A study of the impact of aircraft wind observations on a large-scale analysis and numerical weather prediction system

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SUMMARY

An observing systems experiment to assess the impact of aircraft observations on analyses and forecasts from a numerical model is described. Parallel runs with and without aircraft observations show significant analysis differences in the upper troposphere over northern hemisphere oceans, the aircraft giving a better representation of jet strengths and less reliance on poorer quality observations. This positive impact extends to the shape and position of upper tropospheric features in forecasts from these analyses though the magnitude of the improvements is somewhat less.

These results are in broad agreement with those from a similar experiment carried out at the European Centre for Medium Range Weather Forecasts. Some differences attributable to the response of the different analysis schemes used are discussed in the light of geostrophic adjustment theory and are studied further using model forecasts from perturbed initial conditions. These studies suggest that beneficial effects on forecasts can be achieved by distributing single-level data throughout several model levels and using wind observations to update the rotational component of the wind field.

A simple linearized theoretical model supports these conclusions and is used to investigate the effects of the repeated insertion analysis procedure used in our experiments. This effectively suppresses the generation of high frequency waves but shows undesirable effects in the presence of a large mean advective velocity.

1. INTRODUCTION

It is important when designing future cost-effective composite observing systems to know the likely benefit to numerical weather prediction (NWP) from observations from individual components. The impact of current observations on current NWP systems can be measured in observing system experiments (OSEs). Parallel analyses and forecasts are made with and without data from the observing system being considered, and the impact is assessed from the increase in forecast skill from the analyses with the extra data. The observed impact is dependent to some extent on the observational data set used and a full assessment of the redundancy between different observation types requires several experiments in which this data base is varied. However, OSEs can provide valuable results although they have limitations which mean that their results must be carefully interpreted as guidance in the more general assessment. Firstly, because of practical limitations on the resources available for such experiments and because forecast accuracy is a noisy measure of analysis accuracy, it is difficult to achieve a statistically significant measure of impact. Secondly, OSEs measure only the impact on one current NWP system, not that on future improved systems.

In section 3, we describe and discuss OSEs to measure the impact of aircraft data during two periods of the first GARP Global Experiment (FGGE) on the Meteorological Office FGGE experimental data assimilation system, details of which are given in section 2. To overcome the first limitation we emphasize case studies where a clear causal relationship between observations, analysis differences and forecast differences can be seen. In order to address the second by studying the system dependence of impact assessment, we compare our results with those from a similar experiment using the NWP system of the European Centre for Medium Range Weather Forecasts (ECMWF), and (in section 4) study in detail the characteristics of our techniques for assimilating wind data. This also leads to conclusions about these techniques; indeed it is a common experience that OSEs are as useful in exposing weaknesses in current observing and NWP systems as they are in assessing the impact of future systems. Conclusions about both aspects are summarized in section 5.
In this paper we present a sample of the cases in the two periods in 1979 which we used for our study and upon which our conclusions are based; further cases are available in Barwell (1982) and Lorenc (1982). Of considerable relevance to section 4 is an intercomparison of NWP systems using the same FGGE data sets (Hollingsworth et al. 1985). These experiments were part of a series co-ordinated by the Joint Scientific Committee for GARP, preliminary results of which were presented at the Exeter study conference (Gilchrist 1982). They were planned as a contribution to the fourth and third objectives of FGGE: to design an optimum composite meteorological observing system for routine numerical weather prediction of the larger-scale features of the general circulation; and to develop more powerful methods for assimilation of meteorological observations (GARP 1973).

2. EXPERIMENTAL METHOD

(a) Data assimilation system

These experiments used the repeated insertion data assimilation method, in which a forward running model is relaxed towards observed values over a period of time. The assimilation and forecast model was global and had eleven sigma levels extending into the lower stratosphere (Saker 1975). The horizontal resolution was about 200 km everywhere and the time step was 450 seconds. Data assimilation was performed in six-hourly cycles, data from ±3 hours being used without any correction to asymptotic data to allow for actual time of observation. Thus during the six-hour period the model state evolved, while being relaxed towards a constant set of observations nominally valid at the end of the period. The correction to each model grid point each time step was proportional to a weighted mean of the differences between nearby observations at the same level and the current model field, the weights being precalculated using two-dimensional univariate optimum interpolation:

$$\psi_h(t) = \psi^i(t) + \lambda(t) \sum W_{kl} [\psi^o_l - \psi^i(t)]$$

(1)

where $$\psi^i(t)$$ and $$\psi_h(t)$$ are grid-point values at time $$t$$ before and after insertion, $$\psi^o_l$$ and $$\psi^i(t)$$ are observed and equivalent interpolated grid-point values, and $$W_{kl}$$ are the optimum interpolation weights. The relaxation coefficient $$\lambda(t)$$ was varied linearly from zero at the beginning of the assimilation (six hours before the data time) to 0.5 at the data time itself. A weak time filter was applied to prevent time splitting.

This data assimilation system was very similar to that used in the Meteorological Office to generate analyses experimentally during the Special Observing Periods of FGGE in near real time (Lyne et al. 1982). It included an initial data quality control step in which values of atmospheric parameters were computed at each observation position using optimum interpolation but without using the observation itself or observations which deviated grossly from the analysis made six hours earlier. Observations deviating sufficiently from the interpolated values were rejected. Further details of the model and assimilation are given by Lyne (1981).

(b) Observations used

The observations for the experiments were taken from the FGGE observational data set collected in delayed mode (level IIb). The data set contains a large number of conventional aircraft reports (AIREPs) as well as automatic measurements from modern navigation systems, either transmitted directly via satellite (ASDAR) or recorded in flight for processing later (AIDS). Because of the relatively large number of AIREPs
it was not judged feasible to evaluate the ASDAR and AIDS separately and for this experiment the impact of all three types combined was measured. Typically, each six-hour period contained about 900 AIREPs and 450 AIDS. Numbers of ASDARs increased from about 20 in February to about 150 in November.

The numbers of satellite soundings and cloud-track winds in the observational data set are greater than routinely available. Since these provide information in areas where aircraft would otherwise be the sole source of upper air data, their presence is likely to decrease the measured impact.

The observational errors used for this experiment were based on those given by Lyne et al. (1982) but some revisions were made in the light of available model statistics and published information. Details are given in Barwell (1982).

Two periods in 1979 were chosen for the experiments, one in February and one in November. Both were active meteorologically and had good observational coverage. February was part of the first Special Observing Period of FGGE, and in November, data were available from two polar-orbiting satellites.

For the February experiment, parallel data assimilation runs of the model with and without aircraft data were carried out for the 72-hour period from 12 GMT 14 February to 12 GMT 17 February. The starting analysis for both runs was taken from an experimental run of the scheme using all the level IIb data. Forecasts for 24 hours were performed from the analysis for 12 GMT 17 February generated by these runs.

The starting analysis for the November period was interpolated from the analysis produced by ECMWF for 00 GMT 9 November using the FGGE IIb data. As with the previous experiment, parallel data assimilation runs with and without aircraft observations were performed, this time for the five days to 00 GMT 14 November. Each of the analyses for 00 GMT 11 November from these runs was used as a starting state for a 4-day forecast. These dates correspond with those used for a similar aircraft experiment carried out at ECMWF (Baede et al. 1983), which provides a useful comparison with the Meteorological Office experiments, and some results from which are included in this paper.

(c) ECMWF system

The ECMWF experiment referred to above was carried out jointly with the Royal Netherlands Meteorological Institute (KNMI) using a data assimilation technique which differs from that used here. The ECMWF scheme attempts to maintain a balance between mass and wind fields explicitly by means of a multivariate analysis (Lorenc 1981) and incorporates a nonlinear normal mode initialization (Temperton and Williamson 1981). It also allows single-level data such as aircraft observations to influence levels other than the nearest. For further details see Bengtsson et al. (1982).

In addition to the standard quality control performed by the producers of the FGGE IIb dataset, some additional manual quality control was applied to AIDS and ASDAR data by KNMI. To make the November experiments directly comparable we carried out the same manual selection of data.

3. RESULTS OF EXPERIMENTS

(a) Objective verification

The greatest density of aircraft reports occurred around the 250 mb level where there was the largest impact in the analyses. Figure 1 shows for the February study the distribution of aircraft data at this level at the end of the 72-hour assimilation period, the 250 mb height analysis using these data, and the difference between the 250 mb wind
Figure 1. Impact of aircraft data on 250 mb wind analysis for 12 h 17 February 1979. (a) Locations of AIREP (×) and AIDS (+) observations over the northern hemisphere, and analysis using all available data. Contour interval 12 dam. (b) With-aircraft minus without-aircraft vector wind differences. Isotachs (dotted lines) in m/s. Arrows indicate direction for differences greater than 10 m/s.
analyses with and without them. The data have the greatest impact over the northern hemisphere oceans where aircraft are the major source of upper tropospheric wind data. In most areas the effect is to increase the strength in the main jet streams. In the southern hemisphere (not shown), few aircraft observations are available and much less impact is found.

Global statistics of the fit between analyses and observations for the 250 mb wind field (Table 1) show that when aircraft data are included in the analysis, the root mean square (r.m.s.) vector wind differences for these data (AIDS and AIREP) are significantly reduced without significant detrimental effect on the fit to winds from radiosondes and pilots. The greater improvement for AIDS reports reflects their lower observational error. The fit to satellite cloud-track winds is worse: the subjective assessment in section 3(b) below suggests that the poorer quality of these winds is a contributory factor. Statistics for analyses from the November experiment gave similar results. After a 24-hour forecast (Table 2), much of the analysis improvement has been lost particularly in the subtropical jets where the increased wind strengths in the with-aircraft analysis have largely disappeared.

<table>
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<tr>
<th>Observation type</th>
<th>Analysis with aircraft data (m s(^{-1}))</th>
<th>Analysis without aircraft data (m s(^{-1}))</th>
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<tbody>
<tr>
<td>Aircraft (AIDS)</td>
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<tr>
<td>Aircraft (AIREP)</td>
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<td>Pilots (land)</td>
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<tr>
<td>Cloud-track winds</td>
<td>10.9</td>
<td>9.2</td>
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<td>Aircraft (AIREP)</td>
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<td>Radiosondes (land)</td>
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<td>Pilots (land)</td>
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<td>11.6</td>
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<tr>
<td>Cloud-track winds</td>
<td>14.4</td>
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To illustrate the loss of impact during forecasts, we consider how differences between forecasts and analyses evolve as a function of time. For the November period, time series of the global r.m.s. vector wind differences at 250 mb (Fig. 2) show that the difference between analyses with and without aircraft data (full line) levels off at 5 or 6 m/s and that this level is reached within two days, indicating that 00h 11 November is a reasonable starting time for the forecasts. Some of this difference is due to short wavelength features introduced by the assimilation scheme in the course of fitting the analysis to observations. Scales close to the model’s effective resolution tend to be smoothed during the forecasts, and therefore the r.m.s. vector error between the forecasts decreases from its initial value. Figure 2 also shows the r.m.s. vector differences between the forecasts from the two initial states for 00h 11 November and verifying analyses prepared using all available
observations. It is to be noted that the r.m.s. error for the with-aircraft forecast rises from zero to about 8.5 m/s in 12 hours; in the same time the without-aircraft forecast error rises from 5 to 9 m/s. Thus, at least in terms of this 250 mb statistic, the increased analysis accuracy is largely lost in this initial period. The figure shows nevertheless that a positive impact is retained throughout the forecast period. Verification against the no-aircraft analyses (not plotted) also shows this small residual positive impact after 36 hours. For shorter periods each forecast verifies best against the analysis from which it was started. For all forecasts the difference from the no-aircraft analyses was less than that from the all-data analyses, on average by about 0.5 m/s.

It is difficult to establish statistical significance for objective statistics such as those presented here without performing many more analyses and forecasts for other seasons and synoptic situations. Insight into the processes involved can, however, be obtained from subjective evaluation of the experiments described above in the light of the dynamical properties of the model and analysis scheme.

(b) Subjective assessment of impact

Firstly, consider the impact on the analysis over the north-western Pacific Ocean for 12 GMT 17 February. Figure 3 shows the analyses with and without aircraft data and the difference between them. The impact of the aircraft observations has been mainly to increase the strength and downstream extension of the jet, and to produce a large equatorward flow near 180°E.

The increase in jet strength is a detectable feature of the assimilation throughout the 36 hours up to the time of the charts in Fig. 3 and occurs in an area where aircraft are the major source of wind data. In fact, east of 150°E in the figure, the only available 250 mb wind data from sources other than aircraft are two satellite wind observations near 34°N 166°E, both reporting speeds of 47 m/s, much less than surrounding aircraft reports, which reach 90 m/s. The analysis without aircraft data has fitted the satellite wind speeds within 4 m/s, but for the with-aircraft analysis the error of fit is about
Figure 3. 250 mb analyses over the North Pacific for 1200 MT 17 February 1979: with aircraft data (a); without aircraft data (b); difference (c). Charts show contours in dam (full lines), isolachs in m/s (dotted lines), wind observations used in analyses (one full fleche represents 5 m/s) and vector wind differences greater than 5 m/s (arrows). (In this and later figures, some observations have been omitted where they would obscure others already plotted.)
23 m/s though the fit to the aircraft observations has been improved. Thus the aircraft data have been fitted at the expense of the satellite winds. This may be regarded as a positive impact since the aircraft support another one in indicating that the wind is stronger than the satellite data suggest. Satellite-derived winds are less reliable, especially near the tropopause, due to the difficulty of assigning the wind to the correct level. The poor quality of some cloud-track wind observations in the vicinity of subtropical jet streams has been pointed out by Kallberg et al. (1982).

The equatorward flow at 175°E in the analysis with aircraft data is like a similar flow pattern off the Pacific coast of North America (see Fig. 1). In the latter case the effect occurs in an area where there were no upper air wind observations which could be responsible. It would appear to be a dynamic response of the model to greater wind speeds in the jet at earlier analysis times, the impact being advected into a data-sparse area. The effect in Fig. 3 can be explained similarly though the presence of a few nearby aircraft winds makes the situation less clear.

We now consider the impact of aircraft observations on forecasts from 00 GMT 11 November. Forecasts from the joint ECMWF–KNMI study (Baede et al. 1983) are available for the same time. In the following discussion we refer to these as the ECMWF experiment and those performed at the Meteorological Office as the UKMO experiment. Once again the North Pacific illustrates the main points. The UKMO 250 mb analysis with aircraft data and its difference from that without aircraft is shown at the start time of the forecast period in Fig. 4. The areas of greatest impact are either side of the trough at 170°E and the upstream side of the trough at 150°W. In these areas the effect of aircraft data has been to increase the analysed wind strength, as in the February case study. More detailed charts with wind observations (Fig. 5) show that the increase in isolach maximum near 180°E is due to the aircraft observation of 62 m/s at 238 mb near 175°E 35°N. (In fact there are two similar observations too close for both to be plotted.) The increase near 150°W can also be associated with aircraft observations but that near 165°E is not so readily explained and is probably a dynamic response to observations at earlier times (in fact the effect is very similar to that observed in the February case study (Fig. 3)).

The analysis from the ECMWF experiment with aircraft data, also shown in Fig. 5, is similar to the UKMO with-aircraft analysis. In fact the difference between the ECMWF with-aircraft and without-aircraft experiments shows the same features as the corresponding UKMO difference chart (Fig. 4) in spite of the different analysis schemes.

The similarity between the influence of aircraft observations in the ECMWF and UKMO experiments extends to forecasts from these analyses (Fig. 6). The low at 170°E and its associated wind maxima either side give rise to a high at 175°W which in turn causes a low near 50°N 150°W after 48 hours. This downstream development, which we have also seen in other analysis intercomparison experiments (Hollingsworth et al. 1985), is reminiscent of that described and theoretically explained by Simmons and Hoskins (1979).

The 48-hour forecast fields from the UKMO experiment are shown in Fig. 7 with a verifying analysis. The trough between 150°W and 170°W is not well predicted in either forecast. The trough axis has moved further to the east than predicted and has been filled too quickly. Its detachment from the cut-off low near 180° is insufficiently predicted and the wind round the trough is much too weak, especially round the base and on the downstream side. However, the difference chart in Fig. 8(a) shows that these features are handled better in the forecast from the analysis with aircraft data. The low on this chart centred to the east of the axis of the trough indicates its increased intensity and better position and the arrows indicate an increased flow around it. The impact on the
ECMWF forecast (bottom of Fig. 6) was greater and the surface pressure pattern was also improved in their experiment. Despite these differences in magnitude we can conclude that in both experiments (and in further experiments at ECMWF in which satellite data were not used (Bengtsson 1983)), aircraft data improved the forecast of this trough. A similar impact is apparent in the flow round a much weaker trough extending approximately north-east to south-west through Gibraltar. This impact can be traced back to aircraft observations over the NW Atlantic. Figure 8(b) shows that the trough is barely visible in the forecast from the analysis without aircraft data but the difference field shows that aircraft observations have reduced the height field in this area and increased the extent of the trough in the wind field. The increased winds on the
Figure 5. More detailed charts of 250 mb analyses over the central North Pacific, 00 GMT 11 November 1979, showing contours at 10 dam intervals, isotachs and wind observations. Charts are for with-aircraft analysis (a), without-aircraft analysis (b) and ECMWF IIIb analysis (c).
Figure 6. Height and wind differences between with-aircraft and without-aircraft analyses and forecasts over the northern Pacific Ocean. Charts are at 12-hour intervals from analysis time. 00 GMT 11 November 1979 (top row) to 48-hour forecast valid 00 GMT 13 November 1979 (bottom row). UKMO experiment (left); ECMWF experiment (right). Contours (full lines) are at 8 dam intervals; isotachs (dotted) at 10 m/s intervals. Arrows indicate direction of wind differences where greater than 10 m/s.
Figure 7. 250 mb contours and isolachs for 00h 13 November 1979. Charts show 48-hour forecast from with-aircraft analysis (top), 48-hour forecast from without-aircraft analysis (centre) and verifying ECMWF IIIb analysis (bottom).
upstream side of the trough reflect a forward extension of a strong jet over the North Atlantic. In all these characteristics the impact of the aircraft observations has been to bring the forecast more into line with the verifying analysis although, as before, the extent of the improvement is not great. The ECMWF experiment again showed a similar impact.

(c) Discussion

It is clear from these examples that aircraft data had a significant impact on analyses of upper-level winds over northern hemisphere oceans, where they are an important constituent of the total observational coverage. They caused changes, usually increases in jet speeds of up to 20 m/s, and the with-aircraft analyses were usually reasonably consistent with both aircraft and other types of wind data. Objective measurement of the impact is difficult; other than the observations themselves we have no estimate of the truth for verification.

One mechanism by which the observations had an impact was through the detection and rejection of other data which were probably incorrect, but in the absence of the aircraft data not detected as such by the analysis system. This acts as a reminder that in the more general assessment of observing systems their reliability is very important. Automatically reported aircraft measurements of the type proposed for future observing systems are likely to be very reliable and hence useful in this quality control role.

One measure of the quality of analyses is the skill of forecasts made from them. Viewed in these terms the impact of the aircraft data was rather less. Some cases were found where analysis differences due to aircraft observations could be seen to cause
improvements in subsequent forecasts (e.g. Fig. 5), however, these were small compared to the total error in the forecasts, so large-scale objective measures showed little impact (Fig. 2). Two related reasons can be proposed for this. Firstly, some of the information provided by the observations and used in the analyses was for scales not accurately predicted by the NWP system. The analyses have resolution of approximately 220 km, 80 mb and 6 hours. However, because of finite difference truncation errors, spatial scales must be several times this before they are accurately forecast. It is beyond the scope of this paper to speculate to what extent significantly higher resolution NWP systems might make use of this information; certainly the problems discussed in the next section will remain important. Secondly, where the information provided by the observations was for scales which the NWP system could predict accurately, the analyses did not necessarily make the best use of the information in providing spatially and dynamically consistent fields for the model. This aspect is studied further in the next section.

4. ASSIMILATION TECHNIQUES FOR SINGLE LEVEL WIND DATA

(a) Introduction

Figure 6 shows that although the effect of aircraft data on the 250 mb analysis was rather less in the ECMWF than in the UKMO system, the impact increased during the forecast period so that there are substantial changes at 48 hours. This contrasts with the UKMO results in which the impact decreased with time. It is of interest to enquire what causes this difference in behaviour.

A forecast using the forecast model from the UKMO system but starting from the ECMWF with-aircraft analysis gave the result that all the features which were improved in the original with-aircraft forecast were further improved in this. This seems to indicate that the difference in behaviour noted between the ECMWF and UKMO experiments is primarily a function of the UKMO analysis, and a tendency for useful information in it to be lost in the initial stages of a forecast.

There are a number of features of the analysis scheme which might contribute to this. Firstly, the effect of observations was confined to the model level closest to the height to which they referred and was not spaced through vertical correlations to other levels. This feature of the scheme is inconsistent with the assumptions made in the horizontal but was used in this experimental and non-operational scheme in order to evaluate the effectiveness of continuous insertion in spreading information vertically. Results at the end of an assimilation show vertical wind profiles with shears that are unlikely to be correct, and we conclude that a 6-hour assimilation period is not adequate to achieve realistic vertical wind structures. Excessive shears are gradually removed during a forecast, and this leads to a reduction of the impact of wind data at 250 mb.

Secondly, the scheme contained no explicit balancing of height and wind fields. Its continuous insertion technique damps high frequency oscillations and consequently tends to create the required balance. However, oscillations with periods much in excess of the 6-hour insertion period are ineffectively damped. In particular, oscillations which are primarily inertial can be expected to cause fluctuations about the geostrophic wind with periods of approximately $2\pi f$, i.e. 1 day at 30°N, and are likely to be present in the initial stages of a forecast.

A third feature of the scheme may be noted. When high wind speeds are repeatedly inserted into a jet stream, the maximum wind is often analysed downstream of the observation, with a value in excess of that observed. For example, in Fig. 5(a), the maximum analysed speed of 79 m/s is downstream of the aircraft observation of 63 m/s.
It is, of course, a proper function of an analysis scheme to spread the information contained in observations, and, in a jet stream, it is reasonable that the spread should be mainly along the direction of the wind. The asymmetry introduced by continuous insertion as regards up- and down-stream is, however, more questionable. The ECMWF IIIb analysis of this situation (Fig. 5(c)) fits the aircraft observation less accurately (observation – analysis ~ 20 m/s) and places the jet stream maximum south of it. It is not possible from the evidence available to say which wind analysis is the better.

The behaviour of the forecasts from the UKMO analysis in this case can be studied further in Fig. 9, which shows a portion of Fig. 4(b) in more detail, together with a 6-hour forecast. The initial difference between the analyses is almost entirely ageostrophic, and after 6 hours the main unbalanced wind difference has been advected along the jet and veered by about 90°. This veering is consistent with the Coriolis effect at this latitude, and indicates that the aircraft observations had a significant impact on modes that were largely inertial in character. The lasting impact on the strength of the jet was less; the region with peak impact of 40 m/s in Fig. 9(a) has reduced to a smaller 10 m/s difference in Fig. 9(b). This residual impact is, however, in approximate geostrophic balance with the increased height gradient across the jet. Regions exhibiting a similar wind rotation and loss of impact were also found over the Atlantic and in several areas in the February case study.

An idea of the relative importance of the various analysis scheme characteristics discussed above, as a function of latitude and scale, can be obtained from linearized geostrophic adjustment theory. We do this in (b) below, and apply the theory to the case just discussed. In (c) we describe some further experiments designed to isolate various characteristics of the analysis method.

(b) Geostrophic adjustment theory

The theory of geostrophic adjustment may provide some insight into developments when an analysis containing height and wind fields which are not 'in balance' is used as initial data for a forecast. Being linear, the theory may be expressed in terms of non-interacting, independent modes, which are either non-divergent geostrophic or divergent gravity–inertia in form. The theory assumes that the latter are dispersed or dissipated leaving only the non-divergent modes as stationary solutions. The streamfunction to which the system tends is therefore intermediate between that representing the rotational component of the initial wind field and that implied by the initial geostrophic winds (Temperton 1973). That is

\[ \psi_t = \alpha \psi_h + (1 - \alpha) \psi_i \]  \hspace{1cm} (2)

where \( \psi_h \) is the streamfunction for the non-divergent part of the initial wind field and \( \psi_i \) is derived from the initial mass field. The parameter \( \alpha \) is shown by the theory to be

\[ \alpha = (1 + \frac{f^2 \lambda^2}{4 \pi^2 \Phi})^{-1} \]  \hspace{1cm} (3)

where \( \lambda \) is the two-dimensional wavelength and \( \Phi = gH \), \( H \) being the equivalent depth. From this value of \( \alpha \) it follows that for \( \lambda \) small or \( \Phi \) large the heights tend to adjust to the initial winds, and vice versa for \( \lambda \) large or \( \Phi \) small.

In an analysis system where an observation is used only at nearby levels and grid points, its effects will project onto a large number of modes with various wavelengths and equivalent depths, the distribution of energy among them depending on the vertical
Figure 9. Impact of aircraft observations over the Pacific Ocean. (a) Close-up of part of Fig. 4(b); (b) same after 6-hour forecast.
and horizontal structure of the analysed fields. An observation used at only one level will project significant energy onto modes with small equivalent depths. Inertial gravity modes with small equivalent depth are dominated by their inertial characteristics; the velocities rotate with frequencies slightly greater than $f$ and the effect of divergence on geopotential gradients and their associated acceleration is secondary. In the limit of zero equivalent depth we have a pure inertial oscillation with frequency $f$. In this case in linear theory there is no interaction with the height field and the adjusted state after the inertial mode has dispersed is determined solely by the initial mass field (i.e. $\alpha = 0$ in Eq. (2)).

In order to apply geostrophic adjustment theory to the case shown in Fig. 9, we proceed to estimate approximate values for the wavelength and equivalent depth of a typical mode. We show in (c) below that some of the behaviour seen in Fig. 9 can be reproduced in a model limited to only one wavelength and equivalent depth. However, it must be remembered that in reality a spectrum of values is present, and the dispersion in the horizontal and vertical by which the local adjustment takes place is dependent on this. Thus we cannot discuss the rate of decrease of the unbalanced part of the winds from Fig. 9(a) to Fig. 9(b) without some knowledge of the spectrum. The final balanced state is, however, (in linear theory) independent of the dispersion and dissipation process, and as long as the spectrum can be characterized by a typical wavelength and equivalent depth, we can get an approximate estimate of the residual balanced winds.

The first step is to analyse the wind differences of Fig. 9(a) into their rotational and divergent components. In linear theory the divergent component projects entirely onto gravity modes. The rotational component has a maximum of just under 25 m/s corresponding to the maximum of 41 m/s in Fig. 9(a). In general the direction and pattern of the rotational winds are little altered from Fig. 9(a) (Lorenc 1982). Visual inspection of Fig. 9(a) gives a rough estimate of a typical horizontal wavelength of 1650 km. Estimating the equivalent depth is harder, since we do not have available a linear analysis of the vertical structure of the model used. However, study of the vertical structures of similar models (e.g. Temperton and Williamson 1981) suggests that 50 m is a reasonable average value for the internal modes excited by a perturbation at a single model level. With these values Eq. (3) gives an estimate of about 0.5 for $\alpha$. Thus it seems that during the geostrophic adjustment process the analysed wind differences are approximately halved because they are partly divergent, and halved again because the rotational part is not geostrophically balanced. This is consistent with the residual balanced wind of about 10 m/s visible in Fig. 9(b) and Fig. 6 and represents an order of magnitude reduction in the kinetic energy in the perturbation field. Of course there are many inaccuracies in these estimates: in the use of linear theory, in the assumption that the spectrum can be characterized by a single wavelength and equivalent depth, and above all in the estimation of typical values for these. However, they do give some insight as to which features of analyses caused the larger impact visible in the forecasts in the ECMWF experiment. In the ECMWF analysis system changes are constrained to be locally non-divergent and in approximate geostrophic balance.

An increase in the vertical coupling in the analysis would also result in a larger impact of unbalanced winds on the subsequent forecast, by increasing the equivalent depth and hence $\alpha$. The coupling in the ECMWF scheme was very large, and the features studied in section 3 were all of considerable vertical extent and could readily benefit from the vertical coupling in the ECMWF scheme. The same is not necessarily true for features with less depth, where too much vertical coupling could spread information about shallow but meteorologically significant features through too great a vertical extent, leading to an analysis which underestimates vertical shears.
(c) Further idealized experiments

To isolate the effect of different features of the analysis techniques, a series of perturbation experiments was performed by adding idealized increments to a balanced state selected from a general circulation integration, and comparing the forecast from the perturbed state with a similar forecast from an unperturbed control experiment. Four such experiments were carried out. In each case the perturbation was centred at a model grid point at 232 mb over the Pacific Ocean in the exit region of a straight westerly jet, a situation similar to the area where aircraft data produced the greatest increase in jet strength in the analyses of Fig. 3.

In the first experiment, the wind perturbation shown in Fig. 10(a) was applied to a single level of the model in the upper troposphere. After 6 hours (Fig. 10(b)) a large part of the perturbation has moved and veered through 90° in a manner similar to that shown in Fig. 9. The amplitude of the residual geostrophically balanced part of the impact is small, and cannot easily be estimated from Fig. 10(b) since the decrease in the unbalanced part of the wind is smaller in Fig. 10 than in Fig. 9. A large gravity wave is visible in Fig. 10(b) propagating outwards from the initial perturbation site. This returns after about 36 hours having completed a great circle path round the globe, a speed consistent with external gravity waves. Similar external modes are not seen in Fig. 9 having been suppressed by the repeated insertion technique. These differences in the rate of dispersion of the unbalanced modes and in the amplitude of external modes indicate a significantly different spectrum of modes excited by the repeated insertion analysis as compared to this simple perturbation. This is to be expected because of the frequency dependence of the repeated insertion technique, discussed further below.

In the second experiment the same wind perturbation was applied at all model levels weighted with the function $\exp\{-2 \ln^2(p/p_0)\}$ where $p$ is pressure and $p_0$ is the main perturbation level used in the previous experiment. This function is the one currently used operationally in the Meteorological Office. Note that the vertical coupling is still much less than in the ECMWF experiment. Vertical coupling projects more energy onto modes with greater equivalent depths, leading to the stronger external gravity mode in the 6-hour forecast visible in Fig. 10(c) and also, according to Eq. (3), a greater impact on the balanced geostrophic mode in the final state. The inertial character of the unbalanced part of the wind remains similar to the single-level experiment results in Fig. 10(b), with the winds turning through about 90° in 6 hours. This is consistent with inertial oscillations at 30°N. The rate of decrease of the unbalanced part of the wind is greater from the multi-level perturbation. This may be because the greater equivalent depths of the modes excited by the multi-level perturbation cause the frequencies (given approximately by $(4\pi^2\Phi/l^2 + f^2)^{1/2}$ (Haltiner 1971)) to be more dependent on $\Phi$, and this increases the vertical dispersion.

The wind perturbation of Fig. 10(a) is consistent with a perfect wind observation 20 m/s stronger than the model field and the assumption that model wind field errors have horizontal correlations of $\exp\{-\frac{1}{2}(r/s)^2\}$, where $r$ is distance and $s = 600$ km. If instead we assume that model wind field errors are non-divergent, and that the stream-function error correlation has the same Gaussian form, then a consistent wind perturbation for the same perfect observation is shown in Fig. 11(a) (Lorenc 1981, Eq. 35). Two further experiments were performed using this non-divergent perturbation. In the first of these, the wind perturbation by itself was used; in the second the geostrophically balanced height field also shown in the figure was applied as well. Perturbations were distributed through all model levels using the function given earlier. After six hours, the impact in the former experiment is markedly different from previous experiments
Figure 10. Wind perturbation field (a) and impact on 6-hour forecasts when applied at 232 mb ('single-level perturbation' - b) and at all model levels weighted with $\exp(-3\ln^2(p/232))$ where $p$ is pressure in mb ('multi-level perturbation' - c). Height contours (full lines) are shown at 5 m intervals and isotachs (dotted) at 2.5 m/s intervals. Arrows indicate vector winds.
Figure 11. Non-divergent wind perturbation field and corresponding geostrophically balanced height field (a), and impact on 6-hour forecasts using wind field only ('non-divergent perturbation' - b) and both wind and height fields ('geostrophic perturbation' - c). Vertical weighting as for the multi-level perturbation (bottom of Fig. 10). Contour intervals: height field (full lines) 10 m, isotachs (dotted) 2.5 m/s.
A pattern has quickly developed in the height field largely balancing the wind field and keeping the main wind perturbation approximately zonal, although some veering is visible. This height impact is larger than corresponding features in the univariate perturbation experiment (Fig. 10(c)); note that the height contour interval in Fig. 11 is larger. The forecast from the geostrophically balanced perturbation (Fig. 11(c)) is similar to Fig. 11(b), but has slightly more intense features. In both cases the outward propagating gravity wave is greatly reduced by the removal of the divergent wind component.

It is difficult to quantify the impact of these perturbations on the 'balanced' adjusted state, since this is not reached before nonlinear effects in the model have caused the differences to grow. However, most of the results are consistent with linear geostrophic adjustment theory, justifying its use to study results from a complex multi-level primitive equation model. The experiments also give some insight into the relative importance of vertical coupling, non-divergence and geostrophy when analysing isolated wind data. However, they do not model the repeated insertion analysis technique. This is designed to avoid the generation of high frequency modes by relaxing gradually towards the observed values over a six-hour period. This preferentially excites modes with periods greater than about twelve hours; for instance a mode with a six-hour period will be excited for the first half of the insertion, but this will be partly cancelled by excitation with opposite sign for the second half. The external gravity wave seen in Figs. 10(b) and (c) is made up of modes with wavelengths near 2500 km, propagating about 8000 km in 6 hours. The excitation of such modes will change in sign several times during repeated insertion, with only a small net effect. It is difficult to quantify this frequency dependence, since the repeated insertion of an isolated observation prevents a separation into independent modes. We studied this aspect in a set of experiments with a simple geostrophic adjustment model. If we linearize the two-dimensional shallow water equations with cyclic boundary conditions and a constant advective velocity, and assume that the analysis technique spreads the information from an isolated observation in such a way as to excite only modes of one equivalent depth and horizontal scale, then only these modes need be considered, and we are left with a spectral predictive model with only twelve degrees of freedom, eight describing inertial gravity modes and four describing geostrophic modes. For further details see appendix. We first validate the model by reproducing features from the perturbation experiments, taking 3142 km as the horizontal wavelength and 50 m/s as the constant advective velocity, with an equivalent depth of 10 m to simulate the single-level case and 100 m for the other three cases. Clearly this model cannot reproduce the dispersion of energy from a local perturbation by waves with differing phase speeds, but the initial behaviour of the inertial gravity modes and the partition between these and geostrophic modes can be studied.

After six hours the impact is as shown in Fig. 12, whose layout is the same as Figs. 10 and 11. The single-level and multi-level simulations exhibit the same advection (to the right by about 1/3 wavelength), and veering of the unbalanced wind as Fig. 10, though the interpretation of the height field is complicated by interactions between propagating gravity waves. The frequency of the inertial gravity mode in the experiment with 100 m equivalent depth is greater than the inertial frequency, and the wind has veered nearly 180° in 6 hours. In the non-divergent case a substantial height field has built up at the expense of the wind field whereas in the geostrophic case, the impact on the wind field is retained and the whole pattern advects downstream unchanged.

If we perform a repeated insertion data assimilation, as described in section 2(a), then the behaviour of the real example of Fig. 5(a) can also be simulated (Fig. 13) reproducing the effects previously noted: the isotach maximum is greater than the
Figure 12. Response of linear single wavelength shallow water equation model simulating Figs. 10 and 11. Wind perturbation (a) and its impact on 6-hour forecasts using equivalent depths of 10 m (b) and 100 m (c). Non-divergent wind perturbation and corresponding height field (d) and impact on 6-hour forecasts of wind field only (e) and both wind and height fields (f) with equivalent depth 100 m. Latitude 33° N, wavelength 3142 km, advective velocity 50 m/s, isotachs (dotted) at intervals of 0.25 of maximum of initial perturbation.
observed value, is displaced downstream from the observation position and exhibits some veering of the wind.

In a series of experiments varying equivalent depth and advective velocity, with either univariate, non-divergent, or geostrophic analysis increments and either single or repeated insertion, we studied how much energy was excited in each mode. Some results of these experiments are summarized in Fig. 14.

The first experiments were designed to study the benefit obtained by repeated as compared to single insertion; they used univariate analysis increments, wavelengths and latitude similar to the perturbation experiments, and zero advective velocity. We assume that the geostrophically balanced pattern of Fig. 12(d) is the correct analysis to fit the observed wind. The experiments showed (curves A and B of Fig. 14) that for equivalent depths greater than about 400 m repeated insertion did indeed avoid the generation of gravity waves and gave the correct geostrophic solution. This explains why the fast external gravity wave visible in Fig. 10 was not seen in Fig. 9. For smaller equivalent depths, however, the inertial gravity wave period is long compared to the 6-hour insertion time, and inertial gravity waves tend to be excited to fit the observation. For a single univariate insertion of the wind observation as in Fig. 12(a) the energy in the correct geostrophic mode is always less than 1/4 of its correct value, so at least for large equivalent depths repeated insertion is beneficial. However, in a similar series of experiments using the non-divergent wind increments like those in Fig. 12(d), the improvement due to repeated insertion was less marked (curves D and E of Fig. 14). This was because a single insertion of the winds in Fig. 12(d) put 4 times the energy into the correct geostrophic mode as did an insertion of the univariate wind perturbation of Fig. 12(a). For large equivalent depths almost all of the perturbation energy went into the correct geostrophic mode, in agreement with Eq. (3). Thus for large equivalent depths repeated insertion had less scope for improvement, while for small equivalent depths the inertial gravity wave period was longer than 6 hours.
Figure 14. Energies, as a percentage of the correct energy in the correct geostrophic mode, excited in the correct mode (top) and the incorrect modes (bottom) of a simple linear spectral model, as a function of equivalent depth, for various insertion methods.

We then went on to study the effects of repeated insertion of an observation when the correct solution varies in time. A mean advective velocity gives the 'correct' geostrophic mode a finite period and hence reduces the discrimination between modes of the repeated insertion technique. Thus excitation both of inertial gravity modes and of incorrect geostrophic modes increases with advective velocity, eventually becoming larger than excitation of the correct mode. The effect of a 35 m/s advective velocity on the repeated insertion univariate system, which simulates the OSE system, is shown in Fig. 14 curve C. The incorrect mode excited corresponds to the jet maximum visible in Fig. 9(a) downstream of the observation, a typical simulation of which has been shown in Fig. 13. The 6-hour forecast from Fig. 13 shows some of the characteristics of Fig. 8. However, since during adjustment such a local perturbation largely disperses, and this is not included in the simple model, the comparison cannot be precise. The effect on an advective velocity was inversely proportional to the scale of the feature being analysed; the examples have wavelength 3142 km. The effect when using non-divergent analysis increments (Fig. 14 curve F) was large, particularly in the generation of an incorrect geostrophic mode.
5. **Summary and Conclusions**

An observing system experiment was conducted to evaluate the impact of aircraft wind observations on numerical model analyses and forecasts from them. Two periods in 1979 were selected for study, one in February and one in November. For the latter period, results of a similar experiment carried out at ECMWF were available for comparison.

The greatest impact on analyses was found in the upper troposphere over the northern hemisphere oceans where aircraft are the major source of wind information. Positive features included better resolution of jet strengths with increases of up to 20 m/s. The better quality of the observations led to some improvements in analyses partly through less reliance on poorer quality data such as satellite cloud-track winds.

Forecasts from these analyses were improved to a lesser extent but a subjective analysis indicated that some positive impact still remained. Improvements were found mainly downstream of analysis differences and included better shape, intensity and position of upper troughs. Comparison with corresponding results from the ECMWF experiment indicated that the impact on wind analyses was similar and the forecast impact, though qualitatively similar, was greater in the ECMWF experiment.

The effects of different characteristics of the analysis schemes used were isolated using forecasts from idealized perturbations to a model state and also a simple linearized model, and were discussed in terms of linearized geostrophic adjustment theory. The experiments indicate that, for the assimilation of isolated wind data in the extra-tropical upper troposphere, (i) a vertical spreading of the effect of single-level data aids their assimilation by avoiding the excitation of complex vertical structures, (ii) it is important to use wind information to update the rotational component of the wind field, and (iii) correcting the mass field geostrophically in accordance with the wind observations has a significant but less important effect. These conclusions apply in the cases studied for the impact of aircraft data on large-scale features of considerable vertical extent and do not necessarily apply to shallower features or other regions of the globe. They explain the increased retention of information in the ECMWF experiment.

The repeated insertion analysis technique was found to be beneficial in avoiding the generation of high frequency modes and exciting instead the slowly varying geostrophic modes which we assume are more like atmospheric motion. This was particularly true for large equivalent depths, i.e. when the effect of observations was spread in the vertical. However, if the analysis technique was modified to give non-divergent winds, the scope for improvement by repeated insertion was less. In the presence of a mean advection repeated insertion tends to generate unsubstantiated maxima downstream of the observations, as seen in some of the with-aircraft analyses.
APPENDIX

Linearized low-order shallow-water-equation model for the study of repeated-insertion data assimilation

The linearized basic equations on a cyclic $f$ plane are

$$\frac{\partial u}{\partial t} = fu - \frac{\partial \phi}{\partial x} - U \frac{\partial u}{\partial x}$$  \hspace{1cm} (A1)

$$\frac{\partial v}{\partial t} = -fu - \frac{\partial \phi}{\partial y} - U \frac{\partial v}{\partial y}$$  \hspace{1cm} (A2)

$$\frac{\partial \phi}{\partial t} = -\Phi \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) - U \frac{\partial \phi}{\partial x}$$  \hspace{1cm} (A3)

where $\Phi / g$ is the equivalent depth, $U$ the basic advective velocity, and other symbols have their usual meanings. We now assume that a single observation exists of $u = u_0$, $v = 0$, at $x = 0, y = 0, t = 0$. The repeated interpolation and insertion of this observation are modelled by assuming that the interpolated values have the form $\cos kx \cos ky$. This means that only modes of a particular wavenumber $k$ and equivalent depth $\Phi / g$ are excited; all solutions can then be expressed in terms of

$$u = u_{cc} \cos kx \cos ky + u_{ss} \cos kx \sin ky + u_{ss} \sin kx \cos ky + u_{ss} \sin kx \sin ky$$  \hspace{1cm} (A4)

and similarly for $v$ and $\phi$. Substitution into (A1–3) gives us a predictive equation for each of the twelve coefficients $u_{cc}$ etc. Linear analysis of these equations easily identifies four geostrophic and eight gravity wave eigenmodes. The forecast equations are solved using analytic space differencing and identical time finite differences to those of the model described in section 2.

Univariate data assimilation then just requires the addition of one extra term to the predictive equations for $u_{cc}$ and $v_{cc}$, giving the analogue of Eq. (1):

$$u_{cc} = u^*_{cc} + \lambda(u_0 - u^*_{cc})$$  \hspace{1cm} (A5)

$$v_{cc} = v^*_{cc} + \lambda(0 - v^*_{cc})$$  \hspace{1cm} (A6)

where $\lambda$ is the relaxation coefficient as used in section 2(a).

The ‘correct’ geostrophic mode consistent with this observation has the form (at $t = 0$) of

$$u_{cc} = u_0, \hspace{1cm} v_{ss} = u_0, \hspace{1cm} \phi_{ss} = -fu_0/k$$  \hspace{1cm} (A7)

with all other coefficients zero.

Non-divergent data assimilation is modelled by adding additional terms to the predictive equations for $u$ and $v$ to balance those of (A5) and (A6), consistent with the non-divergent geostrophic modes such as that of (A7) e.g.

$$v_{ss} = v^*_{ss} + \lambda(u_0 - u^*_{ss})$$  \hspace{1cm} (A8)

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REFERENCES


Bengtsson, L. 1983  "Results of the Global Weather Experiment". Lecture presented at the 34th session of the WMO Executive Committee. WMO No. 610. 1–40


"The first GARP global experiment: objectives and plans". Global Atmospheric Research Programme Joint Organising Committee, GARP Publications Series No. 11, ICSU, WMO

Gilchrist, A. 1982  "JSC study conference on observing systems experiments". Exeter 19–22 April 1982. GARP WCRP WGNE Report No. 4


Kallberg, P., Uppala, S., Gustafsson, N. and Pailleux, J. 1982  "The impact of cloud track wind data on global analyses and medium range forecasts". ECMWF Technical Report No. 34


Simmons, A. J. and Hoskins, B. J. 1979  The downstream and upstream development of unstable baroclinic waves. J. Atmos. Sci., 36, 1239–1254
