DATA ASSIMILATION EXPERIMENTS WITH THE HIRLAM SYSTEM

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Summary: The HIRLAM system is used to investigate short-range forecast failures by backward integration of the adiabatic forecast model. This simple technique is capable of identifying analysis errors in data sparse areas by projecting backward the dynamical information from data rich analysis areas. Its possible use in operational forecasting is examined.

1. Introduction

Errors in numerical weather forecasts can be attributed to errors in the initial conditions (*i.e.* analysis) and errors in the model formulation. With limited area models any errors arising from the treatment of boundary conditions must also be taken into consideration. However, experience suggests that deficiencies in the initial conditions are often the main cause of forecast failures.

In recent years the adjoint model has been used extensively to relate the sensitivity of short-range forecast error to initial conditions via the gradient of a model parameter with respect to all input parameters (Gustafsson *et al.* 1998; Rabier *et al.* 1996). At the European Centre for Medium-Range Weather Forecasts (ECMWF) this approach is routinely used to identify so-called key analysis errors (Klinker *et al.* 1998). Implicit in such methods is the assumption that the error in the verifying analysis is small relative to the forecast error. Also, the model error is assumed to be relatively small and the tangent-linear model is assumed to be appropriate to handle the development of initial errors. The objective of these methods is not just to identify the errors and weaknesses of the assimilation system: in principle, correction of the short-range forecast error can be used operationally to improve the medium range forecasts.

The HIRLAM analysis/forecast system is primarily aimed at producing short-range (up to 48 hours) forecasts with the main area of interest covering the North Atlantic and Europe. The forecast model uses boundary field data from a global model (*e.g.* from ECMWF). Forecast failures are usually associated with baroclinic developments in data sparse areas over the Atlantic, which are not properly identified in the analyses. As weather systems move into data rich areas over western Europe the data assimilation does not always respond quickly enough to the data: occasionally, even very short-range forecasts have major errors.

If the forecast errors are mainly associated with the dynamics, then a backward integration of the forecast model (with no physics) should enable us to identify the initial errors provided we start from an accurate analysis. The method does not need an adjoint model and is cheap to implement.

This note describes the method and its application to two recent forecast failures (section 2) involving Atlantic storms which affected Ireland. Section 3 describes experiments aimed at incorporating the scheme into a revised assimilation system.

2. Forecast experiments

The operational HIRLAM configuration used in Met Éireann was used for all experiments. The horizontal resolution is approximately 0.3° (218 x 144 horizontal points with 24 levels in the vertical). Details of the analysis and forecast models are documented by Källén (1996).

The HIRLAM data assimilation is based on the ECMWF so-called optimal interpolation (OI) scheme and uses conventional land based observational data in addition to SATOB and SATEM data. A 3-hour assimilation cycle is used but some experimental results are also shown for a 1-hour cycle.

In the experiments, analysis fields from ECMWF were used as boundary fields. The assimilation was started from 'cold' at least 1 day before the event of interest to provide a reference set of analyses and forecasts, and continued until the storm was reliably analyzed over a data rich area. A backward forecast, starting from a reference analysis, which was assumed to be of high quality, provided a background ('first-guess') for the next assimilation cycle. The process was repeated, cycling back in time to produce new analyses (hereafter referred to as 'backward') over the experiment period.

The first experiment is based on a severe storm, which crossed Ireland on 24 December 1997. The developing storm moved rapidly from the Azores during the early morning, deepening by more than 20 hPa in 12 hours, and caused widespread damage as it moved NE over the country. It was unusual in that while some of the medium range guidance over the previous days suggested a deep low in the area, the later short-range guidance was quite poor. For example, compare the operational 18-hour HIRLAM forecast with the verifying analysis in Fig. 1. The equivalent forecast from ECMWF was similar to the HIRLAM product and in general both models failed to capture the intensity of the system and its track over Ireland. Forecasts based on the 12 UTC analyses on the previous day were also defective and placed the storm track too far south. An examination of the observational data did not reveal any major quality problems. However, the rapid deepening, and poor quality of the background fields, did impact on the HIRLAM assimilation as the storm moved over land: several SYNOP pressures and the Valentia (03953) TEMP data were rejected. By 18 UTC the storm was over a data rich area and the corresponding analysis, based on a 3-hour assimilation cycle, agrees reasonably well with the observations.

Using the 18 UTC analysis, the assimilation was cycled backwards to produce new first-guess fields and a backward analysis for 00 UTC. An 18-hour forecast (full physics) from the backward analysis is shown in Fig. 2. It agrees quite closely with the verifying analysis, which suggests that, ignoring the influence of any model error, the backward analysis is a more accurate description of initial conditions. It is instructive to compare the two analyses and the fit to the observational data. Figures 3 and 4 show the mean sea level (msl) pressure analysis with the superimposed observations over the development area. The low is deeper in the backward analysis and agrees with the BUOY report near the low centre; this observation was rejected in the reference analysis. At upper levels, the fit between the analyses and data are broadly similar but there are no observations in the critical development area. The backward analysis shows a pronounced trough at mid levels (Fig. 5) which is absent from the reference. It has a typical baroclinic structure, tilted in the vertical, extending from the surface to mid levels.

The absence of the physics in the backward integration is obviously a source of error in the method. To check the influence on the assimilation cycle length, the period was reduced to one hour. The impact was relatively minor: the reference analyses fit the data slightly better over land and the cycled forecast from 18 UTC is also slightly better (Fig. 6). However, if the cycling (3-hour or 1-hour cycle) is extended back 24 hours, *i.e.* to 18 UTC on 23 December, the 24-hour forecast from the new analysis does not agree so closely with the verifying analysis: the position is reasonable but the low is not deep enough (Fig. 7). Cycling back 30 hours did not produce any improvement over the operational forecasts.

The second forecast failure to be investigated is based on a major rainstorm over Ireland on 2-4 August 1997 (see McDonald and McGrath 1997, for synoptic details). The situation is summarized in Fig. 8 which shows the reference analysis and verifying forecasts for 12 UTC 3 August. The analysis shows a well developed low just south of Ireland and a ridge to the north. Again, the medium range guidance was particularly poor – forecasts from the main Centres consistently indicated that the ridge would be the main influence giving mostly dry, settled weather, over the country with the low further south. In reality, the rain belt associated with the depression gave very heavy rain over all but the extreme north and northwest regions. The short-range forecasts from the HIRLAM model were also of particularly poor quality (Fig. 8): the heavy rain was forecast to remain south of Ireland. A careful examination of the development of the storm as it moved across the Atlantic over the previous days did not reveal any significant problems with data quality. As a general assessment it seems that defects in the analyses were the main cause of the forecast failure. Due to a lack of observational data the errors remained unchecked until the depression encountered western Europe on 3 August.

Assuming the 12 UTC analysis for 3 August was correct, it was used as the starting point for a backward assimilation (3-hour cycle). Figures 9 and 10 show 24-hour forecast fields based on the backward analysis for 12 UTC on 2 August. The msl pressure and upper-level forecasts show reasonable agreement with the verifying analysis and the precipitation pattern over Ireland is also quite good, even though the amounts are significantly underestimated.

Again, it is instructive to examine the differences between the backward and reference analyses for 12 UTC on 2 August. The differences are small at the surface but at upper levels the trough west of Ireland is more pronounced (compare Figs. 11 and 12). Also, the background or 'first-guess' fields for the backward analysis fits the land based TEMP observations more closely below 200 hPa (Fig. 13) and also the aircraft wind observations (with fewer rejections in the case of the latter). Interestingly, the TEMPSHIP wind observation from DBBH at 00 UTC on 2 August (positioned at 50.8N, 37.1W) hinted at a more developed trough near the 600 hPa level - in agreement with the backward analysis; the data were used in the reference analysis but without any significant impact.

Again, the cycling can be extended further backward (*e.g.* to 00 UTC on 2 August) but the identification of analysis errors becomes less reliable, presumably due to the exclusion of the physics in the integration.

3. Cheap 4D-Var?

The results discussed in section 2 suggest that backward cycling can improve the reference analyses. One way to extend the method with a view to operational use would be to incorporate the backward steps directly into the assimilation. A possible strategy would be to

- Perform a normal forward assimilation for the current cycle.

• Cycle backwards for 1 or more cycles using new background fields created by backward integration of the adiabatic model.

• Cycle forwards to produce an updated analysis for the current cycle using new background fields created by forward integration of the full model.

Tests on the two storms do indeed show improved forecasts with such an assimilation scheme. For example, using a 3-hour cycle and cycling backward and forward 6 hours for each analysis, sample forecasts were produced from revised analyses for the two storms previously discussed. The results, shown in Figs. 14 and 15, should be compared with the operational products in Figs. 1 and 8 respectively. Unfortunately, extended tests show that the scores are systematically worse for the enhanced assimilation compared with the standard system (see Fig. 16). This is perhaps not unexpected. In general, backward integration will project the information in data rich areas over western Europe into a data sparse ocean region. It will also project the information in data sparse areas, information that may be flawed and heavily dependent on the first-guess fields. Over a large area such as the North Atlantic, with relatively few multilevel observations, the cycling backward and forward in time seems to accumulate these errors and also those arising from the lack of physics in the backward step.

4. Conclusions

In this study, the backward integration of the adiabatic HIRLAM model has been shown to be a useful diagnostic tool in identifying short-range forecast errors. In the two test cases studied the failures appear to be related to defects in the analyses, which are most probably due to a lack of observational data over the North Atlantic. The method gives reasonable estimates of the analysis error for forecasts out to 18-24 hours.

Incorporation of the backward step into the normal forward assimilation, to correct previous cycles, has been shown to lead to an improved analysis in specific cases. However, extended tests show that in general the scheme has a detrimental effect on forecast skill.

References

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Klinker, E., Rabier, F., and Gelaro, R — 1998 — Estimation of key analysis errors using the adjoint technique. *Q.J.R. Meteorol. Soc.*, **124**, 1909-1933

McDonald, A., and McGrath, R.	1997	'August bank-holiday floods'. In HIRLAM Newsletter No. 29. November 1997.
Rabier, F., Klinker, E., Courtier, P., and Hollingsworth, A.	1996	Sensitivity of forecast errors to initial conditions. *Q.J.R. Meteorol. Soc.*, **122**,121-150

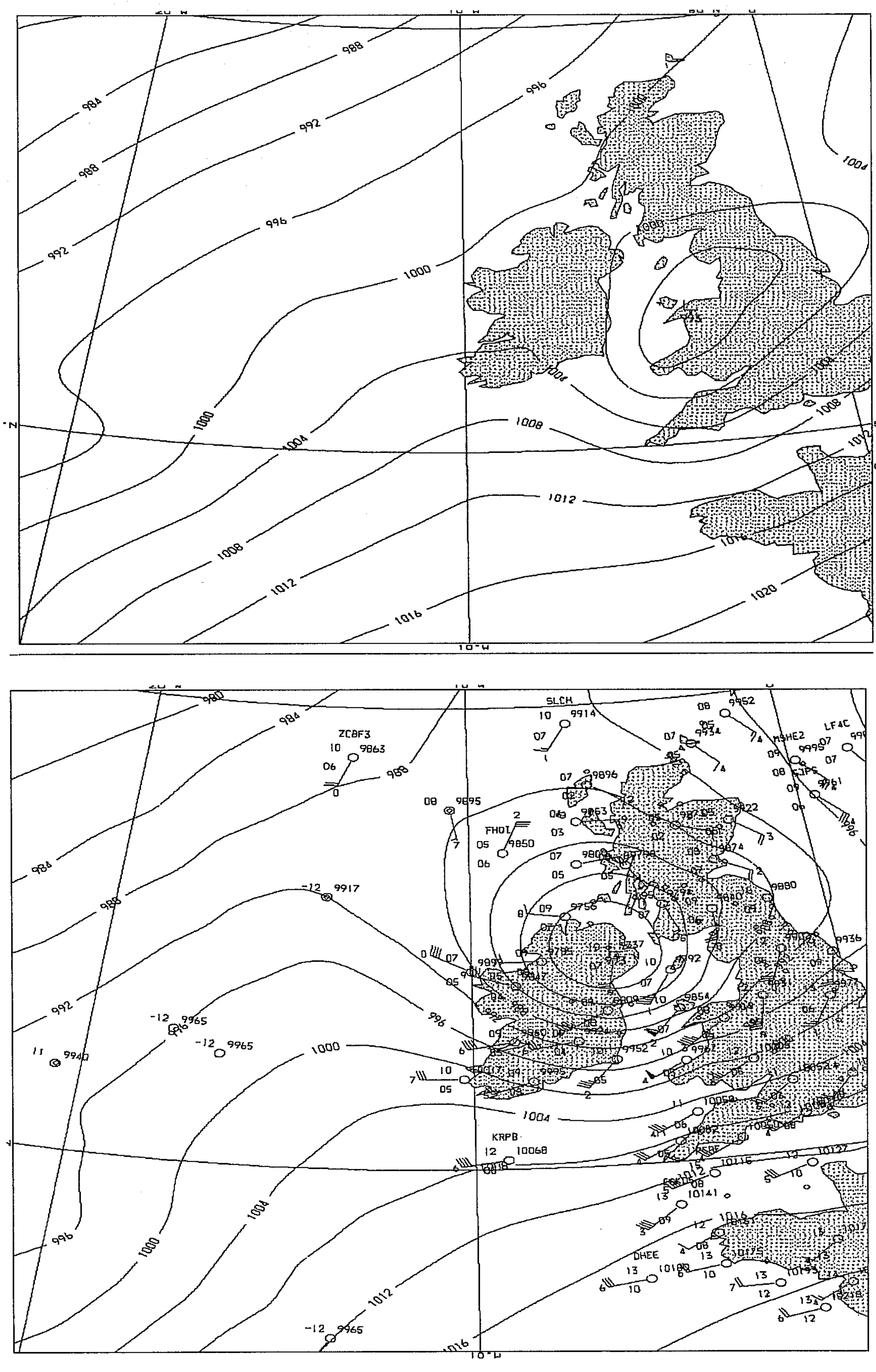


Figure 1. Top: HIRLAM 18-hour msl pressure forecast from 00 UTC 24 December 1997. Bottom: verifying analysis with observations.

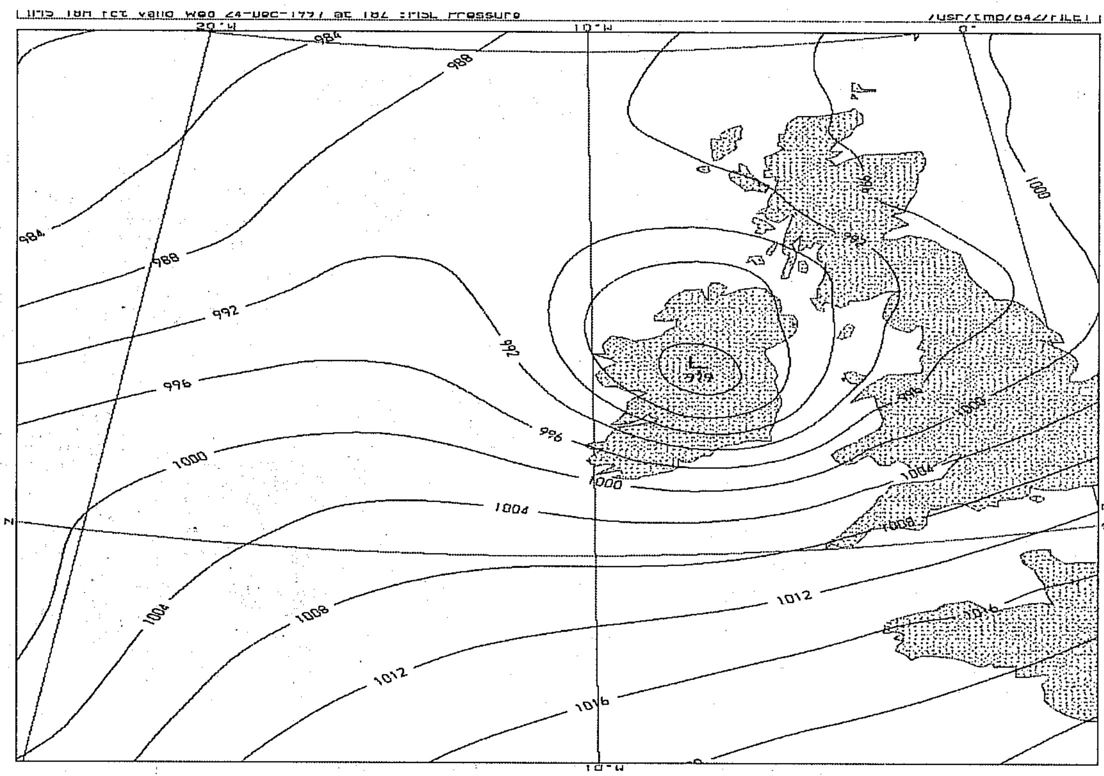


Figure 2. 18-hour forecast of msl pressure from a "backward" analysis for 00 UTC 24 December 1997.

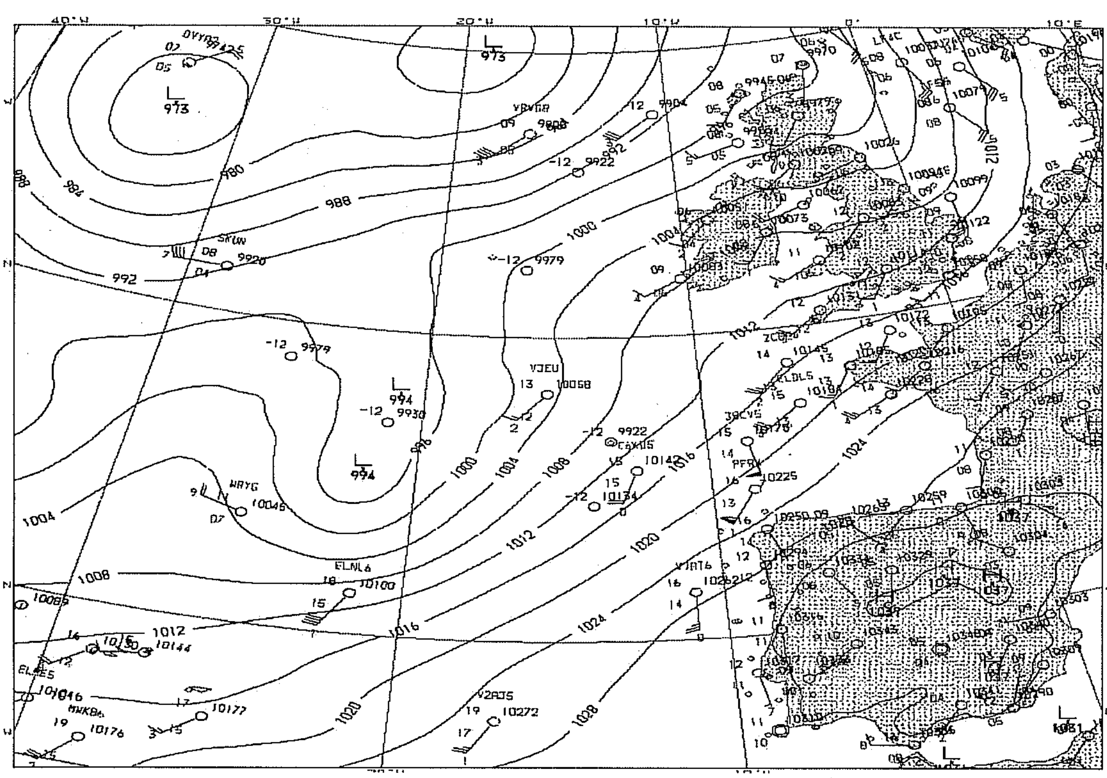


Figure 3. "Backward" analysis for 00 UTC 24 December 1997. Msl pressure with observations.

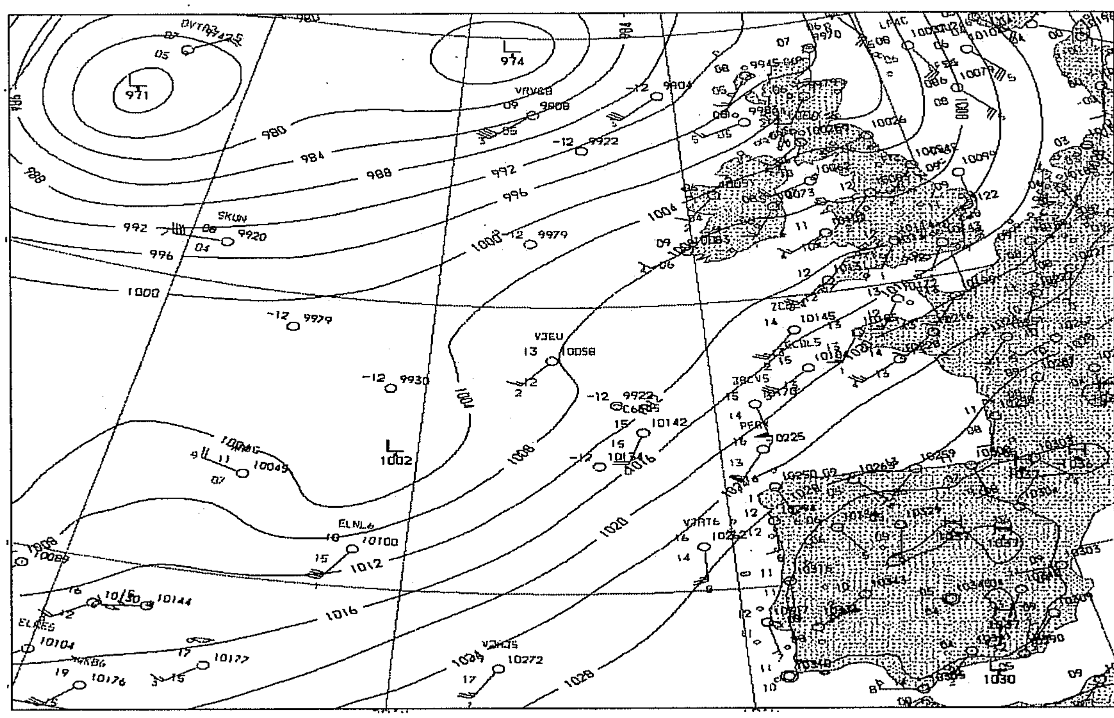


Figure 4. Reference analysis for 00 UTC 24 December 1997. Msl pressure with observations.

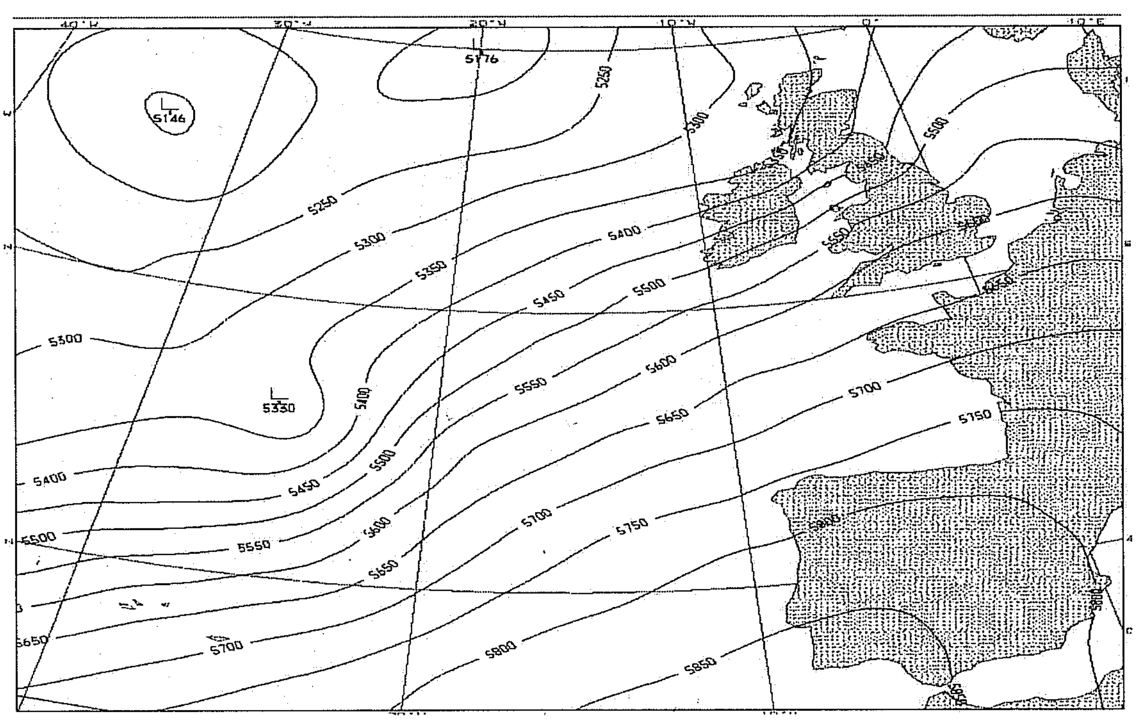


Figure 5. "Backward" analysis for 00 UTC 24 December 1997. 500hPa geopotential field.

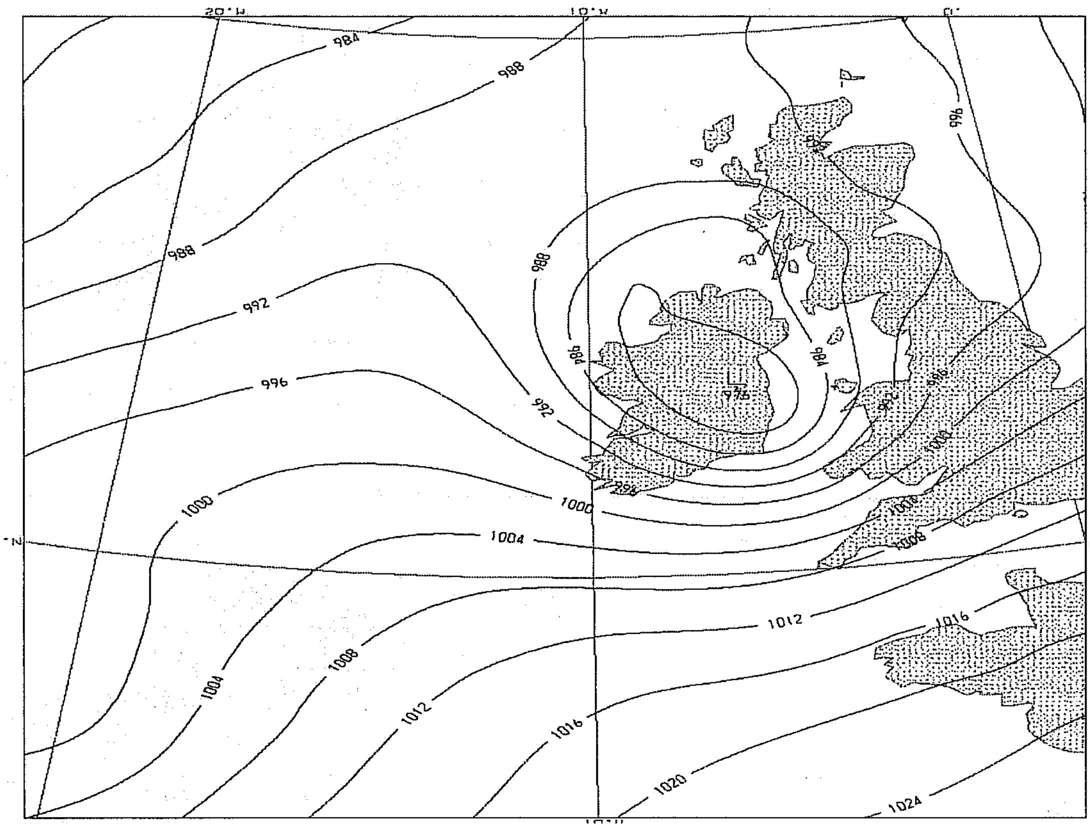


Figure 6. Msl pressure 18-hour forecast valid for 18 UTC 24 December 1997 from a "backward" analysis based on a 1-hour data assimilation cycle.

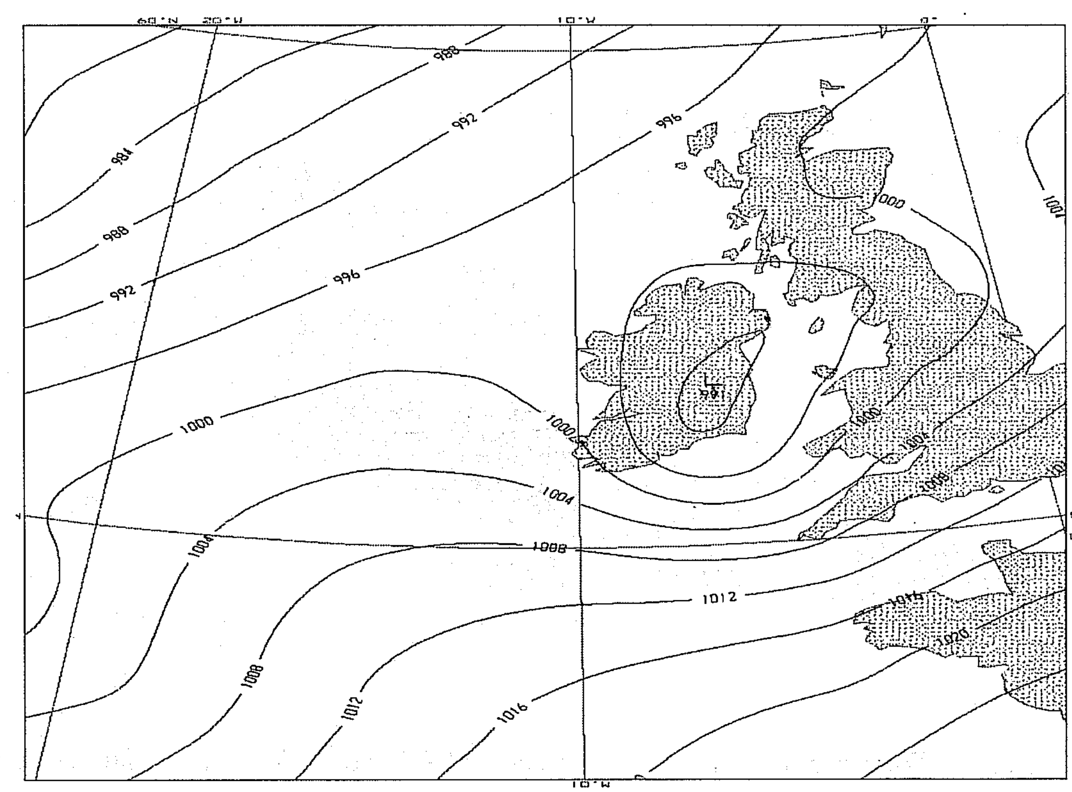


Figure 7. Msl pressure 24-hour forecast valid for 18 UTC 24 December 1997 from a "backward" analysis based on a 1-hour data assimilation cycle.

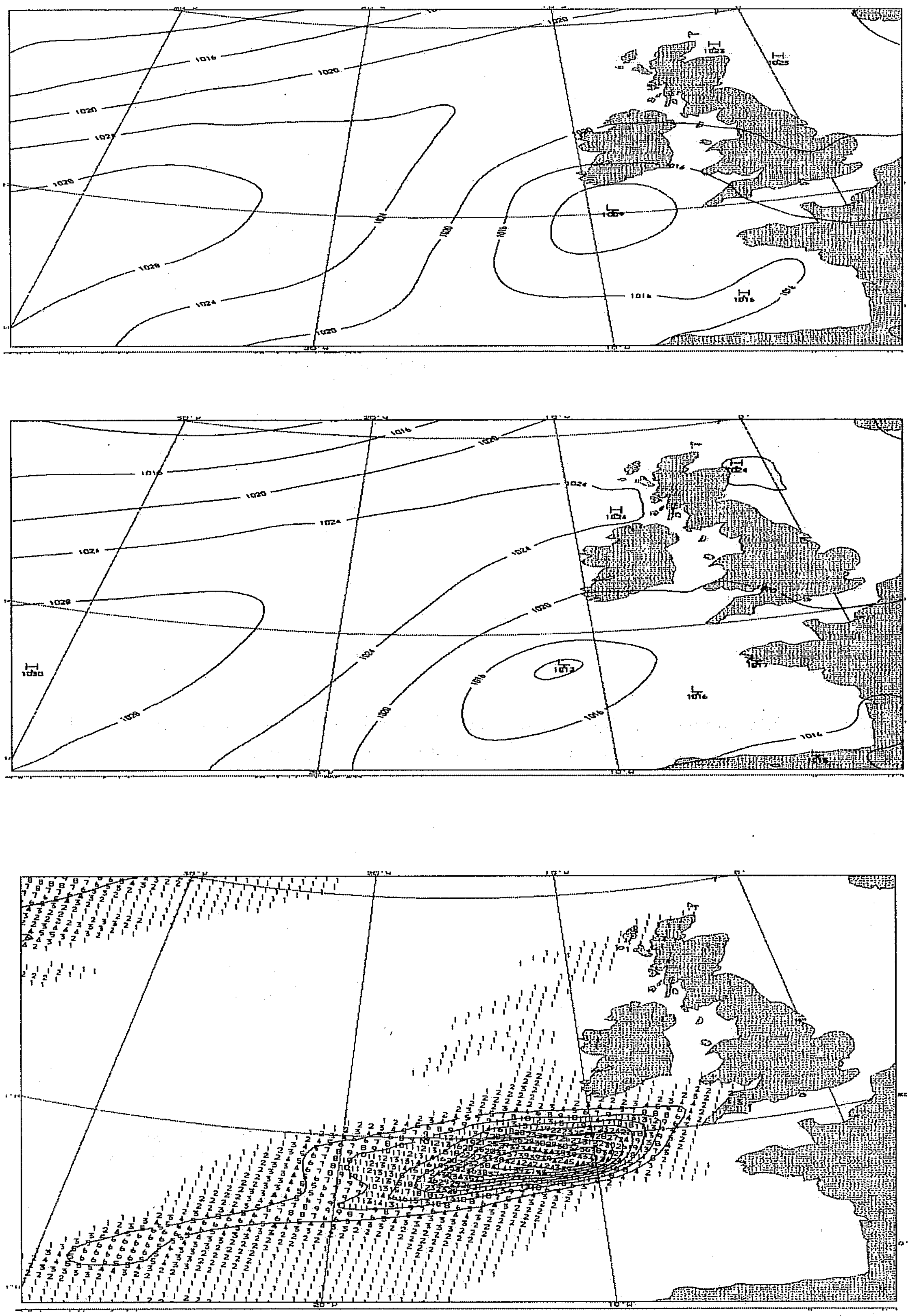


Figure 8. Forecasts for 12 UTC 3 August 1997. Top: Verifying reference msl pressure analysis. Middle: 24-hour msl pressure forecast. Bottom: 24-hour forecast of total precipitation (mm)

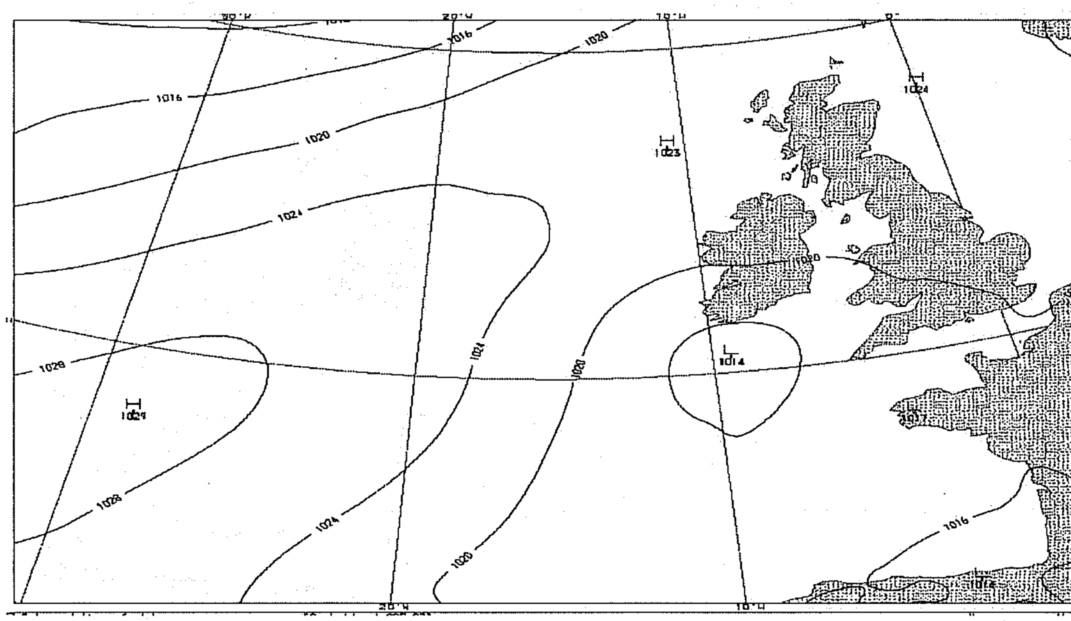


Figure 9. 24-hour forecast valid 12 UTC 3 August 1997 based on a "backward" analysis (3-hour assimilation cycle). Msl pressure.

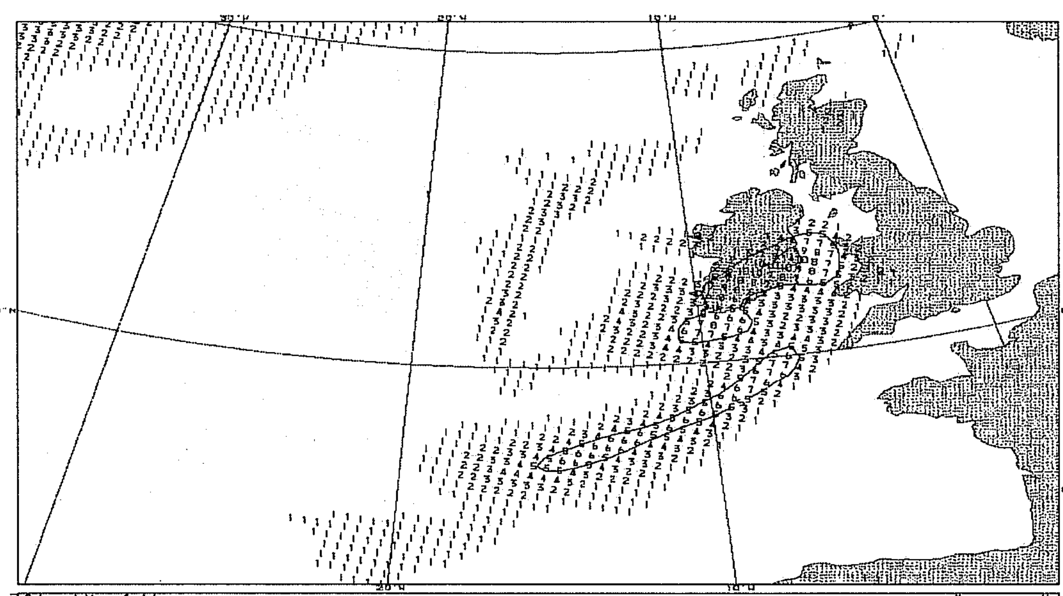


Figure 10. As in Fig. 9. Total precipitation (mm).

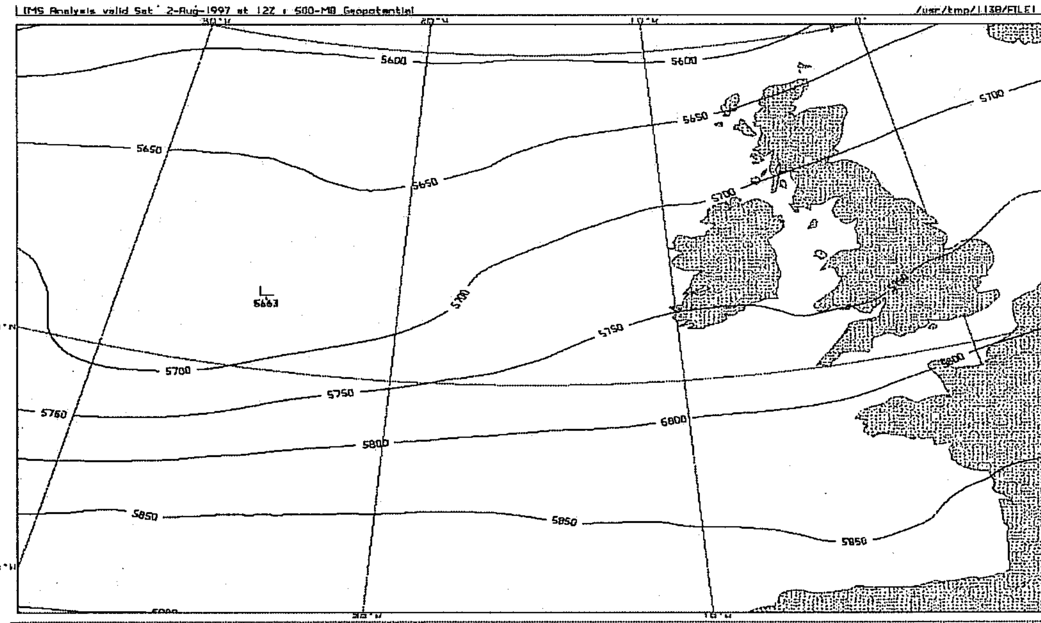


Figure 11. 500 hPa geopotential reference analysis for 12 UTC 2 August 1997.

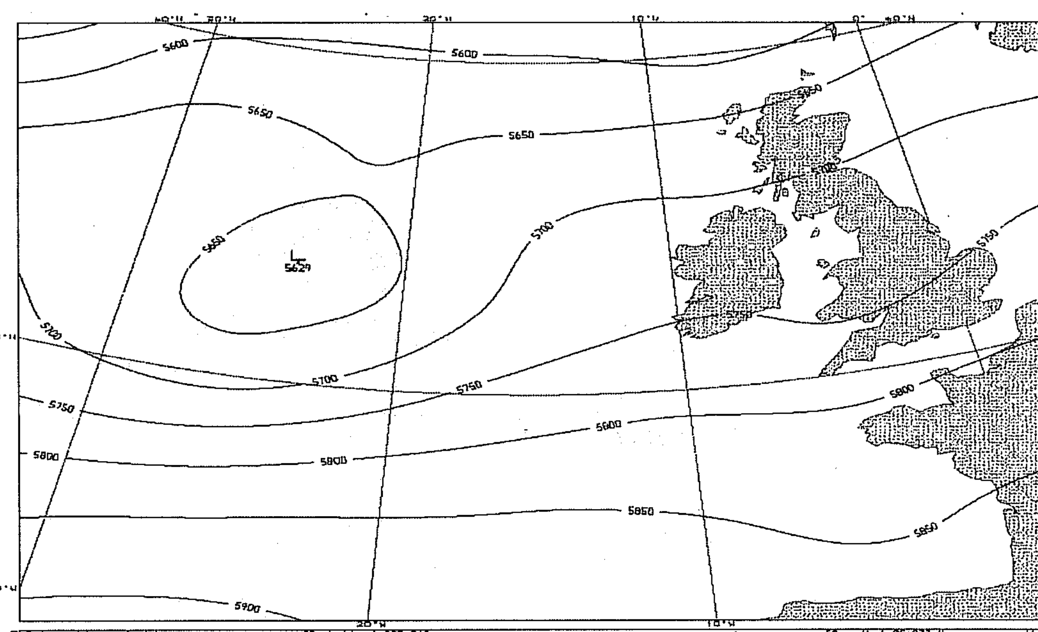


Figure 12. 500 hPa geopotential "backward" analysis for 12 UTC 2 August 1997.

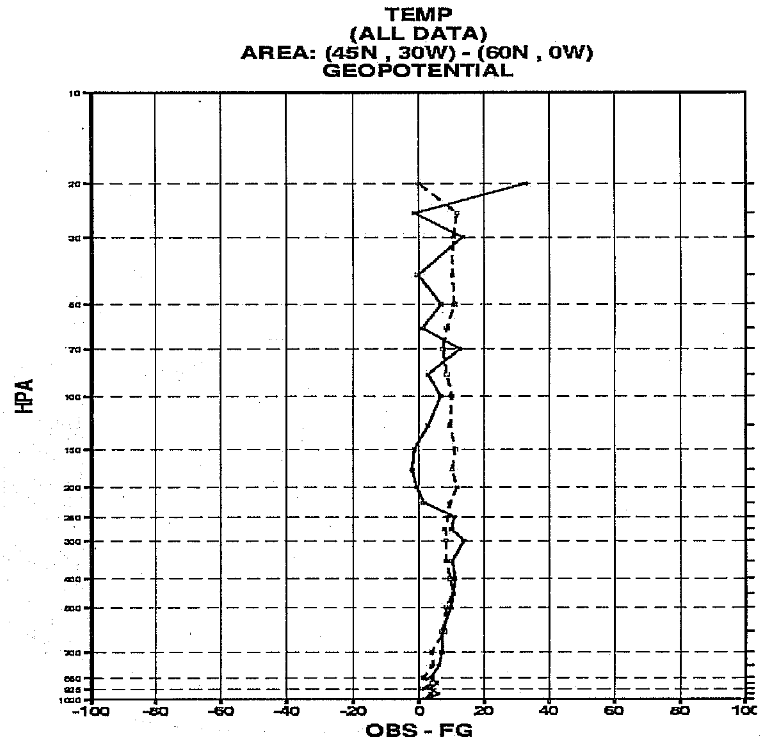
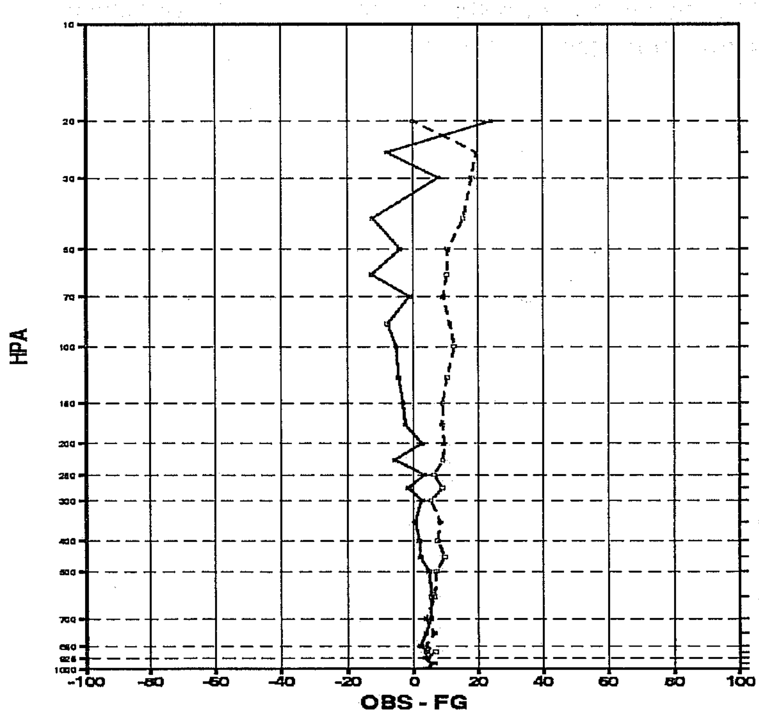


Figure 13. Geopotential differences in the vertical between the TEMP observations and the background ('first-guess') fields for 12 UTC 2 August 1997. Top: reference analysis. Bottom: "backward" analysis. Mean (solid) and standard deviation (dashed) of differences shown. Unit: geopotential metres.



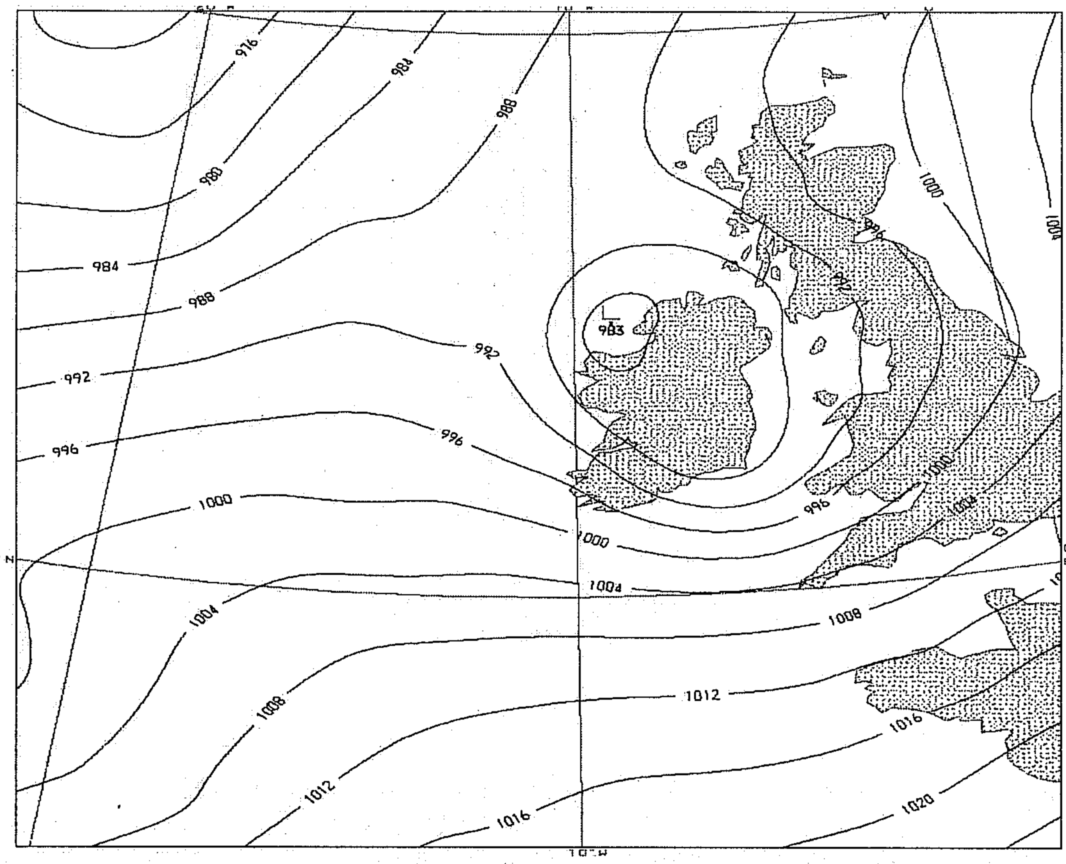


Figure 14. 24-hour forecast of msl pressure for 18 UTC 24 December 1997 based on revised assimilation (see text for details).

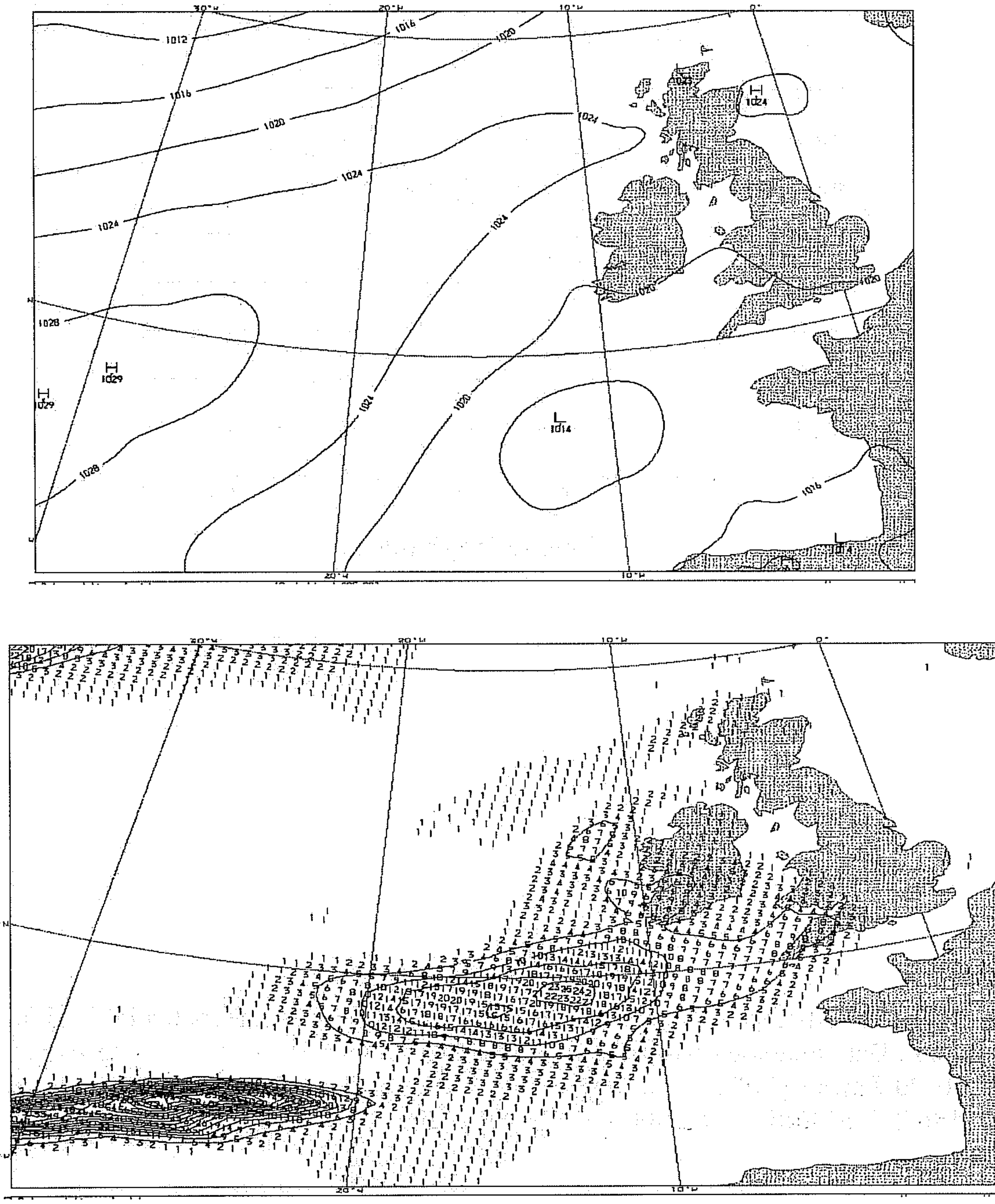
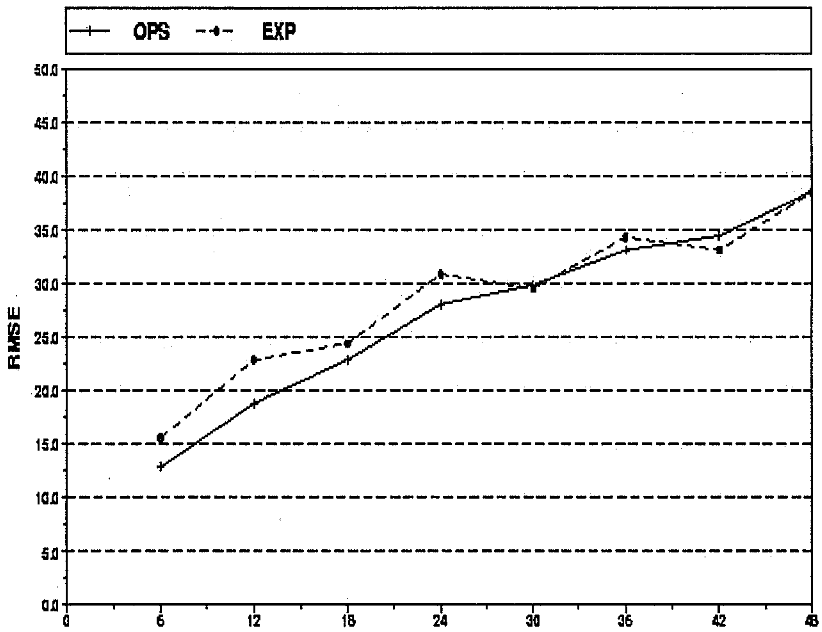


Figure 15. 24-hour forecast of msl pressure (top) and total precipitation (bottom) for 12 UTC 3 August 1997 based on revised assimilation (see text for details).



Forecast length (hours)

Figure 16. Root-mean-square forecast errors for the 500 hPa geopotential field (units: gpm). Data are based on forecasts produced at 6-hour intervals, covering the period 10–20 January 1997. Solid: operational. Dashed: revised assimilation (see text for detail). Verification area: 40N – 65N, 25W– 10E.