describes the use of singular vectors (SVs) for objective targeting during FASTEX, and the evaluation of the impact obtained from targeted dropsonde data, satellite wind data, and other observations on 1–2 day forecast skill in intensive observation periods (IOPs) 17 and 18.

In IOP17, targeted dropsondes improve a 42 h forecast of L41 (Low 41; cyclones were numbered in sequence throughout FASTEX) in terms of sea-level pressure, but the forecast skill is degraded in the upper troposphere. It is suggested that the degraded forecast may be caused by an incomplete survey of the SV target area, that improved the analysis in one region, but made the analysis less accurate in an adjacent part of the target area where no dropsonde data were provided. In a series of experiments, the best 42 h forecast of L41 is obtained by the addition of a few dropsonde profiles provided specially for FASTEX at off-times, that provide observational data in the most sensitive part of the SV target area. The analysis differences introduced by the dropsonde profiles are much smaller in magnitude than those from the dropsonde data, but have a larger forecast impact, because they occur in an area that has larger error growth rates in this forecast.

In a series of experiments for IOP18, the best 24 h forecast of L44 is obtained using a combination of targeted-dropsonde data and satellite wind data. Both data types can also be used separately to improve this forecast. The assimilation of satellite wind data and ship-based soundings in areas of weak initial-condition sensitivity ('null' areas) is shown to have minimal impact on the forecast error. The target areas identified by SVs in these two IOPs occur in strongly baroclinic regions, tending to favour the right-entrance and left-exit regions of the upper-level jet, but with greatest sensitivity near 600 hPa.

KEYWORDS: Adjoint methods Analysis error Extratropical cyclones Predictability Targeted observations

1. INTRODUCTION

Adjoint methods, developed primarily for their application to data assimilation problems in numerical weather prediction, provide an efficient means of quantifying dynamical sensitivity in many different types of forecast situations. For example, adjoint gradient sensitivity has been used to study the development of idealized frontal waves (Horanyi and Joly 1996), to quantify the impact of small initial perturbations in model variables on the development of idealized and real extratropical cyclones (Langland et al. 1995; Errico and Vukicevic 1992), and to identify features in the initial conditions that might cause large forecast errors (Rabier et al. 1996; Zou et al. 1998).

Recently, it has been suggested that adjoint methods can be applied to the general problem of so-called targeted (or adaptive) observing strategies, whereby it is proposed that short-range numerical forecasts of significant weather features such as extratropical cyclones can be improved by the assimilation of a limited number of additional observations in dynamically sensitive areas (Snyder 1996; Palmer et al. 1998).

In targeted observing, it is hoped that improvements to forecast-model initial conditions (e.g. the correction of analysis error by the assimilation of special observational data) in the relatively localized ‘target area’ will reduce a significant fraction of the total forecast error that may be attributed to all initial-condition deficiencies. It should be emphasized that the problem of targeted observations does not centre on attempting to

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estimate and correct the largest analysis errors, but rather on correcting analysis errors in
dynamically sensitive areas of the atmosphere, where even relatively small initial error
can amplify greatly and cause forecast failures.

In principle, the most appropriate locations for targeted observations can be identified
in advance under operational conditions using 'objective targeting methods' such as
singular vectors (SVs; Bergot et al. 1999; Buizza and Montani 1999), ensemble trans-
formation (Bishop and Toth 1999), or quasi-inverse sensitivity (Pu et al. 1997); these
locations can then be sampled using a variety of relocatable (piloted or pre-programmed)
observing platforms. Given the ever-increasing costs of maintaining and expanding the
current observational network (consider, for example, the expense of developing new
remote-sensing platforms), it is worthwhile to assess the value added by various data
types, especially in forecasts of weather events with significant societal impacts. In ad-
dition, the definition of an 'optimal mix' of observing systems that provides maximum
benefit to forecast skill is of interest when considering the design and cost of future
observing networks.

The Fronts and Atlantic Storm-Track EXperiment (FASTEX), which took place
during January and February 1997, provides an opportunity to assess the impact of
targeted observations on model-forecast skill applied to North Atlantic cyclones in
the one- to three-day time range, as well as other questions related to predictability
and cyclone life cycles. An overview of general FASTEX objectives and observational
resources is contained in Joly et al. (1999).

In this study, we test the idea that observations provided in 'target' regions identified
by SVs can improve short-range forecast skill in two FASTEX cyclone forecast cases.
The observations used include dropsondes targeted in real time during FASTEX field
operations, as well as satellite wind data and special radiosonde ascents located in target
regions. In a companion paper (Gelaro et al. 1999, hereafter G99) it is shown that the
component of analysis error that is most relevant to forecast error growth (in the 1- to
2-day time range) is highly correlated with the leading energy-norm SVs, and that these
structures typically have largest initial amplitude in localized areas of the mid–lower
troposphere (400–800 hPa).

The paper is organized in the following way: section 2 is a brief overview of the
SV-targeting approach used by the Naval Research Laboratory (NRL) during FASTEX.
Section 3 summarizes a few issues related to the use of aircraft in the FASTEX 'far
upstream' domain, and the selection of Intensive Observational Periods (IOPs) 17 and
18 for evaluation of targeted-observing impact in this study. Target structure and data
impact experiments in IOP17 and IOP18 using the Navy global forecast model are
described in sections 4 and 5, respectively. The paper concludes with a summary of
results and discussion of targeted-observing issues in section 6.

2. Targeting methodology

In FASTEX, targeted-observing guidance used by NRL was based on SVs and
gradient sensitivity obtained from the Navy Operational Global Atmospheric Prediction
System (NOGAPS, Rosmond 1997; Hogan and Brody 1993). The SV and gradient
sensitivity methods are closely linked from a dynamical and mathematical perspective
and, as configured in FASTEX, generally identify similar target regions. Here, we will
focus on the use of SVs for objective targeting. The reader is referred to Palmer et al.
(1998) or Gelaro et al. (1998) for a mathematical definition of SVs, and to Errico (1997)
for a definition of how gradient sensitivities can be derived using an adjoint model.
SVs provide a set of dynamically consistent structures, ordered by amplification factor, that maximize perturbation growth for a specified forecast interval. The leading SVs are those structures that grow most rapidly with respect to a selected norm. In a targeted-observing context, it is the correction of analysis error within the subspace of the leading SVs that is considered most likely to have a significant impact on the growth of forecast error.

The NRL SV calculations during FASTEX use a norm based on perturbation energy at both initial and final time (G99) and were produced at T47 spectral resolution with 18 levels (T47L18). Final time SVs are constrained to a defined optimization area (roughly 15° × 15° latitude and longitude) centred on the forecast position of a cyclone and extending from near 150 hPa to the surface. There is no constraint on the location of SVs at initial (targeted-observing) time. The SVs are produced using a dry adjoint model with simplified vertical mixing, but linearized with respect to a diabatic basic state trajectory produced at T79L18 resolution.

In targeted observing, the norm (or metric) used in the SV calculations would ideally include information about the covariances of analysis errors. Techniques to produce SVs with an approximate analysis error covariance metric are under development at NRL, and elsewhere (Barkmeijer et al. 1998). We note that Palmer et al. (1998) show that a metric based on perturbation total energy, as used here, is a reasonable first-order approximation to the analysis error covariance metric. A total energy metric also has appeal in that winds, temperature and pressure are used to validate weather forecasts, and measure their errors.

Target regions for special observations in FASTEX were generally defined to include the extrema of the leading (fastest growing) SVs. Ideally, the goal would be to minimize the projection of analysis error onto the entire structure (and not just the extrema) of the leading SVs but, in practical terms, this is effectively impossible to accomplish with limited observational resources and imperfect data assimilation procedures. Typically, the first 3 SVs were considered in target area definition, although other SVs may suggest slightly different target regions, and observations in these other areas could be helpful for controlling the error growth if the singular values (SV growth rates) are large. If the growth rate of the leading SV is dominant, then from a targeted-observing perspective, the SV and gradient sensitivity methods point to the same observing location. In the event that separate, viable, targets occur they can be prioritized based on, for instance, the SV growth rates, structure of evolved SVs, or density of conventional observations.

3. Far upstream observational resources and case-study selection

During FASTEX, several aircraft provided observations of cyclones in the “far upstream domain” (see Fig. 1 of Joly et al. 1999). These included a Learjet and two US Air Force C-130s based in St. John’s Newfoundland, and the National Oceanic and Atmospheric Administration (NOAA) Gulfstream-IV (G-IV) based primarily in Shannon, Ireland. Each of these aircraft was able to provide high-quality dropsonde measurements of temperature, pressure, and wind in regions designated for observational enhancement. A problem with dropsonde measurements of relative humidity during FASTEX is noted by Jaubert et al. (1999).

The NOAA G-IV accomplished five cross-Atlantic missions in FASTEX using St. John’s, Newfoundland, and Goose Bay, Labrador as recovery locations, and was tasked for targeted observations on several of these opportunities by scientists of NRL and Météo-France, using adjoint-based objective targeting methods. The Learjet and C-130s in FASTEX were tasked for targeted observations by a group of scientists led by Kerry
Emanuel, using objective targeting guidance from ensemble transformation and other methods, with results reported by Szunyogh et al. (1999).

Although more than 30 aircraft missions were completed during the field phase, the set of targeted-dropsonde data in FASTEX provides a limited set of observations for the validation of SV targeting. There are many IOPs in which SV target areas were partially surveyed with dropsondes, but few in which aircraft provided the type of detailed surveys that would be required to reduce substantially the possible analysis error in the subspace of the leading SVs.

A major limitation for targeted observing with the NOAA G-IV in FASTEX was simply the difficulty of reaching the defined ‘far upstream area’ in the western Atlantic from the operations base at Shannon, Ireland. Target-area surveys were thus limited in time and duration by the necessity of long ferry flights from Ireland or recovery stops in Canada. In addition, even during missions in which the NOAA G-IV was used for objective targeting, the flight patterns were usually modified to obtain observational data for other purposes such as subjective feature evaluation or phenomenology, or restricted from certain areas by air traffic control, and this imposed significant constraints on dropsonde surveys of SV target areas.

A statistical overview of targeted-observing data impact using a large set of Learjet and NOAA G-IV flights is provided by Bergot (1999). Here we describe, in more detail, the objective targeting and data impact in FASTEX IOP17 and IOP18, on 17–19 February and 22–23 February 1997, respectively. These two IOPs are selected because they include synoptically interesting cyclone developments with relatively good coverage of SV target areas by the NOAA G-IV or other data sources, such as wind observations derived from GOES-8 (Velden et al. 1997) or land- and ship-based radiosonde (RAOB) ascents. Although not specifically targeted, these other data types can be used selectively to provide observations in sensitive or weakly-sensitive ("null") regions. The use of several data sources allows a more comprehensive proof-of-concept for targeted observing in these cases, and demonstrates the importance of using a mix of observational data types.

Another motivation in performing relatively detailed studies of these two FASTEX IOPs is to demonstrate that SV targeting-guidance points to synoptically relevant parts of developing cyclones, and to describe target structure in both the upper and lower troposphere. These results are presented in sections 4 and 5, and extended in G99, where analysis differences are projected onto leading SVs and allowed to evolve in the nonlinear forecast model.

4. FASTEX IOP17

IOP17 (termed ‘the FASTEX cyclone”) provides a dramatic example of explosive cyclogenesis, with a maximum deepening rate of 40 hPa in 24 h, and the lowest analysed central pressure of any FASTEX storm (943 hPa at 0000 UTC 20 February 1997). A more extensive synoptic description of IOP17 is provided elsewhere; here the focus is on the impact of observational data on forecast error and the correspondence of the SV targeting guidance to the primary synoptic features.

Short-range (36–60 h) forecasts of the IOP17 cyclone (L41*) that did not include special FASTEX observations were subject to relatively large position and/or intensity errors in the European Centre for Medium-Range Weather Forecasts (ECMWF) model (Montani et al. 1999), the ARPEGE\(^\dagger\) model (T. Bergot, personal communication) and

\* Lows were numbered sequentially throughout FASTEX for easy reference.
\^ Action de Recherche Petite Echelle Grande Echelle.
in NOGAPS, for forecasts verifying at 1200 UTC 19 February 1997. Relatively large forecast errors in 1–5 day forecasts of L41 in the UK Met Office model are also documented by Clough et al. (1998).

(a) 72 h operational forecast

A 72 h NOGAPS forecast of L41 valid at 1200 UTC 19 February 1997 indicates a 979 hPa surface low on the extreme north-west corner of Ireland (Fig. 1(a)). This forecast (termed E17oper) was made using all observations assimilated in an operational context, at T79L18 resolution. Based on this forecast and earlier operational guidance indicating a significant FASTEX cyclone, SV targeting guidance was prepared, using the optimization area (15°W–5°E, 47°N–60°N) shown in Fig. 1(a). This optimization and forecast verification area (FVA) includes the surface low centre anticipated from the 72 h forecast, as well as a larger area over the British Isles likely to be affected by frontal precipitation and winds associated with L41. The verifying position of L41 at 1200 UTC 19 February 1997 (shown by L in Fig. 1(a)) is near the north-west corner of the SV optimization area. There is a positional error of 455 km for L41 in this 72 h forecast (Table 1).

(b) Singular vectors

The structure of the leading SV at the targeted-observing time of 1800 UTC 17 February in terms of vorticity and temperature components at 300 and 600 hPa is shown in Fig. 2. These SV fields are identical to those produced in real time for final targeting guidance during FASTEX operations. There is a 42 h SV optimization interval (1800 UTC 17 to 1200 UTC 19 February) and a 30 h lead-time (1200 UTC 16 to 1800 UTC 17 February) in the SV calculations to allow for tasking of the NOAA G-IV from St. John’s to the observational target area (following a ferry flight from Shannon to St. John’s earlier on 17 February). The nonlinear trajectory used in the SV calculations is based on the 72 h forecast whose sea-level-pressure forecast is shown in Fig. 1(a).

The maximum SV amplitude is found in the temperature component at 600 hPa (Fig. 2(d)), in a region of strong thermal gradients below the left-exit region of the upper-level jet that extends over eastern Canada. This concentration of sensitivity in the mid–lower troposphere is a typical feature of energy-norm SVs in baroclinic situations (Buizza and Palmer 1995). The rapid energy growth achieved by the leading SVs is at least partly related to conversions of available potential to kinetic energy that occur in baroclinic instability. For a dynamical interpretation, in a potential-vorticity context, of

### Table 1. FASTEX IOP17: Forecasts of minimum central pressure in L41, valid at 1200 UTC 19 February 1997

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Pressure (hPa)</th>
<th>Forecast error (hPa)</th>
<th>Positional error (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E17control</td>
<td>981</td>
<td>+17</td>
<td>390</td>
</tr>
<tr>
<td>E17drop</td>
<td>975</td>
<td>+11</td>
<td>255</td>
</tr>
<tr>
<td>E17sat</td>
<td>974</td>
<td>+10</td>
<td>315</td>
</tr>
<tr>
<td>E17raob1</td>
<td>977</td>
<td>+13</td>
<td>335</td>
</tr>
<tr>
<td>E17raob2</td>
<td>974</td>
<td>+10</td>
<td>280</td>
</tr>
<tr>
<td>E17null</td>
<td>978</td>
<td>+14</td>
<td>335</td>
</tr>
<tr>
<td>E17oper</td>
<td>979</td>
<td>+15</td>
<td>455</td>
</tr>
</tbody>
</table>

1The verifying central pressure is 964 hPa in a NOGAPS T79L18 operational analysis using all regular observations and special FASTEX data. All experiments are 42 h forecasts started at 1800 UTC 17 February, except E17oper which is a 72 h forecast from 1200 UTC 16 February 1997, containing all available observational data.
Figure 1. IOP17 fields valid at 1200 UTC 19 February 1997: (a) 72 h operational forecast, E17oper, of sea-level pressure used to define the SV optimization area for real-time targeted observing in IOP17; (b) 42 h E17control forecast of sea-level pressure; (c) surface pressure error of the 42 h E17control forecast. Contour interval is 4 hPa in all panels. L indicates the best analysed position (using all data) of cyclone L41. The outlined box is the SV optimization and Forecast Verification Area for IOP17. See text for further details.
Figure 2. JOP17 initial-time SV1 fields at 1800 UTC 17 February 1997 used for real-time targeting: (a) vorticity and (b) temperature at 300 hPa; (c) vorticity and (d) temperature at 600 hPa. SVs are shaded with contour intervals of 4 K for temperature and $20 \times 10^{-5}$ s$^{-1}$ for vorticity; note that the fields shown are not scaled to represent perturbations of conventional temperature or vorticity. Unshaded contours are E13/control wind speed (m s$^{-1}$) in (a) and (c), and potential temperature (K) in (b) and (d). Crosses indicate dropsonde positions. L indicates the best analysed position (using all data) of cyclone L41. The outlined box is the SV observational target area for IOP17. See text for further details.
fast-growing instabilities in the lower troposphere, it is interesting to refer to Hoskins et al. (1985, p. 924).

In 300 hPa vorticity, the extrema of SV1 are found in the right-entrance region of the primary jet that crosses the Atlantic, and the left-exit region of the weaker jet over eastern Canada (Fig. 2(a)). A similar pattern is found at 600 hPa in the vorticity component of the leading SV (Fig. 2(c)). The 300 hPa temperature component of SV1 is relatively weak (Fig. 2(b)). The SV1 amplification factor of 16.3 (square root of the singular value) in this IOP17 forecast is the largest of any during FASTEX over a comparable optimization interval, consistent with the explosive development of L41. The amplification factors for SV2 and SV3 (fields not shown) are 11.0 and 7.8, respectively.

For the purpose of designing data-impact experiments, an upstream target area (50°W–75°W, 30°N–50°N) for special observations can be defined from inspection of the leading SVs. This IOP17 target area is defined primarily to include the extrema of SV1 temperature and vorticity at 600 hPa (Figs. 2(c) and (d)). While, in theory, a target area of this size might be surveyed to an adequate extent by reconnaissance aircraft of the type used during FASTEX, in practice such surveys were difficult or impossible to accomplish during the field programme, for reasons described in section 3.

(c) NOAA G-IV mission

A 5 h NOAA G-IV mission from St. John's (takeoff at 1500 UTC, landing at 2000 UTC 17 February) deployed 18 Global Positioning System (GPS) dropsondes along the track shown in Fig. 2, with most sondes released near 45 000 ft. This flight track was designed to survey a target area based on adjoint guidance from the ARPEGE model (in a configuration for optimization of enstrophy near 850 hPa in the L41 forecast (T. Bergot, personal communication), and SV guidance from NRL. However, the actual pattern of sonde deployment was not optimal for the NRL SV target area shown in Fig. 2, which includes areas south and west of the actual NOAA G-IV flight track. This difference may indicate that observations over a larger region are required to improve the L41 forecast at both upper and lower levels (the NRL SV configuration) while the forecast of L41 in the lower troposphere (the ARPEGE configuration) may be improved by observations over a more limited region.

(d) Data-impact experiments

A 42 h control forecast for IOP17 was started from initial conditions at 1800 UTC 17 February, using a 6 h (multivariate optimal interpolation) data assimilation cycle containing no special FASTEX dropsonde, ship, or radiosonde data during the previous 36 h. The 42 h control forecast (E17control) of L41 has a positional error of 390 km and a central-pressure error of 17 hPa (Table 1), due to under-deepening and southeastward shift of the low centre (Fig. 1(b) and (c)). The verifying NOGAPS analysis at 1200 UTC 19 February includes all available data that were transmitted in real time for assimilation, including special FASTEX observations and satellite wind data.

A series of forecast experiments is conducted to investigate the effect of assimilating targeted dropsonde data, satellite wind data, and radiosonde observations in 42 h forecasts of L41. The results of these experiments are summarized in Table 1, in terms of sea-level pressure error. We also use a 42 h forecast-error norm as a measure of forecast quality (Table 2). Each forecast experiment involves a separate 42 h integration of the nonlinear, full-physics, global forecast model at T79L18 resolution, starting from initial conditions which add to E17control only the specific observational data denoted in the
'additional observations' column of Table 2. In these experiments we use a horizontal resolution (T79) that is reduced from the operational configuration (T159) because a large number of nonlinear model integrations are required.

We first consider the addition of only the G-IV dropsonde observations to the control analysis (experiment E17drop). The dropsonde data produce temperature analysis differences at 600 hPa north-east of the surface low centre (Fig. 3(b)) that are, at least partially, in an area indicated as sensitive by the SV guidance (Fig. 2(d)). At 300 hPa there are differences of vorticity in the region of maximum wind speed (Fig. 3(a)), but these differences are in a weakly sensitive area (Fig. 2(a)). There is a maximum surface pressure change of about −6 hPa just east of the analysed surface low position (Fig. 3(c))—however no dropsonde data were obtained directly over the low centre or on its western side.

At 42 h (1200 UTC 19 February) the forecast including the dropsonde data has lower surface pressure in a region extending from the analysed position of L41 south-east over Scotland, coupled with a pressure increase through a zone extending south-west from Ireland along the trailing cold front (Fig. 3(f)). The E17drop forecast improves the E17control forecast of L41 central pressure by 6 hPa and moves the low centre 135 km closer to the analysed position (Table 1). A reduction of 8% in the 42 h forecast-error norm below 700 hPa (Table 2) also indicates a forecast improvement.

Although the dropsonde data in IOP17 improve the 42 h forecast of L41 in the lower troposphere, forecast skill is degraded in the middle and upper troposphere, as measured by a 32% increase in the error norm in the levels above 700 hPa (Table 2). There is a 20% increase in the complete error norm (at all levels from 150 hPa to the surface). Forecast differences of 300 hPa vorticity and 600 hPa temperature for E17drop are shown in Figs. 3(d) and 3(e), respectively.

Apparently, the dropsonde data have improved the analysis in a region to which the 42 h forecast in the lower troposphere is sensitive (consistent with the Météo-France targeting guidance), but have degraded the analysis in areas to which the upper-tropospheric forecast is sensitive. There are several possible factors that could account for this result. Perhaps the most likely reason is that the particular flight pattern used in IOP17 did not provide an adequate (or complete) survey of the appropriate target area—only the eastern section of the most sensitive area was surveyed with dropsonde data (Fig. 2(d)).

Essentially, the target in IOP17 represented by the leading SV is an unstable frontal wave and its surrounding baroclinic environment of the middle and lower troposphere south-east of Nova Scotia. The complete structure of such a wave is not accurately refined or re-analysed through the addition of new data (in this case, dropsonde data) that describe only one section of the target. It can be speculated that the addition of dropsonde data in IOP17 in only the eastern section of the target frontal wave may have distorted other parts of the wave structure, and thereby introduced new analysis errors in adjacent (un-surveyed) regions of strong sensitivity. Inaccuracies introduced into the analysis can be especially detrimental in target areas which, by definition, are regions of enhanced dynamic instability.

Wind data from GOES-8 also provide observational coverage over the North Atlantic during IOP17. Unfortunately, in IOP17 cirrus cloud cover restricted this satellite wind coverage (not shown) over much of the target area. Assimilation of all available GOES-8 wind data in experiment E17sat reduces the forecast-error norm by 16% below 700 hPa (Table 2), causes a 14% increase in the error norm between 400 and 700 hPa (it can be speculated that this forecast degradation also results from 'partial' observational coverage of the target area), and has little impact above 400 hPa. In terms of forecast
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Additional observations</th>
<th>$\epsilon_42$ (J kg$^{-1}$)</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$E17_{control}$</td>
<td>Control (excludes research aircraft data, satellite wind data, FASTEX ship soundings and all 0600 and 1800 UTC 17 February RAOB data)</td>
<td>0.2498</td>
<td>0.2214</td>
<td>0.2067</td>
<td>0.6777</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$E17_{drop}$</td>
<td>18 targeted GPS dropsondes deployed from the NOAA G-IV during a 5 h mission centred on 1800 UTC 17 February</td>
<td>0.3303</td>
<td>0.2912</td>
<td>0.1910</td>
<td>0.8123</td>
<td>+32</td>
<td>+32</td>
<td>–8</td>
<td>+20</td>
</tr>
<tr>
<td>$E17_{sat}$</td>
<td>GOES-8 wind data (visible, IR, and water vapour) in all areas during a 2 h interval centred on 1800 UTC 17 February</td>
<td>0.2460</td>
<td>0.2524</td>
<td>0.1741</td>
<td>0.6723</td>
<td>–2</td>
<td>+14</td>
<td>–16</td>
<td>–1</td>
</tr>
<tr>
<td>$E17_{raob1}$</td>
<td>5 selected RAOBs in the SV-based target area at 1800 UTC 17 February</td>
<td>0.1955</td>
<td>0.1730</td>
<td>0.1635</td>
<td>0.5318</td>
<td>–22</td>
<td>–22</td>
<td>–21</td>
<td>–22</td>
</tr>
<tr>
<td>$E17_{raob2}$</td>
<td>5 selected RAOBs in SV-based target areas at 0600 UTC and 1800 UTC 17 February</td>
<td>0.1846</td>
<td>0.1680</td>
<td>0.1435</td>
<td>0.4960</td>
<td>–26</td>
<td>–24</td>
<td>–31</td>
<td>–27</td>
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<tr>
<td>$E17_{null}$</td>
<td>GOES-8 wind data, RAOB$^1$ and ship$^2$ soundings outside the SV-based target area (50°–75°W, 30°–50°N) at 1800 UTC 17 February</td>
<td>0.2181</td>
<td>0.2235</td>
<td>0.1928</td>
<td>0.6342</td>
<td>–13</td>
<td>+1</td>
<td>–7</td>
<td>–6</td>
</tr>
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</table>

See Gelaro et al. (1999) for the definition of the error norm. Verification is against a NOGAPS T79L18 operational analysis using all regular and special FASTEX observational data.

$^1$RAOB soundings for the null experiment are from regular stations in Greenland; Iceland; Kulusuk and Goose Bay, Canada; and Charleston, South Carolina.

$^2$Ship soundings for the null experiment are from the FASTEX vessels: Knorr (61.4°N, 50.6°W), Bugaev (40.9°N, 35.1°W) and Aegir (51.8°N, 34.8°W), and another sounding is provided at 54.9°N, 39.4°W.
Figure 3. IOP17 differences ($E17_{drop} - E17_{control}$) of: (a) analysed vorticity at 300 hPa; (b) temperature at 600 hPa; and (c) sea-level pressure, all at 1800 UTC 17 February 1997. (d), (e) and (f) are as (a), (b) and (c) but for 42 h forecast differences at 1200 UTC 19 February 1997. The differences are shaded with contour intervals of: $1 \times 10^{-5}$ s$^{-1}$ in (a); $2 \times 10^{-5}$ s$^{-1}$ in (d); 1 K in (b) and (e); and 1 hPa in (c) and (f). Unshaded contours are: $E17_{drop}$ wind speed (m s$^{-1}$) in (a) and (d); potential temperature (K) in (b) and (e); and sea-level pressure (hPa) in (c) and (f). Crosses in (a), (b) and (c) indicate dropsonde positions. L indicates the best analysed position (using all data) of cyclone L41 at the initial or forecast time. The outlined box defines the IOP17 SV-based observational target area in (a), (b) and (c) and the forecast verification area in (d), (e) and (f). See text for further details.
L41 central pressure, the satellite wind data produce a decrease of 7 hPa (greater than in *E17drop*), and a 75 km positional improvement.

As another alternative data source for IOP17, we examine the impact of special FASTEX RAOB ascents at off-synoptic times. Special ascents took place at 0600 and 1800 UTC (and sometimes more frequently) during most IOPs at the regular coastal Canadian and US observing sites. In forecast experiment *E17raob1* we assimilate RAOB data at five stations (St. John's, Sable Island, Chatham, Wallops Island and Bermuda) located inside the SV target area, at 1800 UTC 17 February, without the inclusion of any dropsonde or satellite wind data. This produces a 22% reduction in the 42 h forecast-error norm (Table 2), but only a 4 hPa improvement in L41 central pressure and a 55 km reduction in the positional error (Table 1).

Given the proximity of coastal RAOB stations to the target area, an interesting question is whether assimilation of additional observations in a sensitive area at a *previous analysis time*, in addition to the target time of 1800 UTC 17 February, might provide an even greater reduction in forecast error. To investigate this, special RAOB observations from five coastal stations were added to the control assimilation at both 0600 and 1800 UTC 17 February (experiment *E17raob2*). The stations used at 0600 UTC are the same as those used at 1800 UTC, except that Charleston is included instead of St. John's. This choice is made because the area of largest sensitivity at 0600 UTC (not shown) is to the south-west of the 1800 UTC target area. At 1800 UTC the assimilation of special RAOB data is repeated in this experiment as in *E17raob1*.

The analysis differences for *E17raob2* (Fig. 4(a) to (c)) can be directly compared to those for the dropsonde experiment (Fig. 3(a) to (c)). First, it is evident that the assimilation of this RAOB data has produced much smaller changes to the analysis for each of the fields shown. At 300 hPa the RAOB data have changed the vorticity in a few widely dispersed areas in the region of the jet (Fig. 4(a)), while the dropsonde data change the vorticity in a more concentrated region along the path of the NOAA G-IV (Fig. 3(a)). Some of the analysis differences in *E17raob2* have propagated outside the target area due to the earlier assimilation at 0600 UTC, but these differences have no discernible interaction with the IOP17 cyclone.

At 600 hPa, the RAOB data produce a positive temperature increment with a maximum difference of about +2 K centred on 60°W just north of the surface low (Fig. 4(b)). This analysis difference is well-positioned for projection* onto the structure of the leading SV for this forecast (Fig. 2(d)). In contrast, the temperature increment produced by the dropsonde data (Fig. 3(b)) is much larger, but mainly outside the region of greatest sensitivity. Similarly, the surface pressure analysis difference from the dropsonde data (Fig. 3(c)) is much larger than that produced by the RAOB data (less than 1 hPa in the target area, Fig. 4(c)).

At 42 h forecast time, the differences between *E17raob2* and *E17control* shown in Fig. 4(d) to (f) are more closely focused on the FVA, in contrast to *E17drop* in which much of the signal propagated east of the British Isles (Fig. 3(d) to (f)). In particular, the surface pressure difference in *E17raob2* (Fig. 4(f)) is clearly a more well-configured correction of the control run error (Fig. 1(c)) than the corresponding difference from the dropsonde experiment (Fig. 3(f)). The improvement achieved in *E17raob2* is most evident in the 42 h forecast-error norm, which is a 27% overall reduction of the *E17control* error, providing improved skill at all levels (Table 2).

It is noteworthy that the relatively small analysis differences associated with the RAOB data have a more beneficial impact on the 42 h forecast of L41, even though

* The actual projection of analysis differences into the subspace of the leading SVs for IOP17 and IOP18 is presented in G99.
Figure 4. As Fig. 3 but for IOPI7 differences (E17raob2 - E17control). In this case unshaded contours are for E17raob2, and solid dots in (a), (b) and (c) indicate positions of land-based raobs assimilated at 0600 UTC and 1800 UTC 17 February 1997. See text for further explanation.

the dropsonde data created substantially larger changes to analysed wind, temperature and pressure. This demonstrates a basic principle of targeted observing—small changes to the analysis in sensitive regions (in this case the locations of the RAOB data) can have equal or greater impact on error growth than larger changes in less-sensitive regions. The success of targeted observing depends on the identification and proper
Figure 4. Continued.
survey of these sensitive areas, even when they are adjacent to conventionally well-observed regions, such as North America. In IOP17, these few well-positioned RAOB observations are more effective than the set of 18 more poorly positioned dropsondes deployed by the NOAA G-IV at correcting a rapidly growing part of the analysis error. The additional forecast skill obtained by assimilating RAOB data in sensitive regions in two consecutive analysis cycles also suggests that the effectiveness of targeted observations may be increased by more frequent surveys of target areas.

The final experiment performed for IOP17 involves assimilation of land- and ship-based soundings and GOES-8 wind data outside the target area. In this null forecast experiment (E17null) the forecast-error norm is reduced by only 6% (Table 2) and we find the smallest impact for any IOP17 experiment on the central pressure and positional forecast of L41 (Table 1). The null result demonstrates that the 42 h forecast of IOP17 is more sensitive to observations within the SV-based target area than to observations in other locations. In another type of null forecast experiment (see Fig. 13 of G99), it is shown that a few dropsondes positioned in the most sensitive area surveyed (the western segment) of the NOAA G-IV flight track in IOP17 have much greater impact than a similar number of dropsondes in more weakly sensitive (eastern) sections of the flight track that are outside the NRL SV target area.

5. FASTEX IOP18

IOP18 includes NOAA G-IV dropsonde and GOES-8 wind data coverage of a SV-based far-upstream target area, facilitating targeted-observing experiments in the forecast of an explosively deepening cold-air cyclone. The IOP18 cyclone (L44) is noted for a very strong upper-level potential-vorticity anomaly and the lowest tropopause height observed in any FASTEX IOP (Clough et al. 1998). Although the 24 h forecast error in IOP18 is not large, the relatively good upstream observational coverage in IOP18 makes it an interesting case-study for targeted observations.

(a) 48 h operational forecast

A 48 h NOGAPS forecast of L44 valid at 1200 UTC 23 February 1997 shows a 960 hPa surface low south-west of Iceland (Fig. 5(a)). This forecast (E18oper) was made using all observations assimilated in an operational context, at T79L18 resolution. Based on this forecast, final SV targeting guidance was prepared using the optimization area (15°W–30°W, 48°N–63°N), shown in Fig. 5(a). This FVA includes the surface low centre anticipated from the 48 h forecast and the frontal zone to the south. The verifying position of L41 at 1200 UTC 23 February (shown by L in Fig. 5(a)) is 135 km to the east, and the central pressure is 2 hPa lower than in the 48 h E18oper forecast (Table 3). Note that at the time when a decision is made to deploy resources for targeted observing it is not possible to know with certainty whether the forecast to be improved will have a large or small error, although estimates of forecast uncertainty can be obtained from ensemble products.

(b) Singular vectors

The structure of the leading SV at the targeted-observing time of 1200 UTC 22 February is shown in Fig. 6 (note: panel (d) uses SV 3). These SV fields are identical to those produced in real time during FASTEX operations. There is a 24 h SV optimization interval (1200 UTC 22 to 1200 UTC 23 February) and a 24 h lead time (1200 UTC 21 to 1200 UTC 22 February) to allow for the tasking of the NOAA G-IV from Shannon to the upstream observational target area. The nonlinear trajectory used
Figure 5. IOP18 fields valid at 1200 UTC 23 February 1997: (a) 48 h operational forecast of sea-level pressure used to define the SV optimization area for real-time targeted observing in IOP18; (b) 24 h $E18_{control}$ forecast of sea-level pressure; (c) surface pressure error of the 24 h $E18_{control}$ forecast. Contour intervals are 4 hPa in (a) and (b), and 2 hPa in (c). L indicates the best analysed position of the cyclone (using all data). The outlined box is the SV optimization and forecast verification area for IOP18. See text for further details.
TABLE 3. FASTEX IOP18: FORECASTS OF MINIMUM CENTRAL PRESSURE 
IN L44, VALID AT 1200 UTC 23 FEBRUARY 1997

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Pressure (hPa)</th>
<th>Forecast error$^1$ (hPa)</th>
<th>Positional error (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E18control</td>
<td>963</td>
<td>+5</td>
<td>160</td>
</tr>
<tr>
<td>E18drop</td>
<td>959</td>
<td>+1</td>
<td>135</td>
</tr>
<tr>
<td>E18sat</td>
<td>963</td>
<td>+5</td>
<td>100</td>
</tr>
<tr>
<td>E18dropsat</td>
<td>959</td>
<td>+1</td>
<td>80</td>
</tr>
<tr>
<td>E18null</td>
<td>962</td>
<td>+4</td>
<td>160</td>
</tr>
<tr>
<td>E18oper</td>
<td>960</td>
<td>+2</td>
<td>135</td>
</tr>
</tbody>
</table>

$^1$ The verifying central pressure is 958 hPa in a NOGAPS T79L18 operational analysis using all regular observations and special FASTEX data. All experiments are 24 h forecasts started at 1200 UTC 22 February, except E18oper which is a 48 h forecast from 1200 UTC 21 February 1997, containing all available observational data.

in the SV calculations is the 48 h forecast whose sea-level pressure forecast is shown in Fig. 5(a).

For L44, we again examine SV structure at 300 and 600 hPa, which are representative of the upper troposphere and level of greatest sensitivity, respectively. At 300 hPa there is strong sensitivity to vorticity on both sides of the upper-level jet over the extreme east of Canada (Fig. 6(a)). Note that the main concentration of potential vorticity is located east of this sensitivity, at approximately 55°N, 50°W. Sensitivity to temperature is relatively weak at 300 hPa (Fig. 6(b)), but is strong at 600 hPa to the south and east of the surface low (Fig. 6(d)). Note in Fig. 6(d) that the strong sensitivity to 600 hPa temperature extends below the upper-level jet from the right-entrance to the left-exit region.

Maximum sensitivity to vorticity at 600 hPa (Fig. 6(c)) is located south-west of the surface low, more or less directly below the wind speed maximum at 300 hPa. The amplification factor of 5.5 for the leading SV in this forecast is considerably less than in IOP17, since it is only a 24 h forecast and the deepening rate of L44 over this interval (approximately 24 hPa in 24 h) is not as large as for L41 in IOP17. The amplification factors for SV2 (4.5) and SV3 (3.4) are relatively close to that of the leading SV, so they are weighted more heavily in the targeting considerations for IOP18. Additional information about SV structure in both IOP17 and IOP18, including vertical cross-sections, is provided in G99.

The upstream target area for special observations in IOP18 (32°W–60°W, 45°N–58°N) is based mainly on inspection of SV1 to SV3 initial temperature and vorticity at 600 hPa. Areas indicated as sensitive by the leading SVs over eastern Canada were considered inappropriate for aircraft survey as part of FASTEX, but were observed using the satellite wind data.

(c) NOAA G-IV mission

A 6.5 h G-IV mission from Shannon to Goose Bay, Labrador (take-off at 0800 UTC, landing at 1430 UTC 22 February) deployed 24 GPS drop sondes (positions shown in Fig. 6), with most sondes released near 27 000 ft. The flight pattern was based on SV and gradient sensitivity information provided by NRL and Météo-France, and also included a subjective survey of the main upper-level vorticity feature, accomplished by the south-to-north flight segment along 42°W and subsequent westward track to Goose Bay. We note that the sonde spacing of less than 100 km used on this mission was for the subjective feature survey, and fewer sondes could have been deployed for objective targeting. In terms of providing a more complete survey of the primary SV
Figure 6. IOP18 initial-time fields at 1200 UTC 22 February 1997 used for real-time targeting: (a) SV1 vorticity and (b) SV1 temperature at 300 hPa; (c) SV1 vorticity and (d) SV3 temperature at 600 hPa. SVs are shaded with contour intervals of 4 K for temperature and \(20 \times 10^{-5}\) s\(^{-1}\) for vorticity; note that the fields shown are not scaled to represent perturbations of conventional temperature or vorticity. Unshaded contours are E1\&control wind speed (m s\(^{-1}\)) in (a) and (c) and potential temperature (K) in (b) and (d). Crosses indicate dropsonde positions. L indicates the best analysed position (using all data) of cyclone L44. The outlined box is the SV observational target area for IOP18. PV in (a) and (b) indicates the centre of the 300 hPa potential-vorticity feature that is dynamically associated with L44. See text for further details.
target features at 600 hPa, the NOAA G-IV mission in IOP18 was apparently more successful than in IOP17.

(d) Data-impact experiments

A 24 h control forecast for IOP18 was started from initial conditions at 1200 UTC 22 February, using a 6 h data assimilation cycle containing no special FASTEX dropsonde, ship, or radiosonde data during the previous 24 h. The 24 h control forecast (E18control) has a positional error of 160 km and a central pressure error of 5 hPa (Table 3) due to under deepening and a westward shift of the low centre (Fig. 5(b) and (c)). The verifying NOGAPS analysis at 1200 UTC 23 February includes all available data that were transmitted in real time for assimilation, including dropsondes deployed by the NOAA P-3, and satellite wind data.

A series of forecast experiments was conducted to investigate the effect of assimilating targeted dropsonde and satellite wind data on 24 h forecasts of L44. The results of these experiments are summarized in Table 3, in terms of sea-level pressure error. We also use a 24 h forecast-error norm as a measure of forecast quality (Table 4). Each forecast experiment involves a separate 24 h integration of the nonlinear global forecast model at T79L18 resolution, starting from initial conditions which add to the E18control only the specific observational data denoted in the ‘additional observations’ column of Table 4.

We first consider the addition of only the G-IV dropsonde observations to the control analysis (experiment E18drop). These data produce a relatively large negative temperature difference (over 6 K) at 600 hPa (Fig. 7(b)) south-west of the surface low, and directly below the prominent upper-level vorticity feature. A significant fraction of this analysis difference is located in a sensitive area, from inspection of Fig. 6(d). At 300 hPa the dropsonde data produce sizeable differences in vorticity (Fig. 7(a)) on the north side of the jet core, but these occur mostly in areas of weak upper-level SV amplitude (Fig. 6(a)). It is interesting to note that the largest analysis differences in this case are relatively close to the well-observed Canadian coastline.

In comparison to the E18control analysis, the E18drop analysis in the target area has a stronger north–south temperature gradient at 600 hPa south-west of the surface low. This results from lower temperatures in the E18drop analysis on the north side of the baroclinic zone. The surface low is located farther west in the colder air and its central pressure is reduced by several hPa. There is also a strengthening of the upper-level jet and the associated potential-vorticity feature.

At 24 h (1200 UTC 23 February) the forecast including the dropsonde data has lower surface pressure south of the surface low centre and a smaller region of increased pressure to the north-west (Fig. 7(f)). The surface pressure response is well-centred within the FVA, but does not appear to have the proper configuration for optimum correction of the control-run pressure error (Fig. 5(c)). However, compared to E18control there is a 4 hPa improvement in central pressure and a 25 km decrease in positional error for the E17drop forecast of L44 (Table 3). There is a 25% decrease in the 24 h forecast-error norm in E18drop compared to E18control, with improvements as large as 35% in the middle troposphere (Table 4).

Wind vectors derived from GOES-8 provide a considerable amount of observational data in IOP18 (Fig. 8), and are used to conduct several additional forecast experiments. To determine the impact of all satellite wind observations over the north Atlantic, GOES-8 wind data in a 2 h window centred on 1200 UTC 22 February are assimilated within the area 10°W–70°W, 45°N–60°N. In this experiment (E18sat), there is essentially no improvement in the forecast central pressure of L44 (compared to E18control),
TABLE 4. FASTEX IOP18: 1200 UTC 22 to 1200 UTC 23 February 1997. The 42 h forecast-error norm ($\varepsilon_{24}$), and its percentage change ($\Delta\varepsilon_{24}$) with respect to E18control, for data-impact experiments calculated in the FVA: 15°–30°W, 48°–63°N

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Additional observations</th>
<th>$\varepsilon_{24}$ (J kg$^{-1}$)</th>
<th></th>
<th></th>
<th></th>
<th>$\Delta\varepsilon_{24}$ (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>150–399 hPa</td>
<td>400–699 hPa</td>
<td>700 hPa</td>
<td>150 hPa</td>
<td>150–399 hPa</td>
<td>400–699 hPa</td>
<td>700 hPa</td>
</tr>
<tr>
<td>E18control</td>
<td>Control (excludes research aircraft data, satellite wind data, FASTEX ship soundings at 1200 UTC 22 February)</td>
<td>0.0458</td>
<td>0.0724</td>
<td>0.0535</td>
<td>0.1717</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>E18drop</td>
<td>24 targeted GPS dropsondes deployed from the NOAA G-IV during a 6.5 h mission centred on 1200 UTC 22 February</td>
<td>0.0320</td>
<td>0.0469</td>
<td>0.0496</td>
<td>0.1284</td>
<td>–30</td>
<td>–35</td>
<td>–7</td>
</tr>
<tr>
<td>E18sat</td>
<td>GOES-8 wind data (visible, IR, and water vapour) within the area 10°W–70°W, 45°–60°N during a 2 h interval centred on 1200 UTC 22 February</td>
<td>0.0396</td>
<td>0.0511</td>
<td>0.0420</td>
<td>0.1326</td>
<td>–14</td>
<td>–29</td>
<td>–21</td>
</tr>
<tr>
<td>E18dropsat</td>
<td>E18drop + E18sat</td>
<td>0.0313</td>
<td>0.0336</td>
<td>0.0417</td>
<td>0.1065</td>
<td>–32</td>
<td>–54</td>
<td>–22</td>
</tr>
<tr>
<td>E18null</td>
<td>GOES-8 wind data and ship$^1$ soundings outside the SV-based target area (32°W–60°W, 45°N–58°N) at 1200 UTC 22 February</td>
<td>0.0429</td>
<td>0.0770</td>
<td>0.0542</td>
<td>0.1741</td>
<td>–6</td>
<td>+6</td>
<td>+1</td>
</tr>
</tbody>
</table>

See Gelaro et al. (1999) for the definition of the error norm. Verification is against a NOGAPS T79L18 operational analysis using all regular and special FASTEX observational data.

$^1$Ship soundings for the null experiment are from the FASTEX vessel: Aegir (60.0°N, 28.1°W), and other soundings are provided at 38.2°N, 31.0°W, and 34.2°N, 30.1°W.
Figure 7. IOP18 differences (E18drop - E18control) of analysed: (a) vorticity at 300 hPa; (b) temperature at 600 hPa; and (c) sea-level pressure, all at 1200 UTC 22 February 1997. (d), (e) and (f) are as (a), (b) and (c) but for differences between 24 h forecasts at 1200 UTC 23 February 1997. The differences are shaded with contour intervals of: $2 \times 10^{-5}$ s$^{-1}$ in (a) and (d); 1.0 K in (b) and (e); and 1 hPa in (c) and (f). Unshaded contours are E18drop wind speed (m s$^{-1}$) in (a) and (d), potential temperature (K) in (b) and (e), and sea-level pressure (hPa) in (c) and (f). Crosses in (a), (b) and (c) indicate dropsonde positions. L indicates the best analysed position (using all data) of cyclone L44 at the initial or forecast time. The outlined box defines the IOP18 SV-based observational target area in (a), (b) and (c) and the forecast verification area in (d), (e) and (f). See text for further details.
Figure 8. Observed wind vectors derived from GOES-8, valid at 1200 UTC 22 February 1997: (a) above 400 hPa; (b) 400–600 hPa; (c) below 600 hPa. Unshaded contours are E18control wind speed (m s⁻¹) at 300 hPa in (a), and at 500 hPa in (b), and analysed 750 hPa potential temperature (K) in (c). L indicates the best analysed position (using all data) of cyclone L44. The outlined box defines the SV-based observational target area from which wind data is excluded in the E18null experiment. Solid dots indicate locations for two of the three ship soundings used in the E18null experiment. See text for further details.
but the positional error is reduced to a greater extent than in \textit{E18drop} (Table 3). The forecast-error norm in \textit{E18sat} is reduced by 23\%, or about the same amount as in \textit{E18drop}.

We next assimilate both satellite wind data and dropsonde data, in experiment \textit{E18dropsat}, to determine whether combined use of the two different data types provides a greater improvement in forecast skill than either type provides separately. In comparison to \textit{E18drop}, \textit{E18dropsat} contains a larger initial difference in 600 hPa temperature south-west of the surface low (not shown), due to wind data provided in the lower troposphere (Fig. 8(c)). At 300 hPa the inclusion of satellite wind data expands the region affected by analysis differences outside the target area, but does not provide any additional enhancement of the upper-level vorticity feature (compared to \textit{E18drop}).

At 24 h, \textit{E18dropsat} provides the most accurate forecast of L44, with a positional error of only 80 km and a 1 hPa error in central pressure (Table 3). This suggests that the combination of dropsonde and satellite data is an effective mix of observational resources for this forecast. The error norm in \textit{E18dropsat} is reduced by 38\%, compared to 25\% and 23\% in \textit{E18drop} and \textit{E18sat}, respectively. A 54\% error reduction is achieved in the mid troposphere (Table 4). Although these are large percentage error reductions, the magnitude of the forecast-error norm in IOP18 is considerably less than in IOP17.

In a final experiment (\textit{E18null}), GOES-8 wind data and ship-based soundings (Fig. 8) are assimilated outside the defined target area (32°W–60°W, 45°N–58°N) at 1200 UTC 22 February (analysis differences shown in Fig. 9(a) to (c)). The impact of these data which are positioned in less sensitive regions in the forecast of L44 is very small. At 24 h there is little impact inside the forecast verification area (Fig. 9(d) to (f)). In \textit{E18null} there is only a 1 hPa improvement over the \textit{E18control} forecast central pressure for L44, and no correction of positional error (Table 3). The change in forecast-error norm is only 1\%, which is less than in any of the other experiments performed for IOP18.

6. Summary of Results and Targeting Issues

The targeted-observation problem concerns the question: in what location(s) will correction of analysis error through the addition of a relatively small number of special ‘targeted’ observations (by either \textit{in situ} or remote-sensing platforms) have the greatest positive impact on a forecast of a significant weather feature (such as an extratropical cyclone)? In the particular context of FASTEX, targeted observing was designed to improve short-range (three days or less) forecasts of frontal-wave cyclones affecting the British Isles.

In FASTEX it was demonstrated that SVs and gradient sensitivity information, provided by NRL and Météo-France, can be used in an operational framework for targeted observing (see also Bergot 1999). However, during the field programme, only limited use was made of the available reconnaissance aircraft for the purpose of observing SV-based target regions in the far upstream FASTEX domain. As a result, in relatively few FASTEX IOPs were the SV-based target regions adequately surveyed by dropsonde (or other) observations. In this study, we have examined SV target guidance and the impact of dropsonde observations, satellite wind data, and other types of observations in IOPs 17 and 18. Forecast skill is evaluated in terms of surface cyclone pressure and positional error, and using a forecast-error norm (150 hPa to the surface) within a defined verification area.

Dropsondes deployed by the NOAA G-IV in IOP17 provided a partial survey of the NRL SV-based target area, east of the developing surface low centre. The assimilation
Figure 9. As Fig. 7 but for IOP18 differences (E18null - E18control). In this case unshaded contours are for E18null and dropsonde positions are not marked.
Figure 9. Continued.
of these dropsonde data introduces analysis differences that improve a 42 h forecast of L41 in the lower troposphere, but degrade the forecast in the upper troposphere. This partial forecast degradation in IOP17 suggests that the introduction of dropsonde data, in certain configurations, can actually make parts of the model analysis worse. Although the impact of targeted data clearly depends on the particular forecast model and assimilation system being used, forecast degradations related to assimilation of dropsonde data are evidently not uncommon, as shown in the FASTEX summary study by Bergot (1999). The results from FASTEX suggest that greater attention should be given to the design of survey patterns for dropsonde data to provide adequate coverage of target structures, since it cannot be assumed that the addition of new observations in an arbitrary, or a very localized, pattern will necessarily result in an improved analysis or forecast. The development of flow-dependent covariances, as suggested by Fischer et al. (1999), and other improvements in data assimilation are also likely to increase the potential benefits of targeted observations.

In a series of experiments, the best 42 h forecast of L41 in IOP17 was obtained from the addition of several US and Canadian RAOB soundings (special FASTEX reports at 0600 and 1800 UTC) that provided data in the most sensitive part of the SV target area south-east of Nova Scotia. Although the analysis differences produced by the RAOB data in IOP17 are much smaller than those from the dropsonde data, they produce a larger forecast improvement. This demonstrates a key principle of targeted observing—correction of small analysis errors in sensitive locations (within the subspace of the leading SVs) can have equal or greater importance than correction of larger analysis errors in less sensitive locations (for additional results see G99). The use of targeted data even in regions that are considered well-observed by conventional observations (such as the US and Canadian coastal area) can be justified when there are large error growth rates, as implied by the large SV amplification factors in IOP17.

A relatively good coverage of the NRL and Météo France SV-based target area was provided by dropsondes from the NOAA G-IV in FASTEX IOP18. The target area, south of Greenland, includes a region of strong thermal gradients below the left-exit region of an upper-tropospheric jet. In a 24 h forecast of L44, targeted dropsonde data and satellite wind data (used separately) were each able to provide substantial error reduction in the upper and lower troposphere and improve the forecast position and central position of L44, although the magnitude of the forecast error in IOP18 is much less than the 42 h forecast error in IOP17. The best forecast of L44 is obtained by inclusion of both the dropsonde data and satellite wind data which suggests, at least in this case, that a mix of in situ and remotely-sensed data can have an additive positive impact. It is encouraging to note that even a relatively small forecast error, as occurs in this forecast of L44, can be reduced when an objective target area is well-surveyed by dropsondes or satellite wind data.

While the use of SVs for targeted observing may suggest different locations (or levels) than those that might be targeted from a purely subjective approach, there is a dynamical basis for the location and structure of the leading energy-norm SVs that is consistent with traditional understanding of cyclone development mechanisms. In the forecasts examined here, SV target areas occur in proximity to a lowered tropopause, but are centred near 600 hPa in regions of strong thermal gradients below the main concentration of potential vorticity in the upper troposphere (see Fig. 4 of G99 for a cross-sectional depiction of these features in IOPs 17 and 18).

FASTEX has provided an important first step in the efforts to develop, test, and evaluate methods for targeted observing. Future efforts in targeted observing will focus on the refinement of methods to estimate forecast sensitivity, and the design of survey
patterns that may be better integrated with data assimilation requirements. It is also important to consider the potential value of targeted dropsonde data in the context of more advanced satellite wind products, as suggested in preliminary results from the North Pacific Experiment (Langland et al. 1999).

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