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Recent Data Impact Studies at UKMO - a review

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1. Introduction

Results from two series of investigations to help assess the relative utility of each observation type for NWP operations are presented. The first series addresses relative utility for global model forecasts of PMSL. The second series addresses utility for mesoscale model forecasts of precipitation. Results from individual case studies with a Limited Area Model (LAM), including a case of impact from "targeted" observations during the FASTEX experiment, are also described. We use the UKMO NWP model (Cullen, 1991) which employs a "nudging" type assimilation scheme (Lorenc et al.,1991).

A case study approach is used in which the utility of observation types is assessed according to the frequency with which they deliver marked benefits on a sample of forecasts known to be sensitive to initial data. The main advantage of this method is that observation value is assessed according to the benefit delivered to forecasts of events which are of prime importance to operational meteorology (e.g. cyclogenesis or widespread rainfall). In contrast, the statistical approach, in which evaluation is performed over specific regions and periods, can result in important impacts on individual features being masked by negligible impacts during long "quiescent" spells.

Details of methods used are described in Section 2. Results from the global model study are presented in Section 3 and case study examples using the LAM in section 4. Results from the mesoscale model study are given in section 5. Section 6 contains a summary of results and recommendations.

2. Method

2.1 Case selection

The first step of the method is to compile a sample of cases known to be sensitive to initial data. This is achieved by looking for notable improvements in objective skill scores between consecutive operational forecasts valid for the same time (Graham and Anderson, 1995). Large improvements in skill indicate a significant benefit from the additional data assimilated prior to the later run. The objective case selection is used to construct a short-list of cases; the cases selected for study are then chosen from the short-list using subjective criteria. For the mesoscale model and LAM, the updating of boundary conditions between runs may also give marked improvements in skill. Therefore, for suspected cases of impact on these models, the later forecast is re-run without updating the boundaries. If the improvement in skill is still apparent, then we may assume that it derives from a data impact.

2.2. Forecast experiments

The aim of the forecast experiments is to determine, for each case, which observation type or types delivered the major part of the impact detected in the case selection procedure. The value of an observation type may then be assessed according to the frequency, over all cases, with which it delivers major impacts. The forecast experiments run for each case are described below.

The NO OBS and ALL OBS Controls

All experiments involve a period of assimilation (12hrs for the global model studies, 6hrs for the LAM and mesoscale model studies) followed by a forecast. Two control experiments are run. One uses all the available data in the assimilation (the ALL OBS run); the other entails a dummy assimilation using no data (the NO OBS run). The ALL OBS and NO OBS runs correspond, respectively, to the later "more skillful" operational forecast and the earlier "less skillful" operational forecast identified in the selection procedure.

Runs using single data types

To identify the data types which contribute to the observed impact we first perform a series of runs in which only a single data type is presented to the assimilation. The impact obtained with a single data type is referred to as the "individual" impact from that type. For most observation types the different variables reported are assessed separately (e.g. separate runs are performed for aircraft winds and temperatures).

The single-data-type runs give useful insight as to which data types play key roles in the observation network. Moreover, they give a measure of the relative benefit of data types between which some redundancy would normally be expected - and thereby give an idea of which type should have priority in the network. This issue is less easily addressed using the more usual method of withholding single data types from an assimilation using the full network - since a "potential" impact from the data type withheld will not be registered if a similar impact is imparted by one or more of the other data types assimilated.

Runs using combinations of data types

In addition to the single-data-type runs, the impact of combinations of observation types is also addressed to allow the effects of redundancy and synergy to be taken into account.

For the global model study the aim of the combined data runs is to identify, for each case, the smallest subset of data types required to deliver at least 90% of the benefit obtained when all data types are used. Results of the single-data-type runs are used to help construct the subset (referred to as the "90%" subset - for details see Graham and Anderson, 1995). The data types which form the 90% subset are also ranked (from 1 to 4) in order of cumulative benefit. The benefit of a data type may then be assessed according to the frequency and rank of its inclusions in the 90% subset.

3. The utility of observations for global scale (N. Hemisphere) NWP forecasts of PMSL

Using the method described above, the utility of observations for global-scale NWP operations has been assessed according to the frequency and significance of the benefits they deliver to 60-hour forecasts of PMSL. Results are based on twenty case studies which sample the most significant data impact events detected in routine operational forecasts, for Europe and North America, during the period September 1993 to May 1995. Results are therefore generally valid for Northern Hemisphere mid-latitudes. The 20 cases are divided into 10 for which the impact source was located over North America, and 10 where the impact source was located over the North Pacific or the North Atlantic (the latter 10 are referred to as the "oceanic" cases). For each case the benefit of each data type (or combination of types) to the PMSL forecast is measured according to the reduction in root-mean-square error, achieved relative to the NO OBS control, over an area enclosing the feature of interest.

3.1 Example case

An example case is shown in Figs.1a-d. The verifying PMSL analysis for the case is reproduced in Fig.1a and shows a depression of central pressure 989hPa located between the Great Lakes and Nova Scotia at 12GMT 2 November 1994. The corresponding 60-hr NO OBS forecast, shown in Fig.1b, has a considerable error in the location of the depression, which has been placed over Newfoundland, and in the central pressure (which is 10hPa too high). The corresponding forecast from the ALL OBS control run is shown in Fig.1c. Comparison with the analysis (Fig.1a) shows that the ALL OBS forecast was a very good one, both in terms of position and intensity. The greater skill of the ALL OBS run derives from the observations used in the 12-hr assimilation period prior to the forecast. (Recall that no data are assimilated in the NO OBS run over the same period). The aim of the forecast experiments is to identify the observation type or types that played major roles in the observed impact.

For this case the 90% subset was found to comprise aircraft winds, aircraft temperatures, radiosonde temperatures and surface observations. The forecast obtained when only these four data types are included in the assimilation is reproduced in Fig.1d. The similarity with the ALL OBS control forecast (Fig.1c) confirms that use of this subset of the data alone is sufficient to reproduce the major part of the benefit obtained when all the observations are used.

3.2 Results for all global model cases

Figs. 2a&b show the number of times (for the 10 North American and 10 Oceanic cases, respectively) that an observation type has been included in the 90%

subset at a given rank. The Rank 1 and Rank 2 observations contribute, on average, 85% of the benefit achieved by the ALL OBS control and are referred to as "key" observations for the case. The main results are summarised below.

North American Cases (Fig.2a)

- The key role of radiosonde and aircraft observations over North America is confirmed. These networks contribute most often and with similar frequency.

- Conventional surface data and cloud-track winds play the most important support roles.

Oceanic Cases (North Pacific and North Atlantic) (Fig.2b)

- Aircraft winds contribute most frequently.

- Conventional surface data play a key role.

The relatively high score for radiosonde data in the oceanic cases reflects the impact of coastal stations, and is not representative of the impact from the limited number of ship-based radiosondes.

3.3 Discussion of results

In this section we add some further findings and comments in addition to the main results given in the previous sub-section.

- Wind information contributes more frequently than temperature information (Figs.2a&b).

- The fact that radiosonde information contributes as frequently as aircraft information over North America (Fig.2a), despite the greater numbers of the latter, may reflect the advantages of profile information over single-level reports. Aircraft reports are most numerous at cruise-levels, where they will often be too high to give a good description of features important for cyclogenesis (e.g. regions of tropopause descent). At low- and mid-levels aircraft reports give less coverage than in the current radiosonde network.

- The few cases of benefit found from satellite temperatures partly reflect the fact that statistically retrieved temperatures were assessed. Use of direct radiance information from TOVS has been shown to give significantly more impact than statistical retrievals (e.g. Gadd et al., 1995).

- The high frequency of benefit found for radiosonde temperature profiles suggests that global coverage from forthcoming high resolution temperature sounders (e.g. IASI) may bring considerable benefits to NWP forecasts.

- No significant contributions from scatterometer 10m wind data were recorded. This contrasts with the high frequency of impact from (the less abundant) conventional oceanic surface data (Fig. 2b), and suggests that there is scope for improving the assimilation of scatterometer information. (Note, however, that significant positive impact from scatterometer winds has been found for the Southern Hemisphere (see e.g. Bell, 1994).)

4. Case studies with the Limited Area Model (LAM)

4.1 Impact from drifting buoys

An important finding from the studies with the global model described in Section 3 is the high frequency of impact found from the marine surface network. A striking example of the value of marine surface observations has been found in a study with the UKMO LAM (Grant et al., 1996). In this case, assimilation of drifting buoy reports near a small depression in the central North Atlantic greatly improved the 24-hr forecast of the depression's track with consequent improvements in the 24-hr precipitation forecast for the UK. The NO OBS and ALL OBS 24-hr forecasts of 6-hr precipitation accumulation are shown in Fig.3a&b, respectively. The ALL OBS run, with rainfall confined to the SW of the UK was a good forecast; as may be appreciated by reference to the location of the leading edge of the observed rainfall at verifying time, shown on Fig.3b. In contrast the NO OBS run gave a poor forecast, with rain predicted to spread eastward into central England with significant accumulations over Ireland.

After performing runs assimilating single data types it was found that nearly all the impact obtained with the ALL OBS run could be recovered by using only the drifting buoy observations. This may be appreciated by comparing the forecast obtained using only drifting buoys (shown in Fig.3c) with the ALL OBS forecast (Fig.3b). The locations of the drifting buoys used are shown superimposed on the initial analysis in Fig.3d. Further runs disclosed that most of the impact came from the buoys shown highlighted - these buoys were located near the initial position of the low (marked "+").

The impact from drifting buoys found for this case illustrates the potential benefits to be derived from improving the surface observing network over the North Atlantic.

4.2 Impact from FASTEX dropsonde data

The case of beneficial impact from drifting buoy observations, described above, is a striking example of how a few observations in a dynamically "sensitive" area can make significant impact, and is suggestive of the potential benefits of an adaptive observing system which could target such sensitive areas (provided they can be effectively identified in a timely manner). One objective of the Fronts and Atlantic Storm Track Experiment (FASTEX) was to test methods for objective identification of sensitive areas (areas in which analysis errors will grow rapidly in the forecast) and to assess the impact of "targeting" dropsonde observations on these areas.

In this section we describe a case in which targeted dropsonde observations had a beneficial impact on a forecast of a depression which crossed the UK during FASTEX. The verifying PMSL analysis for the case (Fig.4a) shows a shallow depression (central pressure, 1010hPa) located over south-east England at 00GMT 5 February 1997. The corresponding 30-hr NO OBS forecast from 18GMT 3 February (Fig.4b), has significant errors both in the location and intensity of the depression; the depression has been placed over eastern Ireland, and is some 15hPa too deep (central pressure 995hPa). The corresponding ALL OBS run (Fig.4c) produces a much better forecast; the location and shape of the depression are improved and the central pressure (1002hPa) has a smaller error of 8hPa. The greater skill of the ALL OBS run derives from the observations used in the 6-hr assimilation period prior to the forecast; recall that no data are assimilated in the NO OBS run over the same period.

Experiments showed that dropsondes deployed to the east of Newfoundland in a region identified, by objective techniques, as dynamically "sensitive" played an important role in the impact. The dropsondes were deployed from a height of ~400hPa.

Ten dropsonde profiles were used in the 6-hr assimilation step (their locations are shown in Fig.6a). The forecast obtained when only these dropsonde profiles are assimilated is shown in Fig.4d. Comparison with Figs.4a,b&c shows that a substantial part of the impact obtained with the ALL OBS run is recovered by use of the dropsondes alone. Much of the impact derives from an improvement (relative to the NO OBS run) in the location of the depression - though a modest improvement in the forecast central pressure is also attained. Additional use of just one other observation type - namely all the available surface observations - resulted in a forecast (not shown) of very similar accuracy to that of the ALL OBS run.

A potential vorticity (PV) perspective gives useful insight into how the dropsonde information led to an improved forecast. Figs.5a&b show PV on the 300K surface (approximately 550hPa in the area of dropsonde deployment) and the 850hPa potential temperature field for the NO OBS run at T+0 and T+6, respectively. Referring first to the T+0 fields (Fig.5a), the key features are the PV anomaly labelled "A" and the underlying warm "tongue" in the 850hPa isentropes. At this time the incipient depression had the form of a trough located below the PV anomaly and aligned approximately along the warm "tongue". A "phase-locked" relationship between the upper-level PV anomaly and the lower-level warm anomaly, suggestive of cyclonic development (Hoskins et al.,1985), is apparent. At T+6 (Fig.5b) the phase-locked relationship is maintained, and later in the forecast cyclonic development takes place - resulting in the prediction of an overly deep depression (Fig.4b).

The corresponding charts for the "dropsondes-only" run are shown in Figs.6a&b. The location of the 10 dropsondes used in the assimilation are also shown. Comparison of Figs.5a&6a shows that use of the dropsondes in the analysis results in a weaker PV anomaly; note that two of the dropsondes are located near the position of the PV maximum in the NO OBS run (Fig.5a). The warm anomaly is also less pronounced in the "dropsondes-only" run, as may be appreciated by comparison of the 282K isentrope in Figs.5a&6a. The weaker upper-level PV and lower-level warm anomalies suggests that mutual interaction is less likely than in the NO OBS run. This is confirmed by the chart for T+6 (Fig.6b) which shows that the main PV anomaly has moved east of the warm tongue. Thus unlike the evolution in the NO OBS run, "phase-locking" does not take place and little cyclonic development occurs in the subsequent evolution. As a result the "dropsondes-only" run produces a faster moving, shallower depression (Fig.4c) that is more in keeping with the verifying analysis (Fig.4a). Further investigation showed that the dropsonde observations that had most impact were located between 700 and 500hPa.

The example described indicates that dynamically sensitive areas can be successfully identified in a timely manner by objective methods. The case also illustrates the potential benefits to forecast accuracy from sampling such areas with dropsondes.

5. The utility of observations for mesoscale model forecasts of precipitation accumulation

Mesoscale models are designed for short-range forecasting of small-scale structures in weather phenomena (e.g. frontal rainbands), and are therefore likely to have observation requirements that differ from those of global models designed to predict the synoptic evolution at a range of several days. The requirements of smaller scale models, as well as global models, should therefore be kept in mind when planning network changes.

In this section we present a summary of results from 9 cases studied to assess the relative utility of existing observation types for 6- and 12-hr forecasts of 3-hr rainfall accumulation.

5.1 Method

The skill of each forecast experiment is assessed by comparing the accumulation of precipitation over the final 3 hours of the forecast with an analysis of 3-hr accumulation obtained from the UK weather radar network. The measure of skill used is the Equitable Threat Score (ETS) (Schaefer, 1990) which is calculated for precipitation accumulation thresholds of 0.5mm/3hrs and 2.0mm/3hrs. The improvement in skill relative to the NO OBS control is referred to as the observation "benefit" and is expressed as a percentage of the benefit obtained with the ALL OBS control.

Single-data-type runs are performed as in the global model study, and for each case the individual benefit of each observation type is determined. If the individual benefit exceeds a threshold value (set at 25% of the ALL OBS benefit), the observation type is deemed to deliver a useful benefit for the case. The frequency, over all cases, with which each observation type achieves an individual benefit exceeding 25% is then used as a measure of the observation utility. The frequency of individual benefits exceeding 50% is also recorded.

In addition to the observation types assessed in the global model study, the UKMO mesoscale assimilation (Macpherson et al.,1996) makes use of radar analyses of rainfall rate (assimilated using a latent-heat nudging scheme) and relative humidity information derived from a 3-D analysis of cloud fraction. The combined impact from these two observation types (referred to collectively here as remotely sensed humidity data [RHD]) is assessed.

5.2 Results for all mesoscale model cases

Fig.7a shows the number of times an observation type achieved an individual benefit of 25% or more for the 0.5mm/3hrs accumulation threshold. The number of benefits exceeding 50% is also shown. Results for 6-hr and 12-hr forecasts have been combined. At this lower threshold the histogram indicates the utility of the observation type for forecasting the general location of precipitation. Fig. 7b shows the number of benefits at the 2mm/3hr threshold. At this threshold the histogram indicates the utility of the observation types for forecasting the location of precipitation of moderate intensity or greater. The main points are summarised below.

Threshold = 0.5mm/3hrs (9 cases studied so far)

- Radiosonde humidity profiles were beneficial most frequently, with 6 cases of benefit of 25% or more; they also delivered the greatest number (5) of benefits exceeding 50% of the ALL OBS benefit.

- Remotely sensed humidity data, radiosonde winds and temperatures and surface reports were beneficial in 3-5 cases, and each delivered benefit in excess of 50% in at least one case.

- Contributions from aircraft reports, satellite temperatures and cloud track winds were relatively few, with no benefits exceeding 50%; (the numbers of these reports within the mesoscale domain is usually small).

Threshold = 2.0mm/3hrs (6 cases studied so far)

- The observations delivering the most frequent impacts were surface reports (4), radiosonde temperatures (3) and radiosonde winds (3).

- Observations of humidity appeared less important than observations of the mass and wind field for forecasts of precipitation of moderate intensity or greater. This is in marked contrast to results for the lower threshold.

Overall

- Comparison of results for the 0.5mm/3hrs and 2mm/3hrs thresholds (Figs.7a&b) suggests that humidity observations are important for forecasts of the general location of precipitation, while a good analysis of the dynamical structure is required for accuracy in forecasting the location of heavier precipitation.

5.3 A case study showing an impact from PMSL reports

One case in which surface information was found to have a substantial impact has been investigated to determine the relative importance of surface reports of pressure, wind, temperature and humidity. The verifying analysis for the case is reproduced in Fig.8a and shows the location of rainfall accumulations exceeding 1mm/3hrs. The eastern part of Ireland, where rainfall totals in excess of 1mm/3hrs are widespread, is of particular interest. The corresponding 6-hr forecasts from the NO OBS and ALL OBS controls are shown in Figs.8b&c respectively. Forecast hits are shown in dark shading, false alarms in grey shading.

The NO OBS run fails to forecast the accumulations over eastern Ireland - showing very few hits in this area, while the ALL OBS has produced a much better forecast. Single-data-type runs showed that of all the surface data, surface pressure reports gave by far the largest benefit. The result of the "surface-pressure-only" run is shown in Fig.8d and can be seen to recover many of the hits over eastern Ireland obtained with the ALL OBS run. The corresponding PMSL forecasts obtained with the NO OBS run and "surface-pressure-only" run are shown in Fig.8e&f and provide a dynamical explanation for the greater rainfall in the latter forecast. Comparison of Figs.8e&f shows that assimilation of surface pressure has produced a deeper low, located further west than in the NO OBS run. Verification against operational analyses confirms that this represented a better forecast. The greater cyclonic development over Ireland in the "surface-pressure-only" run, with implied greater vertical motion, is consistent with the larger forecast rainfall accumulations.

6. Overall Summary and Recommendations

- Radiosonde winds and temperatures play a key role in NWP analyses over North America. The profile format of the information provided by these reports may add significantly to their value for forecasting cyclogenesis events.

- The large frequency of impact from aircraft observations suggests that increasing the numbers of reports from aircraft, particularly in data sparse areas, would bring substantial forecast benefits to many regions. More reports made during the climb and descent phases would also be beneficial.

- Considerable benefit may derive from enhancing the marine surface network.

- The high frequency of impact from conventional surface data suggests that there is scope for improving the impact of scatterometer winds in the Northern Hemisphere.

- The value of wind information (e.g. from aircraft over the oceans) suggests that benefit would derive from better mid-latitude coverage of satellite pattern-tracking winds.

- The high frequency of impact from radiosonde temperatures over land suggests that global coverage of temperature profiles from forthcoming high resolution temperature sounders (e.g. IASI) will have a substantial impact.

- The importance of radiosonde profiles and surface reports for mesoscale forecasts of precipitation suggests that we should not overlook the needs of high-resolution limited area models when planning network changes.

- Evidence presented from one case suggests that dynamically "sensitive" areas can be identified in a timely manner using objective techniques, and that sampling such areas with dropsondes can deliver significant benefit to NWP forecasts.

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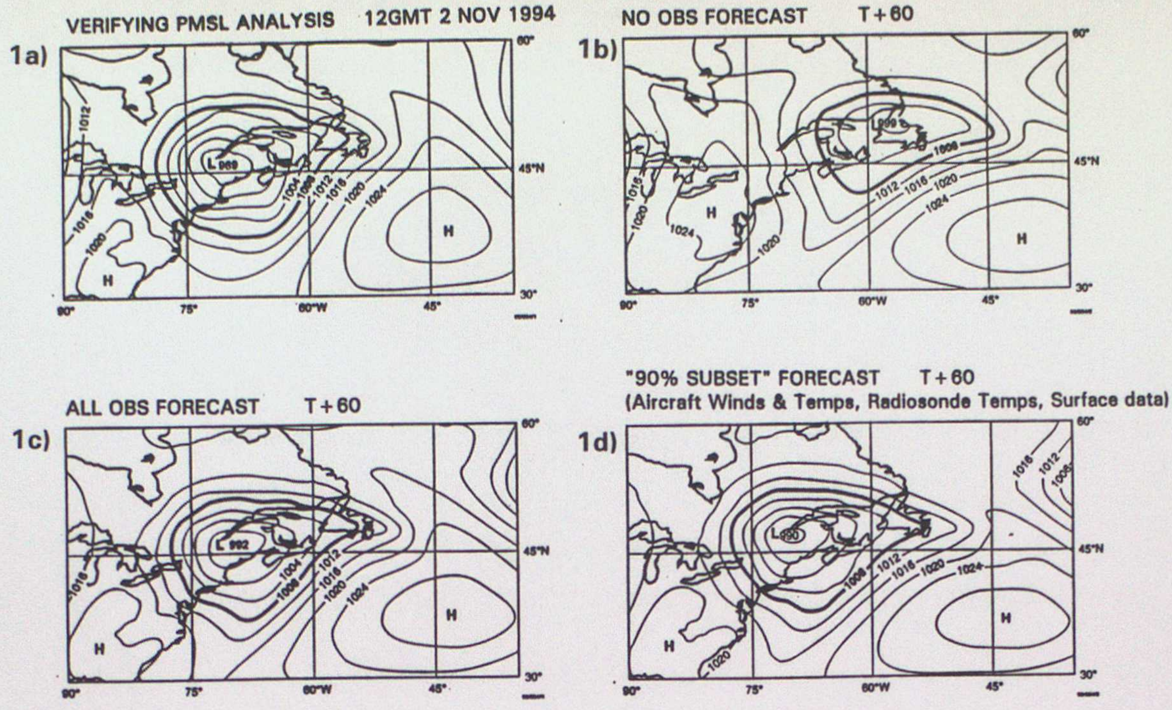


Fig.1a: PMSL analysis for 12GMT 2 November 1994. Contour interval = 4hPa, the 1008hPa isobar has been highlighted

Fig.1b: T+60 forecast for PMSL from the NO OBS control, valid at 12GMT 2 November 1994. Contouring conventions as Fig.1a.

Fig.1c: As Fig.1b, but for the ALL OBS control.

Fig.1d: As Fig.1b, but for a run in which only the data types included in the 90% subset (aircraft winds and temperatures, radiosonde temperatures and surface data) were presented to the assimilation. See text for an explanation of the "90% subset".

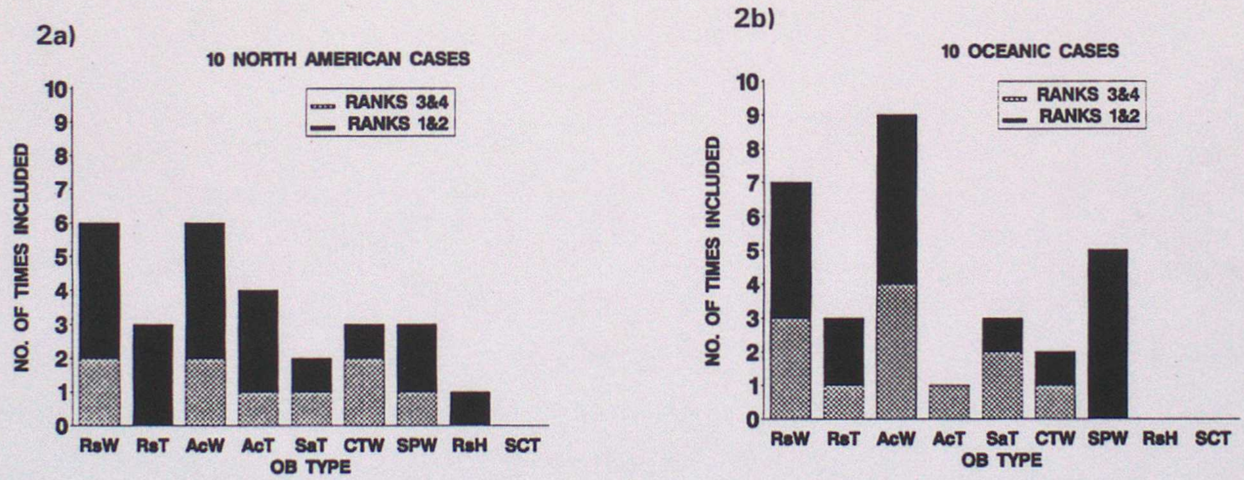


Fig.2a: Histogram for the 10 North American cases showing the number of times a data type qualified as a member of the 90% subset. Dark shading represents the number of times the data type qualified at Rank 1 or Rank 2; hatched shading the number of times at Rank 3 or Rank 4. RsH/W/T = Radiosonde humidities/winds/temperatures; AcW/T = aircraft winds/temperatures; SaT = satellite temperature soundings (statistical retrievals); CTW = cloud-track winds; SCT = scatterometer 10m winds; SPW = surface pressure and conventional wind observations (wind observations over oceans only).

Fig.2b: As Fig.2a, but for the 10 oceanic cases. The bars for radiosonde observations are not representative of the small numbers of ship-based ascents (see text).

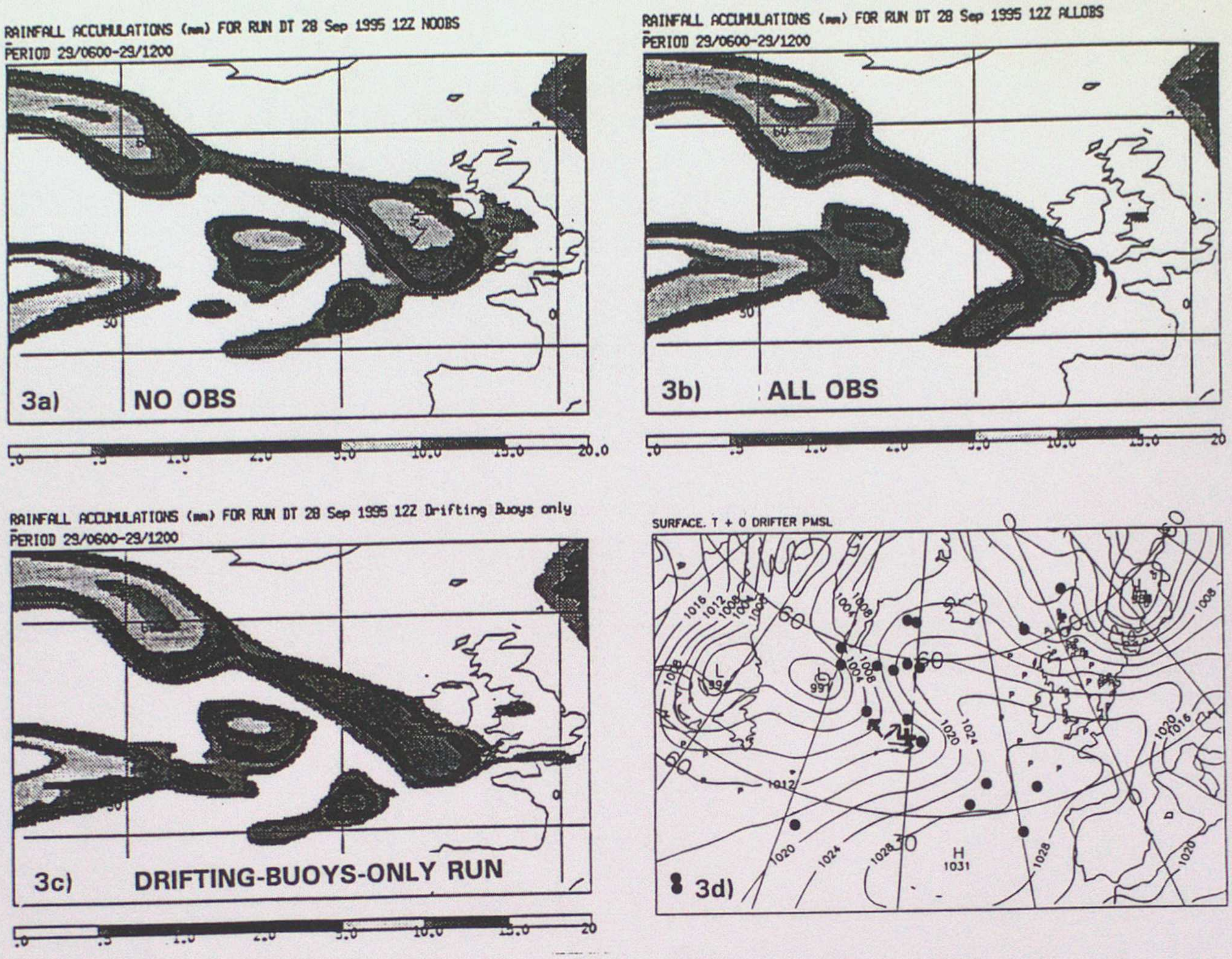


Fig.3a-c: Forecast rainfall accumulations in mm for the period 0600 to 1200 GMT on 29 September 1995.

a) The 24-hr forecast from the NO OBS control,

b) The 24-hr forecast from the ALL OBS control. The scalloped line shows the actual location of the leading edge of the rain at 29/1200, deduced from weather radar.

c) The 24-hr forecast from a run in which only drifting buoy observations were assimilated.

Fig.3d: An initial analysis valid 12GMT 28 September 1995. The locations of the drifting buoys from which surface pressure reports were used are shown "●". The location of the depression discussed in the text is marked "+". Most of the impact obtained from all the drifting buoy data can be reproduced using only the 3 buoys near the depression (marked with arrows).

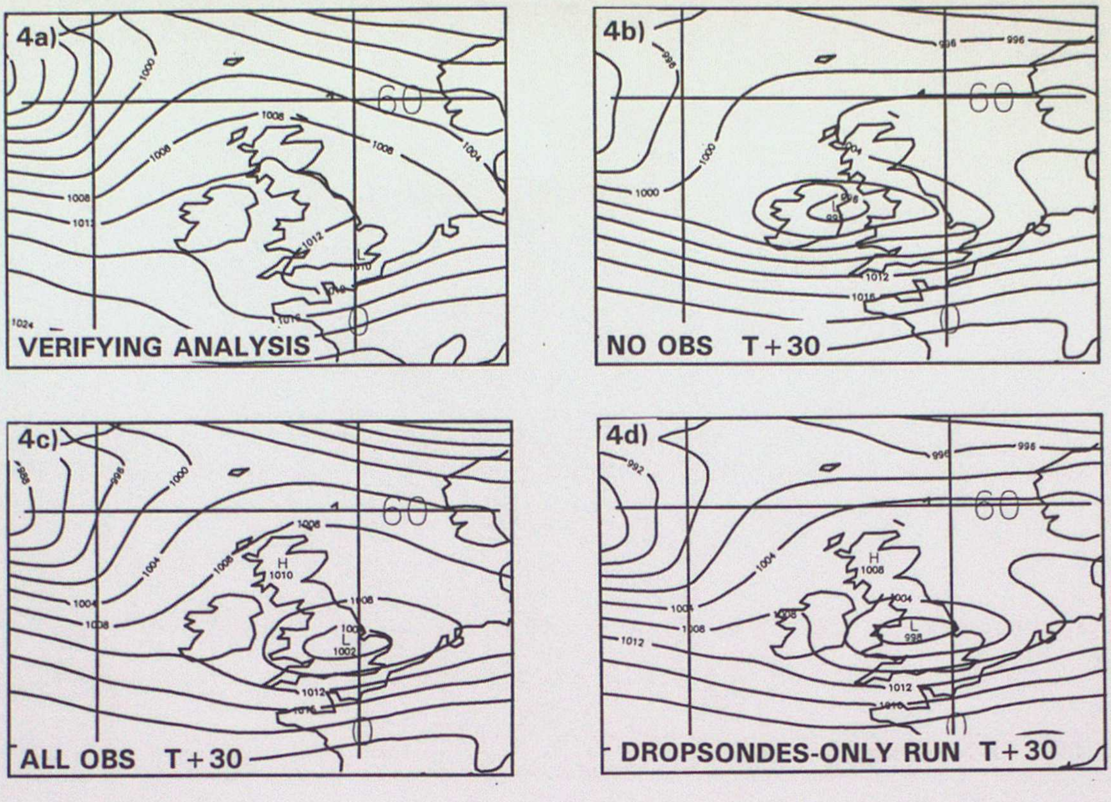


Fig.4a: PMSL analysis for 00GMT 5 February 1997. Contour interval = 4hPa.
Fig.4b: T+30 forecast for PMSL from the NO OBS control, valid 00GMT 5 February 1997. Contouring conventions as Fig.4a.
Fig.4c: As Fig.4b, but for the ALL OBS control.
Fig.4d: As Fig.4b, but for a run in which only dropsonde observations were presented to the assimilation (referred to as the "dropsondes-only" run, see Fig.6a for the locations of the dropsondes).

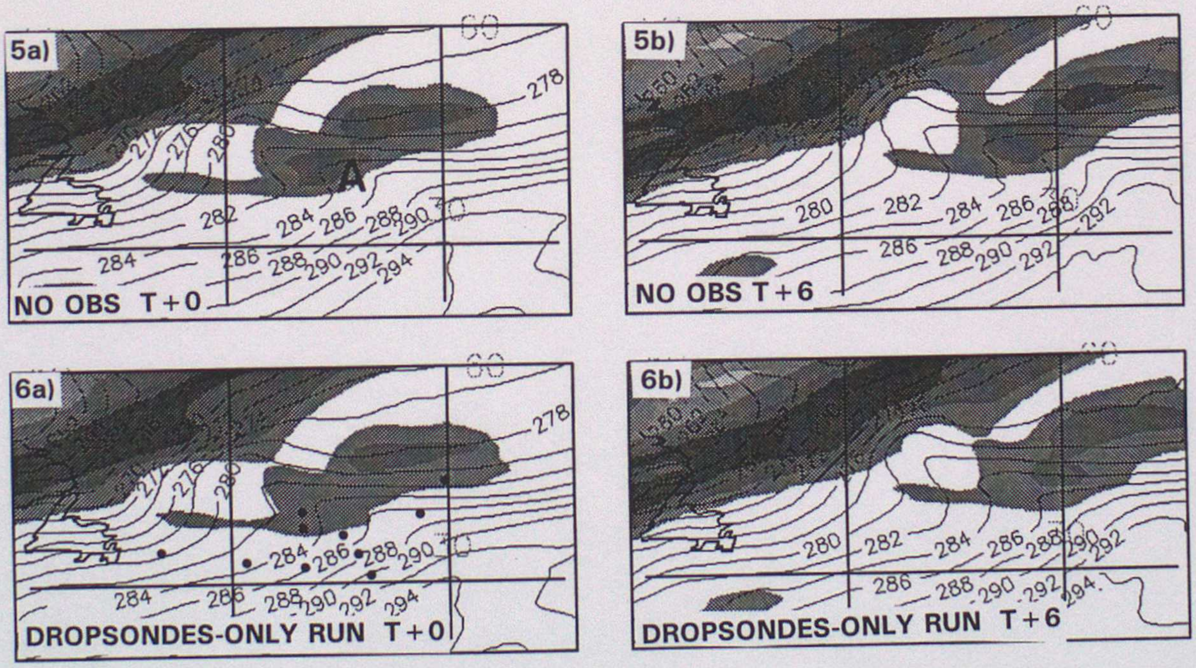
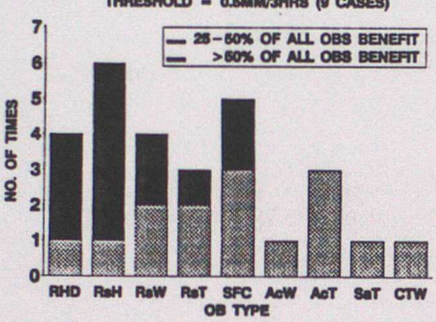


Fig.5a: Potential vorticity on the 300K surface (shading) and 850hPa potential temperature (contours) at T+0 (18GMT 3 February 1997) for the NO OBS control. Shading threshold = 1 PV unit ($1X10^{-6}m^2s^{-2}Kkg^{-1}$), interval = 0.5 PV unit. Contour interval = 2K. The PV maximum referred to in the text is labelled "A".
Fig.5b: As Fig.5a, but for T+6.

Fig.6a: As Fig.5a, but for the "dropsondes-only" run.
Fig.6b: As Fig.5b, but for the "dropsondes-only" run.

7a)



7b)

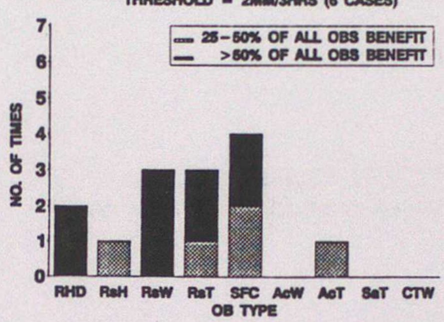


Fig.7a: Number of times an observation type delivered an individual benefit of 25% or more (see text) over 9 forecasts of precipitation accumulation above 0.5mm/3hrs. Results from five 12-hr forecasts and four 6-hr forecasts are combined. Hatched bars show number of times with benefit = 25-50%; solid bars show number of times with benefit > 50%. RHD = remotely sensed humidity data; RsH/W/T = Radiosonde humidities/winds/temperatures; SFC = surface pressure, wind, temperature and humidity; AcW/T = aircraft winds/temperatures; SaT = satellite temperature soundings; CTW = cloud-track winds.

Fig.7b: As figure 1a, but for 6 forecasts (four 12-hr, two 6-hr) of precipitation accumulation above 2mm/3hrs.

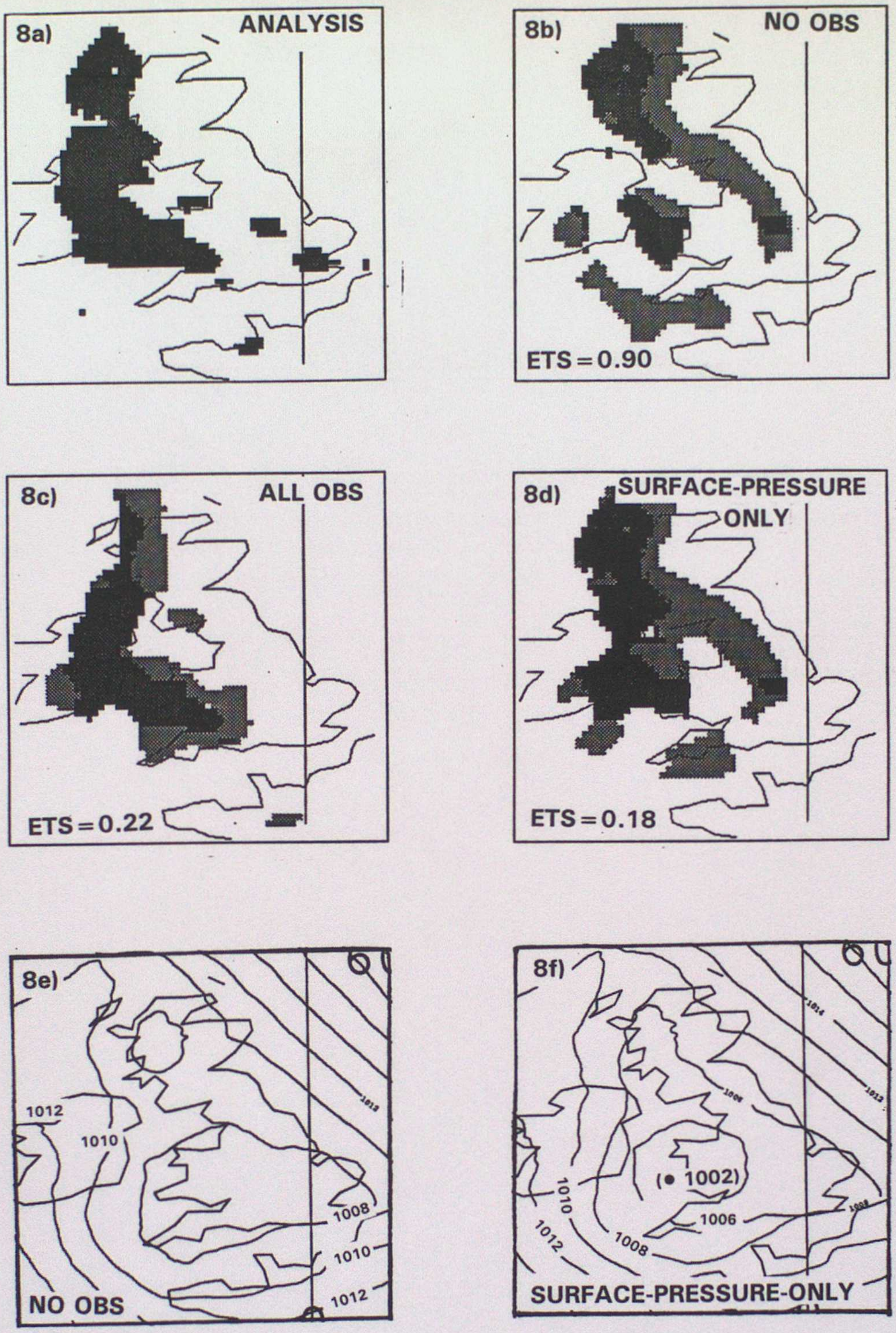


Fig.8a: Location of rainfall accumulations exceeding 1mm in the 3-hr period 03-06GMT 6 August 1996 (derived from weather radar).

Fig.8b: The NO OBS 6-hr control forecast for the location of rainfall accumulations exceeding 1mm in the 3-hr period 03-06 6 August 1996. Black shading = hits; grey shading = false alarms.

Fig.8c: As Fig.5b, but for the ALL OBS control.

Fig.8d: As Fig.5b, but for a run in which only surface pressure observations were assimilated.

Fig.8e: The NO OBS 6-hr control forecast for PMSL valid 06GMT 6 August 1996.

Fig.8f: As Fig.5e, but for a run in which only surface pressure observations were assimilated. The verifying position and central pressure of the depression over Wales have been added (in brackets).