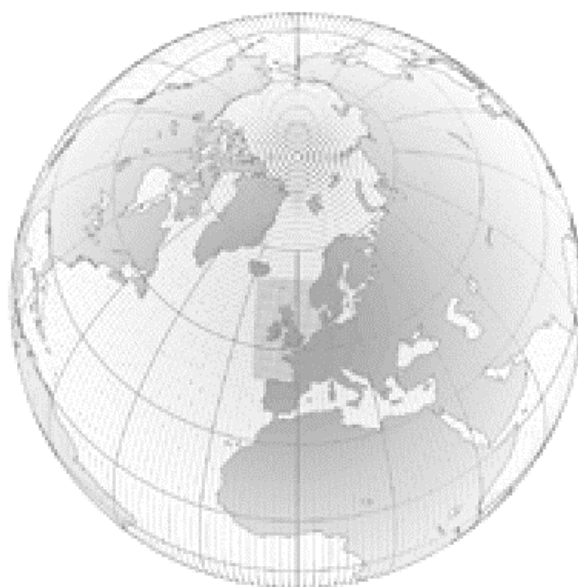


Numerical Weather Prediction

The impact of observations on Limited Area Model forecasts during the
FASTEX Campaign



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A decorative wavy line that starts on the left, dips down, rises to a peak, and then dips down again towards the right.

The Impact of Observations on Limited Area Model Forecasts During the FASTEX Campaign

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The Impact of Observations on Limited Area Model Forecasts During the FASTEX Campaign

S.R. Anderson

1. Introduction

1.1 Background and aims of study

The main aim of this work was to investigate the impact of observations on the accuracy of forecasts of mean sea-level pressure (PMSL) from the UKMO Limited Area NWP model. All the forecasts studied were made during the field phase of the Fronts and Atlantic Storm Track Experiment (FASTEX) in January and February of 1997. During this period there were many more observations than normal made over the North Atlantic region. These included more frequent radiosonde ascents, from selected land stations and ships positioned in the mid-Atlantic, as well as drop-sondes released from specially fitted research aircraft and a greater number of drifting buoy and ship reports. The drop-sonde observations in particular were made during Intensive Observing Periods (IOPs), chosen in real time by an international team of scientists based in Shannon, in SW Ireland. A further aim of the impact studies was to provide evidence to show the real time benefit of such an adaptive observational network, especially regarding the use of targeted drop-sonde observations.

Some of this work has been presented before (see Anderson *et al.*, 1998 (1)), but this paper aims to complete the study. It includes new results as well as further insight, including an assessment of the impact of the targeted drop-sonde observations in synoptically sensitive areas using singular vectors.

A description of the FASTEX campaign is given in Joly *et al.* (1997), and a catalogue of the dates, times and synoptic events for each IOP in Clough *et al.* (1998). A full description of the 50km resolution, 19-level Limited Area Model (the LAM - operational until April 1998) can be found in Cullen (1993).

1.2 Overview of this report

The paper is divided into the following sections. Section 2 contains an analysis of the procedure used to select the cases. The case study method used to obtain the results is described in Section 3. For a greater understanding, however, the reader is strongly recommended to follow the steps in Section 4. This section contains a full account of a worked example for Case 1, in which the impact on model forecasts of drop-sonde data from IOP 10 is shown. Section 5 discusses the impact of drifting buoy data.

The results are summarised in Section 6, and discussed in Section 7. Finally,

conclusions and recommendations are presented in Section 8.

2. Case Selection Technique

Cases in which initial data had a marked benefit on forecasts of PMSL were identified by looking for notable improvements in forecast skill between consecutive operational forecasts valid at the same time (following Graham and Anderson, 1995). Improved skill may be attributed to the additional observations available for assimilation in the later run (provided impact from the more recent boundary conditions used in the later run can be discounted). Cases in which an objective measure of forecast skill indicated a 'significant' improvement in the T+30 forecast over the T+36 forecast, for example, or the T+18 forecast over the T+24 forecast, say, were short-listed for study. The criterion used for such a 'significant' improvement in the PMSL forecast was a reduction in the maximum PMSL error of 55% or more, measured over the entire LAM domain.

Twenty such cases were highlighted during the two months of the FASTEX field phase. Each potential case was studied subjectively to assess whether it was worthy of further investigation. During this process, cases were selected if, for example, forecasts were poor over the eastern Atlantic and western Europe (and not near the western boundary of the model domain). Nine cases were identified. In three of these, the improvements to the model forecasts were found to have come from updated model boundary conditions. However, the remaining six cases showed improvements arising from observations within the LAM area. The summary of results given in Section 6 is therefore based upon these six data impact case studies.

3. Method for assessing impact of observations

3.1 Experiment format

To assess the impact of the observations, a series of model re-runs was performed for each case. For this study, all the data impact experiments comprised a 6-hr assimilation step (using the UKMO analysis correction scheme - see Lorenc *et al.*, 1991) followed by a forecast for up to 30 hours.

For each case, two control runs were performed. The ALL OBS run, which used all the available observational data (i.e. including any FASTEX observations made during the IOPs which were received by UK Met. Office observational fields files in time for the operational LAM runs), and the NO OBS run which entailed a dummy assimilation using no data. Fig. 1 is a schematic showing the two control runs. The NO OBS run represents the earlier, poor forecast, whilst the ALL OBS run represents the next consecutive operational model forecast, which includes the 6 hours of observations made between the two runs.

All the re-run experiments were designed to mimic as closely as possible the operational model runs. However, there was a difference in how the model boundary

data were utilised. Operationally, the boundary data were updated every 6 hours, the fields being created from the UKMO Global Model. In these re-runs, identical boundary conditions were used for both the NO OBS and ALL OBS runs. This meant that, provided the ALL OBS forecast showed a significant improvement over the NO OBS forecast, it could be concluded that the benefit has come from the observations, rather than through the model boundary.

For the remaining experiments in each case study, each observation type was assimilated individually, and its impact recorded (as described in Sub-section 3.3). This method of assessing the impact of observation types separately provides useful insight into which data types play key rôles in an observational network - a requirement for network design. (The alternative method of omitting each observation type in turn from the assimilation has the disadvantage in that some degree of redundancy would normally be expected in the benefit from many data types. If experiments are run omitting one data type, then it is likely that its absence will be compensated by other remaining types).

Further runs were usually carried out to gain more insight into which combination of observation types provided the most benefit in individual cases. More details of the method can be found in Section 4, where the procedure and results from an example case study are described.

3.2 Observation types used

The observation types used in the UKMO Limited Area Model included sonde winds, temperatures and humidities, aircraft winds and temperatures, surface observations (of PMSL, winds from SYNOPs, moored buoys and ships, and temperatures and humidities from SYNOPs), satellite temperatures and cloud-track winds. All these data types were assessed separately.

In addition to the above, a 3-D moisture field, generated by the Moisture Observation Processing System (MOPS), was used. For a detailed description of this system see Macpherson *et al.* (1996). Briefly, the purpose of MOPS was to generate a 3-D analysis of cloud fraction from satellite and radar rainfall imagery, selected SYNOP observations and a short-period forecast. The elements of the SYNOP used were cloud cover, base and type and present weather. The analysis of cloud fraction was then used to derive relative humidity profiles which were assimilated as "pseudo radiosondes", with one profile per grid-square.

3.3 Forecast verification

Forecast skill was assessed by comparing the PMSL forecast with the model analysis of the PMSL valid for the same time. Verification was performed over an area chosen independently for each case. See Section 4 for more details.

The Root Mean Square Error (RMS Error) was calculated over the verification area. The skill of each forecast was then expressed as a percentage of the difference in skill between the ALL OBS and NO OBS controls. For example, for an 'aircraft winds only' (AcW) forecast,

$$\text{BENEFIT OF AcW} = \frac{[\text{RMSE}(\text{AcW}) - \text{RMSE}(\text{NO OBS})]}{[\text{RMSE}(\text{ALL OBS}) - \text{RMSE}(\text{NO OBS})]} \times 100\%. \quad (1)$$

In addition to this objective measure of skill, a synoptic evaluation of each forecast was also performed.

4. Worked example: Case 1 - the impact of drop-sonde data

In this section we work through one of the case studies (Case 1: verifying at 00UTC, 5th February 1997). This case showed a significant impact from a small number of drop-sondes, released on 3rd February as part of IOP 10. The method of objective verification used to gather the results is presented, as well as a synoptic evaluation of the impact on forecast skill made by the observations.

Synoptic evaluation and control runs

Fig. 2 shows the T+36 PMSL forecast from the 12UTC run on 3rd February, valid at 00UTC on the 5th. Fig. 3 shows a forecast from the next operational LAM run - the T+30 forecast from the 18UTC run, valid at the same time. The T+36 forecast (Fig. 2) has a low pressure system positioned over the Irish Sea, with a central pressure of under 996 hPa. The T+30 forecast (Fig. 3) shows a much weaker system, now positioned over southern England, with a central low pressure of around 1004 hPa. The difference between these two consecutive model runs is shown in Fig. 4. There is a peak value of 14 hPa pressure difference over Ireland.

The surface analysis for 00UTC on 5th February 1997 is shown in Fig. 5. The low pressure system over the UK turned out to be weak, represented by a shallow trough over SE England, with a central pressure of about 1010 hPa. Comparing the two forecasts with the analysis (see difference charts, Figs. 6 and 7), we can see how the later model run produced a better forecast. Figs. 2 and 3 therefore represent the earlier, poor, forecast (the NO OBS run) and the later, improved, forecast (the ALL OBS run) respectively.

Verification was performed by comparing the model forecasts with the analysis field shown in Fig. 5. RMS Errors were calculated over the verification area highlighted in Figs. 6 and 7. Note that a different area, over which to verify, was chosen for each case, but that it was always chosen to encompass the main difference between the NO OBS and ALL OBS forecasts - usually an error dipole, caused by the repositioning of a low pressure system for example.

The results for the two control runs for this case are shown at the top of Table 1a. The superiority of the ALL OBS run is reflected in a lower RMS Error (2.98 hPa compared to 5.88 hPa for the NO OBS run). This establishes the fact that data introduced in the 6-hr assimilation cycle prior to the ALL OBS forecast delivered a marked benefit.

	RMS Error (hPa)	%age of ALL OBS benefit	Rank
NO OBS	5.88	0	
ALL OBS	2.98	100	
Sonde winds (SoW)	4.94	32	2nd
Sonde temperatures (SoT)	5.05	29	3rd
Sonde humidities (SoH)	5.28	21	6th
Aircraft winds (AcW)	5.26	21	5th
Aircraft temperatures (AcT)	5.06	28	4th
Surface observations (SFC)	4.79	38	1st
Cloud-track winds (SATOBS)	5.50	13	7th
Satellite temperatures (SATEMS)	6.08	-7	9th
MOPS only	5.79	3	8th

Table 1a - Results for Case 1.
Control experiments and impact from individual observation types.

Impact of individual observation types

We now investigate the rôle that the individual observation types played in the impact. The forecasts were re-run, each time assimilating a different observation type, and the effects on the RMS Error noted. The remainder of Table 1a shows the results of these runs for Case 1. Percentage improvements, as calculated using Equation 1, are included, as well as the ranking of each individual observation type.

The results show that the most beneficial individual observation types were surface observations (38%), sonde winds (32%), sonde temperatures (29%) and aircraft temperatures (28%).

Tables like this were compiled for each of the six case studies.

Impact of combined observation types

Further runs were carried out combining observation types in the hope of finding a small subset of types that would produce a forecast closely resembling the ALL OBS control run. Table 1b shows the results of the further runs for Case 1. The run using surface observations, sonde winds and temperatures and aircraft temperatures produced a 100% improvement in forecast skill. This result shows how only four observation types can match the effect of all the observations used in the ALL OBS forecast.

Impact of drop-sonde data

Another approach was to test the effect of combining all the sonde information (i.e. the wind, temperature and humidity components from the radiosondes and drop-sondes). This produced a 65% benefit. When these combined data were divided differently, it was found that the information from drop-sondes alone provided a 58% benefit, whilst the information from radiosondes gave only 9% of the ALL OBS benefit.

A further re-run showed that the profile data from drop-sondes in the region 45°N - 55°N, 52°W - 25°W provided a 59% benefit. Drop-sondes had been deployed in that region between 15 and 18UTC on 3rd February 1997, as part of IOP 10, from the American Gulf IV aircraft flying at 26,000', and the data from ten of these profiles had reached the UKMO observational fields files in time to be assimilated into the later model run. Fig. 8 shows the positions where these ten drop-sondes were released.

Fig. 9 shows the forecast from the run using those ten drop-sondes alone. We see the low pressure centred over NW England, with a value of about 1000 hPa. This is an improvement on the NO OBS forecast (Fig. 2), but not as good as the ALL OBS run (Fig. 3).

A forecast was also performed using all the observation types except the beneficial drop-sondes. This produced only 70% of the ALL OBS benefit, implying that if the drop-sondes had never been deployed, the UKMO operational T+30 forecast from 18UTC on 3rd February 1997 would have been 30% less skilful, over the UK region, than in reality.

More re-runs, assimilating the drop-sonde observations at various different ranges of vertical model levels, revealed that the profile information in the middle troposphere, between 700 hPa and 500 hPa, gave the most benefit. It is interesting to consider this result from the point of view of attribution theory, regarding vertical motion as an indicator of synoptic development (see Clough, Davitt and Thorpe, 1996). The importance of forcing, which may predominate in determining the short-range development of weather systems, may be seen to be concentrated in space and time in the region of the steering level near 600 - 700 hPa. Further work in this area is continuing. This observational and theoretical evidence may lead to important practical implications for observing over the oceans, especially beneath the cruise level of aircraft, where more high resolution upper air data are required.

	RMS Error (hPa)	%age of ALL OBS benefit
SURFACE + SoW	4.12	61
SURFACE + SoW + SoT	3.33	88
SURFACE + SoW + SoT + AcT	2.97	100
All sonde data (SoW+SoT+SoH)	3.99	65
Drop-sondes only	4.21	58
Radiosondes only	5.63	9
Drop-sondes in area 45°N - 55°N, 52°W - 25°W	4.18	59
ALL OBS - Drop-sondes	3.86	70
Drop-sondes in area 45°N - 55°N, 52°W - 25°W, between 700 hPa and 500 hPa only	4.15	60

Table 1b - Results for Case 1.
Impact from combined observation types.
(See Table 1a for an explanation of the abbreviations)

Comparison with findings of singular vector analysis

Maps of singular vectors, showing the sensitive areas for each case (i.e. the areas where observations would potentially help the most in improving the model analysis and limiting the consequent error growth), were produced by Andrea Montani at the University of Reading, given the dates and times of all our cases, and the areas where the forecast differences had been seen. The adjoint scheme was then able to trace the forecast

differences back in time and space, and highlight the areas predicted to be sensitive at analysis time. Note that the singular vectors are 3-dimensional, depicted over a range of model levels. A full explanation of the technique used, utilising the ECMWF adjoint scheme, and how to interpret the maps is given in Montani *et al.* (1998).

The map showing the most dominant singular vector in the temperature field for Case 1 is reproduced in Fig. 10. It corresponds with model level 12 (at around 600 hPa), and shows that the most sensitive region for this case - shown as the peak in the contour field - is situated east of Newfoundland. This coincides exactly with the area where the ten beneficial drop-sondes were deployed (see Fig. 8), and shows the success of targeting observations in this case.

Note that this was not the only method used to target observations during the FASTEX campaign. For more details of the theory, and for descriptions of the other methods available, the reader is referred to Joly *et al.* (1997) (a pre-FASTEX paper where the structures of singular vectors are discussed, as well as the sampling rates thought to be required for the FASTEX drop-sondes), Pu *et al.* (1998) (where the success of the use adjoint techniques during FASTEX is examined) and Toth *et al.* (1998) (where the use of ensemble-based targeting is discussed).

5. Case 6 - the impact of drifting buoy data

Case 6 (verifying at 12UTC, 15th January 1997) took place during IOP 3. There were no drop-sondes deployed during the 6-hr assimilation period used in the model re-runs. However, the observational network over the North Atlantic was enhanced all the same, with extra radiosondes being deployed from the FASTEX ships for example. This case shows a significant observational impact from a small number of drifting buoys in the North Atlantic, and a lesser impact from the sondes released from the FASTEX ships.

Synoptic evaluation and control runs

Fig. 11 shows the NO OBS control for this case, the T+24 PMSL forecast from the 12UTC run on 14th January 1997, valid at 12UTC on the 15th. The synoptic system of interest is the depression over the North Atlantic, with a central pressure forecast to be less than 980 hPa. Fig. 12 shows the ALL OBS control forecast, the T+18 PMSL chart from 18UTC on the 14th, valid at the same time. The central pressure is now forecast to be below 976 hPa, and centred further south. The analysis for 12UTC on the 15th, shown in Fig. 13, has a very similar pressure pattern to the ALL OBS control run. Difference charts (not shown) confirm that the positioning of the depression in the NO OBS run caused a 10 hPa error dipole, whilst the improved ALL OBS run had a maximum error peaking at only 4 hPa, caused by the poor forecasting of the tight pressure gradient to the south the depression's centre.

Impact of individual observation types

Using the same method as described in Section 4, a table of results was compiled for this case. The verification area chosen is highlighted in Fig. 13. The re-runs using individual observation types revealed that the most beneficial data type in this case was the surface observations (86% of the ALL OBS benefit). Sonde winds (37%), sonde temperatures (31%) and aircraft winds (26%) also gave notable individual benefits.

Impact of drifting buoy data and of combined ship sonde data

Further experiments showed that information from drifting buoys rather than ships gave the largest benefit, and tracing the forecast errors back in time revealed the area where the most beneficial observations had been made. Just 6 drifting buoys in the area 42°N-50°N, 40°W-25°W, producing 17 reports in total in the 6-hr assimilation period, gave 77% of the ALL OBS benefit. Fig. 14 shows the positions of the drifting buoys at that time.

As mentioned previously, the FASTEX ships were in position and releasing radiosondes during this time. A model run using only the ten ship-sondes released from the four FASTEX ships in that 6-hr assimilation period produced 52% of the ALL OBS benefit. The positions of the ships are also shown in Fig. 14.

The singular vector maps for the period (not shown) revealed that the sensitive areas calculated for this case were positioned too far south to coincide with the positions of either the buoys or the ships. This does not constitute a failing of the targeting technique, however, as neither the buoys nor the ships were targeted (unlike the drop-sondes of Case 1). Limitations in the computation of the singular vectors (see Montani *et al.*, 1998) mean that perturbations near the surface are damped, and hence sensitive areas at low levels are difficult to predict. Of course, the impact of the ship-sondes may have been greater if they were collocated with the sensitive areas.

Table 2 summarises the results from this case.

	RMS Error (hPa)	%age of ALL OBS benefit	Rank
NO OBS	3.30	0	
ALL OBS	1.46	100	
Surface observations	1.72	86	1st
Sonde winds	2.62	37	2nd
Sonde temperatures	2.73	31	3rd
Aircraft winds	2.83	26	4th
Surface obs, ships only	2.16	62	
Surface obs, drifting buoys only	1.97	72	
Surface obs, drifting buoys only in area 42°-50°N, 40°-25°W	1.89	77	
Ship-sondes only in area 35°-55°N, 45°-30°W	2.34	52	

Table 2 - Results for Case 6.
Control experiments and summary of observation type impacts.

6. Results from all the cases

Table 3 contains the results from all six case studies. Results for the 18-hr, 24-hr and 30-hr forecasts have been combined.

The results of the study of these six cases are summarised below.

- Surface observations play a major rôle in two cases and a supporting rôle in three

more. In both Cases 3 and 6, it was found that the information supplied by a small number of drifting buoys in the mid-Atlantic provided notable benefits to the later forecasts. As described in Section 5, in Case 6, observations from only six drifting buoys gave 77% of the ALL OBS benefit. In Case 3, eight drifting buoys provided 41% of the benefit seen in the later forecast.

- Profile information from conventional radiosondes and the special drop-sondes plays a strong rôle in two cases and has some impact in two more. Case 1, in which just ten drop-sondes provide 59% of the ALL OBS benefit, is described in Section 4. In Case 4, radiosondes gave the most benefit (56%, compared to 12% from the available drop-sondes). For Case 6 there were no drop-sonde data available. However, a 52% impact was gained by only using radiosonde data from the four FASTEX ships (see Section 5 for more details). Note that in Cases 3 and 9, the drop-sonde information arrived too late to be included in the operational forecast. (The map in the Appendix shows the locations of the sonde stations used during the FASTEX campaign, including the typical positions of the FASTEX ships based around 35°W. Note that during the IOPs, many of these stations reported every 3 hours).
- Maps of singular vectors acquired for each case consistently show the sensitive areas to be located in the middle troposphere, between 700 and 600 hPa. For the cases in which the impact of profile information dominated, one case (Case 1) showed that the observations were collocated with the sensitive areas, both in the horizontal and vertical (see Section 4 for details), whilst in the other case (Case 4), the drop-sondes deployed by the UKMO over the eastern N.Atlantic just coincided with the southern edge of a sensitive area over Iceland, leading to a small impact of 12% of the ALL OBS benefit. Note that in this case, it was not possible to determine which stations helped to provide the dominant radiosonde impact.
- In two of the cases - Cases 8 and 9 - surface and sonde data contributed towards the impact, thus retaining the theme of the results from the other cases. However, SATEMS and aircraft winds also figured prominently. These cases have not been studied in detail. However, it is not surprising to see impact from other observation types in some cases because the impact will depend on the sensitive areas (in the horizontal and vertical) being collocated with the observations. The importance of aircraft winds in Case 9 is consistent with the result found in the study by Graham and Anderson (1995) in which the impact of different observation types was compared using the UKMO's global model.

Case	VT	I.O.P.	Dominant impact from...	Secondary impact from...	Notes
1	T+30	10	Drop-sondes (65%)	Surface obs (38%)	10 targeted drop-sondes provided a 59% benefit to forecast. Obs in sensitive area. See Section 4 for details.
3	T+18	19	Surface obs (88%)		8 drifting buoys in area 47°N-56°N, 41°W-24°W provided 41% of the ALL OBS benefit. No drop-sonde data available in UKMO observation files.
4	T+30	19	Radio-sondes (68%)	Surface obs (51%)	Radiosondes provided 56% of ALL OBS benefit, and drop-sondes provided 12%. Beneficial radiosondes could not be pin-pointed.
6	T+18	3	Surface obs (86%)	Ship-sondes (52%)	6 drifting buoys in area 42°N-50°N, 40°W- 25°W provided 77% of the ALL OBS benefit. No drop-sondes deployed during assimilation period. See Section 5 for details.
8	T+30	4	SATEMS (74%)	Surface obs (37%)	No drop-sondes deployed during assimilation period.
9	T+24	5	Aircraft winds (71%)	Radio-sondes (59%)	No drop-sonde data available in UKMO observation files.

Table 3 - Results from all cases.
(Percentages refer to benefit with respect to ALL OBS benefit, as calculated using Equation 1)

7. Discussion of results

This discussion is based on the results described in Table 3 as well as information gained during the FASTEX Conference held at Météo France in April 1998 (of which no reference can be given at this time).

a. Significance of results and discussion of case selection procedure

It is recognised that the results from just six case studies, over such a short period, may not fully represent the true benefit that each observation type makes. This study was deliberately set up, however, to study cases which showed sensitivity to initial data over the North Atlantic during the two months of the FASTEX field phase, and, according to the selection criteria, from all the forecasts made during that period, only six showed an observational benefit.

The reason that so few cases were selected can be partly explained as follows. A feature of this type of case selection procedure is that if forecasts during the period chosen are generally good, then relatively few cases will be selected. The FASTEX period was, for the most part, predictable. The period can be divided up into three distinct synoptic patterns. For most of January 1997, high pressure dominated over Greenland; then towards the end of January and into to the start of February, a blocking pattern developed. Both of these synoptic regimes posed few problems for the UKMO LAM. For the rest of February there existed an Atlantic-wide zonal flow. It is this final period which contains the most interesting FASTEX cases being studied internationally.

All our cases occurred within designated IOPs (and hence took advantage of an enhanced version of the conventional observational network), although only one case showed a major benefit from drop-sonde information. The case selection technique utilised, however, was not set up to highlight cases in which drop-sondes, in particular, had been deployed, and, in fact, only two cases featured data from drop-sondes.

b. Comparison with other FASTEX studies

During the FASTEX conference, many speakers presented work using data from the FASTEX Archive, which has been compiled at Météo-France. This archive contains all the observations made during the field study, and furthermore, the data have been cross-checked and corrected if necessary. Results from other studies showed significant impacts from the targeted drop-sonde data. The ECMWF adjoint scheme has been used successfully by Montani *et al.* (1998), for example. For IOPs 9, 11, 12 and 17, drop-sondes deployed in regions highlighted as sensitive by the singular vectors have been assimilated, and the re-runs have shown increases in forecast accuracy of, on average, 15% up to Day 2 (using RMS Errors of geopotential height).

The data impact studies carried out for this project could only assess the impact of the data which reached the UK Met Office observational fields files before the cut-off time was reached for each operational model forecast. Many FASTEX data arrived too late to be included, due to technical difficulties. It is encouraging that our results for Case 1 back

up the results of other studies.

Although it is recognised that the significance of any conclusions drawn on the FASTEX data in particular, is limited, the results of our studies into IOP 10 (Case 1) show how targeted data influenced *real-time* forecasts from an operational NWP model.

One recommendation may be to perform further data impact studies using the data in the FASTEX Archive, provided that problems with code formats can be resolved.

c. Comparison with other studies outside FASTEX

Studies outside FASTEX have also shown results to support these. The importance of profile information in NWP model forecasts has been highlighted by Pailleux (1998) using both global and limited area models, and more recently shown by Anderson *et al.* (1998 (2)) using a regional model. Surface observations were found to be highly beneficial in the global data impact studies by Graham and Anderson (1995), and a drifting buoy impact was found by Grant *et al.* (1998).

8. Conclusions and recommendations

The following conclusions may be drawn from the results of our six case studies looking at the impact of observations over the UKMO Limited Area Model domain on forecasts of PMSL:

- Surface observations and profile data supplied by radiosondes and drop-sondes over the North Atlantic have shown marked benefits to the forecasts of PMSL at ranges of up to T+30 over Western Europe.
- It was possible to deploy drop-sondes in synoptically sensitive areas in real time and for them to subsequently show significant data impacts of up to 60% of the benefit seen with all observation types. The sensitive areas could be identified using the techniques employed during the FASTEX field phase, including the use of singular vectors.
- In one case, profile data observed in the middle troposphere appeared to be especially important. This result confirms the work by Montani *et al.* (1998) which found that the most sensitive areas, identified using analysed singular vectors, usually coincide with these levels (where, importantly, there is a lack of profile data with high vertical resolution over the oceans).

These conclusions help achieve the aims of the study. The effectiveness of the drifting buoy data in Cases 3 and 6 suggests that the programme of deploying buoys should be continued, ideally at an increased rate. Also, the proof from Case 1 that real-

time operational forecasts can be improved, by up to 30%, by the inclusion of targeted drop-sonde observations taken over oceanic storm tracks, suggests that priority should be given to obtaining more profile data over the North Atlantic in particular.

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**Appendix: Map showing sample
locations of observations**

(from Clough *et al.*, 1998)

Appendix 2: Methods used to target observations

As mentioned in the introduction, during the FASTEX field study, an international team of scientists was gathered at Shannon primarily to decide when the intensive observing periods should take place over the two-month period. The aim of course was to target the extra drop-sonde observations (in particular) in areas where it was thought they would most benefit the forecast, i.e. in "sensitive areas" where initial errors were predicted to grow.

Although not part of this study, it is interesting to consider some of the methods used, especially as some of our results appear to back up the theories, and plots of sensitive areas produced by Andrea Montani were calculated using similar techniques.

The general idea is this: Errors in the initial conditions (the model analysis) will amplify during the course of a model forecast, and may lead to marked forecast errors downstream. If regions of potential forecast errors can be traced back to their origins in time, then by observing the atmosphere in these sensitive regions, the reduction in analysis errors will limit the consequent growth in forecast errors.

This process depends upon a reliable method of reversing the model forecast in order to trace back potential predicted model errors in time and space. Developments in this field are still progressing, but during the FASTEX field phase various methods were used, with varying degrees of success, to predict the areas where extra targeted observations would be of most benefit. These methods included the use of quasi-inverse linear and adjoint models and ensemble transform techniques.

For more details of these methods, the reader is referred to Joly *et al.* (1997) (a pre-FASTEX paper where the structures of singular vectors are discussed, as well as the sampling rates thought to be required for the FASTEX drop-sondes), Pu *et al.* (1998) (where the success of the use adjoint techniques during FASTEX is examined) and Toth *et al.* (1998) (where the use of ensemble-based targeting is discussed).

Further References

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