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Impact of the additional FASTEX radiosonde observations on the High-Resolution Limited-Area Model (HIRLAM) data-assimilation and forecasting system

By BJARNE AMSTRUP* and XIANG-YU HUANG
Danish Meteorological Institute, Denmark

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SUMMARY

During the Fronts and Atlantic Storm-Track EXperiment (FASTEX) the radiosonde network was considerably enhanced over the North Atlantic area, making this an ideal period for assessing the impact of additional radiosonde observations, in data-sparse regions, on the atmospheric data-assimilation and numerical weather-forecast systems.

We have carried out an observing-system experiment (OSE) with a limited-area data-assimilation system. Two parallel experiments have been run, one with and one without the extra radiosonde data.

We have used both observation verification and field (or analysis) verification to compare the analyses and forecasts from the parallel experiments. On a daily basis, the extra data can have both positive and negative impacts on the different meteorological variables considered here. However, averaged over the whole period the impact is definitely positive, especially on upper model levels. Our results strongly support the inclusion of extra radiosonde data, like those provided by FASTEX. They could be of significant benefit in reducing the errors in operational numerical weather-prediction products if they were available routinely.

KEYWORDS: Data assimilation Fronts and Atlantic Storm-Track EXperiment (FASTEX) Numerical weather prediction Observing-system experiments (OSEs)

1. INTRODUCTION

Until now the radiosonde network has been considered one of the most important observing systems for atmospheric data-assimilation and numerical weather-forecasting systems. Källén and Huang (1988) have shown that under certain circumstances the inclusion of just one isolated radiosonde in oceanic areas of the southern hemisphere is sufficient to have a large impact on the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses and forecasts. Heming (1990) showed that radiosonde data from two Atlantic ships had a large impact on the United Kingdom Meteorological Office (UKMO) analyses and forecasts of a severe storm. Lönnberg (1996) showed a positive impact of two Greenland radiosondes on the HIgh-Resolution Limited-Area Model (HIRLAM) analyses and forecasts. He also found some benefit from doubling the radiosonde reporting frequency at one of the stations. Atlas (1997) and Undén (1997) showed that by removing all radiosondes the quality of 48 h forecasts is reduced to that of 72 h forecasts. Lord *et al.* (1997) showed that by reducing the number of Rawinsondes by 50% over the continental United States, the degradation of the analyses and forecasts is equivalent to about 1–2 years worth of model and data-assimilation development. Although it is difficult, in general, to detect the impact from one or a few (e.g. less than five) radiosonde stations, the impact of a somewhat larger number (10 or more) of 'extra' radiosondes has been demonstrated to be positive and significant (Pailleux 1997).

The existing radiosonde network is by no means ideally designed. Most radiosonde stations are located on land, although many weather systems originate over the oceans.

* Corresponding author: Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark. e-mail: bja@dmi.dk

One natural step forward is to expand the network in data-sparse oceanic areas as was done in the Fronts and Atlantic Storm-Track EXperiment (FASTEX). Currently, most of the radiosonde stations report twice daily with a 12 h interval and only very few radiosonde stations report four times daily, although most major weather centres run their numerical weather-forecasting system with a 6 h assimilation window. To increase the observation frequency is therefore a natural expansion. However, to expand the existing radiosonde network is expensive and it is important to ensure a cost-effective deployment of observations. Observing-system experiments (OSEs) have been used to assess the impact of specific observations on analyses and forecasts. Overviews of OSEs for different observation types can be found in Bader and Graham (1996), Atlas (1997) and Pailleux (1997). An overview of OSEs with the HIRLAM forecasting system, which is the system to be used in this study, can be found in Huang (1997).

It can be difficult to assess the impact from radiosondes additional to the existing network on atmospheric data-assimilation and numerical weather-forecasting systems. To perform such an experiment we need additional radiosonde data over a sufficiently long period. During FASTEX the upper-air network of observations was considerably enhanced in the North Atlantic area. A total of 29 normal land stations and 15 Automated Shipboard Aerological Programme (ASAP) stations increased their scheduled launch frequency from twice a day to four times a day. In addition, four new ASAPs were scheduled, launching four times a day. Thus, there was also a very good coverage at 0600 and 1800 UTC in the North Atlantic area during the FASTEX period. These extra data make it an ideal period for using an OSE to assess the impact of additional radiosondes, in a data-sparse region, on atmospheric data-assimilation and numerical weather-forecasting systems. The additional radiosondes were only available for a short period (January and February 1997), but are considered to be of great importance for the future design of the atmospheric observing system. On a number of occasions during FASTEX dropsondes were launched from special flights in targeted areas. Although they can be very important in specific cases, this study concentrates on the impact of the additional radiosondes.

OSEs with the additional FASTEX radiosonde and dropsonde data were carried out and reported by ECMWF (Undén 1997) and by Météo-France (Lacroix *et al.* 1997), each using their own data-assimilation systems. A positive impact on forecasts was detected in some weather situations, and a neutral impact in other situations. Both systems are global and, in addition to the conventional data, assimilate a number of satellite datasets. The results from such OSEs may be different in a limited-area forecasting system, in particular if it is unable to assimilate satellite data efficiently. For example, several European countries use the HIRLAM forecasting system operationally. Like all other limited-area systems, HIRLAM relies on lateral boundaries provided by global systems (in this case, ECMWF analyses and forecasts). The formulation of lateral boundary conditions often leads to larger errors in the regions close to the lateral boundaries (Gustafsson 1990). The additional data in these regions (e.g. the FASTEX data) may be more important for limited-area systems than for global models. The satellite data have so far not been used efficiently by the HIRLAM systems, although research activities have been reported. The operational HIRLAM system at the Danish Meteorological Institute (DMI) does not assimilate any satellite data. The additional FASTEX data may, therefore, be the only available observational data over a large area and could potentially be more important for the HIRLAM system at DMI than, for example, for the global model system at ECMWF.

The motivation of this study is to assess the impact of additional radiosonde observations on a limited-area data-assimilation system.

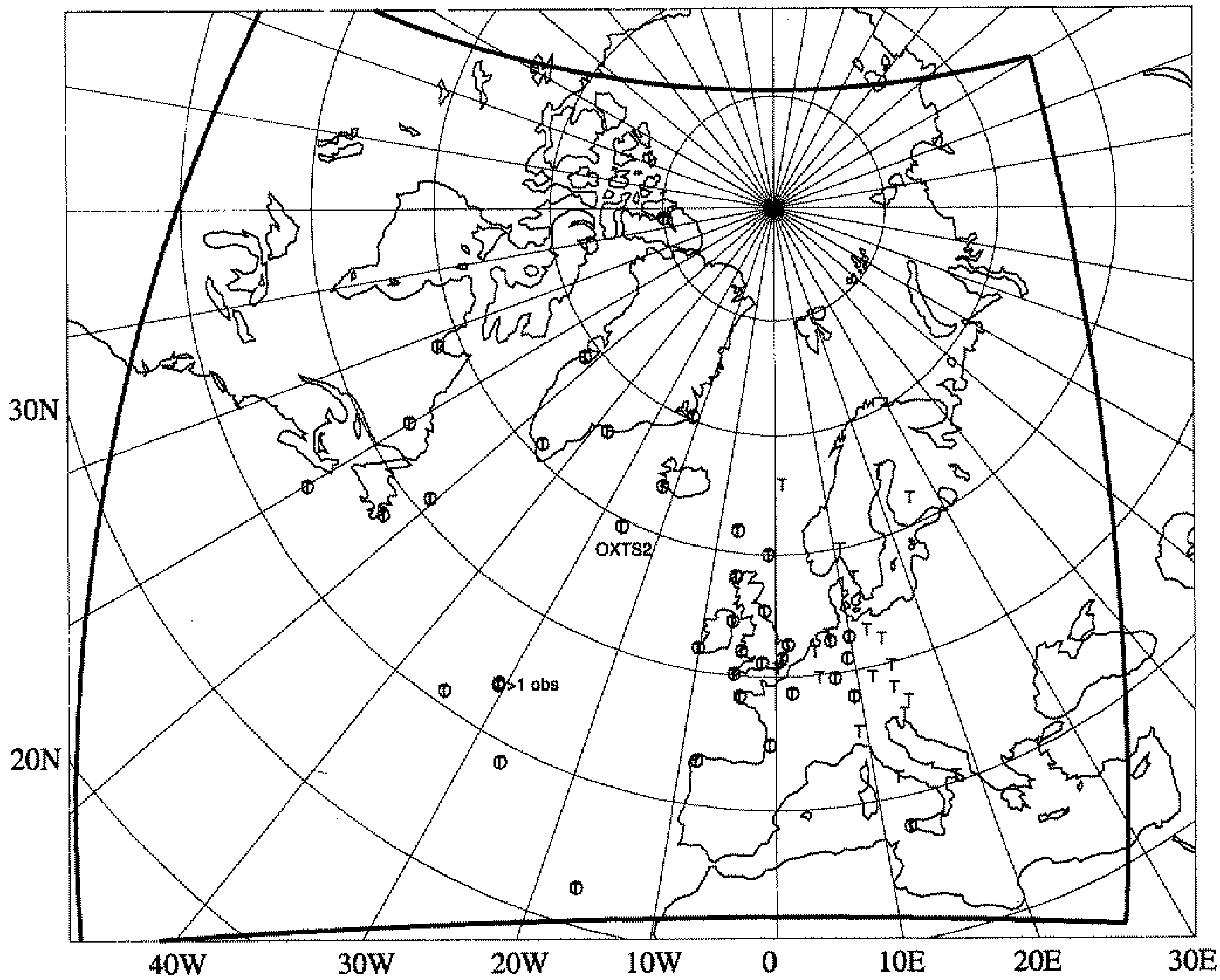

Figure 1. The domain of the model used is shown with a thick line. The TEMPs (radiosondes) available for the 0600 UTC analysis on 6 February 1997 are labelled with a T and the extra FASTEX TEMPs are marked with a circled T. The 'extra' (see appendix) ASAP (Automated Shipboard Aerological Programme) station named OXTS2 is located with the label OXTS2 below it.

2. THE OBSERVING-SYSTEM EXPERIMENT SET-UP

A 14-day period, from 0000 UTC 28 January 1997 to 0000 UTC 11 February 1997, is chosen for the data-assimilation experiments. This is the third standard test period used at DMI for pre-operational parallel experiments and has been documented by Nielsen *et al.* (1998). It is a period characterized by intense cyclonic activity over the North Atlantic Ocean. Some of the additional FASTEX observations have been made in the same area. We have chosen the model domain which was used operationally at DMI during the FASTEX period. The model domain is shown in Fig. 1. In the figure, we have also shown the positions of the regular and additional radiosondes at one reporting time.

In order to compare the performance of different data-assimilation experiments a +48 h forecast is made from each analysis (including those at 0600 UTC and 1800 UTC). The forecasts are verified directly against observations from European radiosonde and synoptic stations to give an objective evaluation of the experiments. Since the stations involved in this observation verification (obs-verification) cover a limited area with very few stations in the Atlantic, the forecasts are also compared with analyses from their own data-assimilation suite. The DMI observation- and field-verification packages are used. Twelve parameters are chosen as in the DMI operational set-up: geopotential height Z, temperature T and wind vector V all at 250 hPa, 500 hPa and 850 hPa (Z250, Z500, Z850, T250, T500, T850, V250, V500 and V850); mean sea level pressure (m.s.l.p.); 2 m temperature (T02M); and 10 m wind (V10M).

The data-assimilation system used for the experiments is the operational HIRLAM forecasting system at DMI. The system has been developed in a collaborative research project between the national meteorological institutes of Denmark, Finland, France, Iceland, Ireland, the Netherlands, Norway, Spain, and Sweden (see, for example, Machenhauer 1988; Gustafsson 1993). It is an intermittent data-assimilation system including an optimal interpolation (OI) analysis scheme (version 2.7.11) and a forecast model (version 2.5.7). The system is documented in Källén (1996) and a brief description can be found in Huang *et al.* (1994).

The HIRLAM OI is a limited-area version of the ECMWF OI scheme (Lönnberg and Shaw 1987). The first-guess field is the 6 h forecast from the previous data-assimilation cycle. Three-dimensional multi-variate statistical interpolation is used for the wind, geopotential, and surface pressure. Three-dimensional uni-variate statistical interpolation is used for relative humidity. The observation window covers a 6 h span around the analysis times (0000, 0600, 1200 and 1800 UTC). A standard observation set is used, including synop observations, ship observations, (drifting and moored) buoys, pilot balloons, radiosonde data and aircraft data. Here we would like to point out again that no satellite observations have been included.

The forecast model is a primitive-equation model with horizontal wind, temperature, specific humidity and surface pressure as prognostic variables, which are staggered on the Arakawa C-grid. It has a rotated latitude–longitude horizontal grid; a hybrid sigma-pressure vertical coordinate; second-order accuracy in the finite-difference scheme; a leap-frog, semi-implicit scheme with Asselin time filtering; and linear fourth-order horizontal diffusion. It contains a comprehensive physics parameterization package including a Kuo-type convection scheme; a stratiform condensation scheme; a surface scheme; a radiation scheme (Savijärvi 1990; Sass *et al.* 1995) and a non-local vertical-diffusion scheme (Holtslag and Boville 1993; Nielsen and Sass 1994).

In this study the DMI operational data-assimilation set-up is used with two differences. One is the use of lateral boundaries. Instead of using the *available* ECMWF analyses and forecasts (which could be as old as a +60 h forecast) at the analysis time, we use the *best possible* ones, i.e. ECMWF analyses at 0000 UTC and 1200 UTC and +6 h forecasts at 0600 UTC and 1800 UTC. By doing this we hope to reduce problems due to old lateral boundaries (Gustafsson 1990). Another difference is the forecast length at 0600 UTC and 1800 UTC. While in the operational set-up only a +6 h forecast is scheduled at these times for data-assimilation purposes, in both experiments a +48 h forecast is made after every analysis to expand the data samples and to regularize the verification statistics. We have performed the following two data-assimilation experiments:

WIF: The first experiment is named WIF (WIth the additional FASTEX radiosondes).

NOF: The second experiment is named NOF (NO additional FASTEX radiosondes) and is used as a 'normal data' reference to discuss the impact of the extra data. In practice, the additional FASTEX radiosondes are removed by using a blacklist in the creation of the analysis observation file from BUFR (Binary Universal Form for the Representation of meteorological data) data. A detailed description of the blacklist is given in the appendix.

In the experiments the horizontal resolution is 0.42°, the number of vertical levels is 31, the number of grid points is 194 × 163, the time step is 240 s, and the lateral-boundary update frequency is every 6 h.

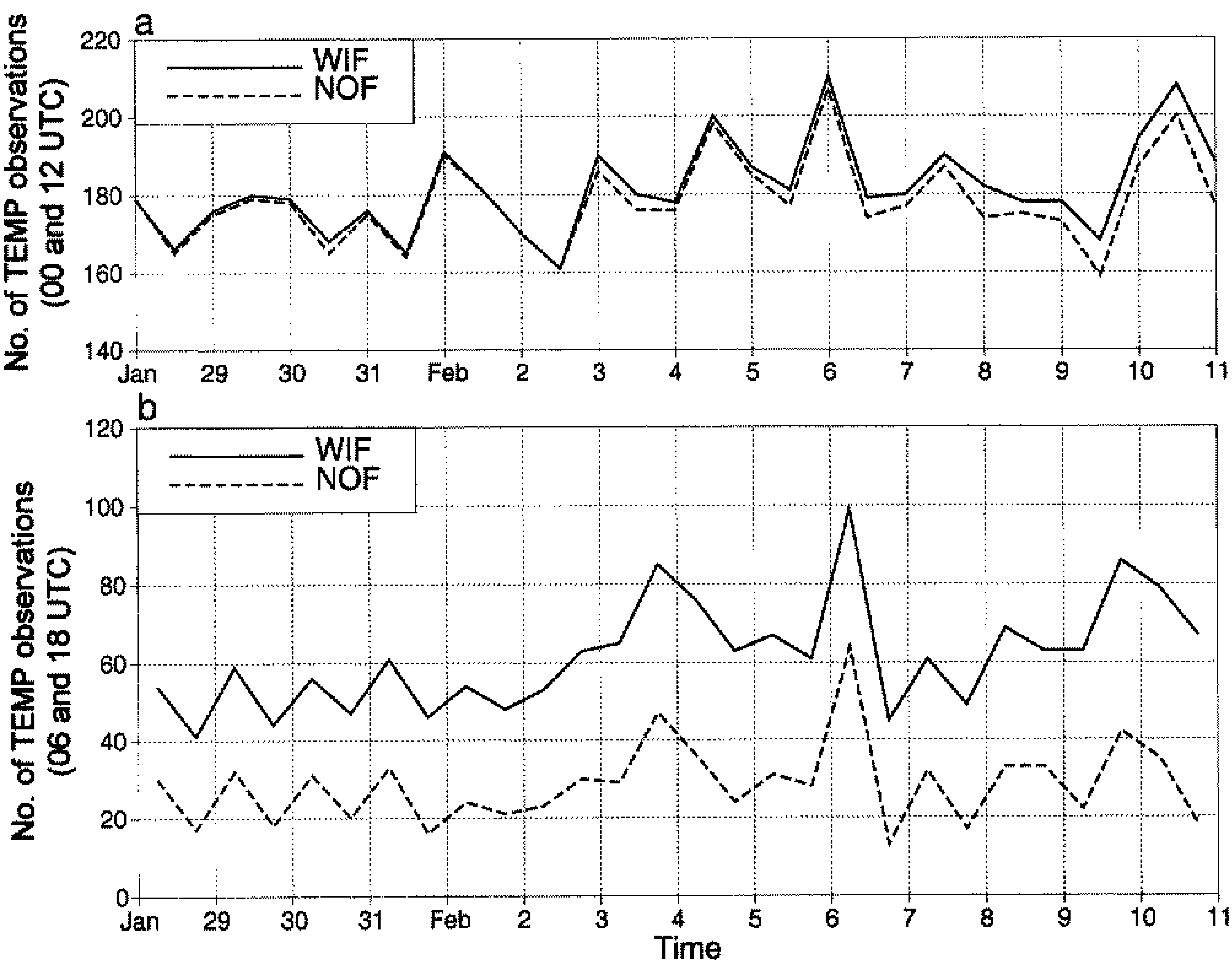

Figure 2. The number of TEMP (radiosonde) observations that are used as input to the analyses. (a) shows that almost the same number of TEMPs are used in the two runs at 0000 and 1200 UTC. (b) shows that the NOF experiment (see text) has 20 to 40 less stations than the WIF experiment (see text) in the runs at 0600 and 1800 UTC.

The numbers of radiosondes (TEMPs) assimilated at the four analysis times are shown in Fig. 2. It can be seen that the same number or slightly more TEMP stations are used at 0000 and 1200 UTC in WIF compared with NOF, and that 20 to 40 fewer TEMP stations are used at 0600 and 1800 UTC in NOF compared with WIF. The reason for the difference being larger than 4 in some cases at 0000 and 1200 UTC is that some of the extra 4 ASAPs were launched more frequently than every 6 h. An example (marked >1 obs) is given in Fig. 1. At 0600 and 1800 UTC the numbers of TEMPs are about a factor of two larger than normal with the FASTEX TEMPs.

3. Results

(*a*) *Results from obs-verification*

Obs-verification has been done using an extended EWGLAM (European Working Group on Limited-Area Modelling) station list for the full period and for daily verification of 24 h forecasts. Note that bias (mean error) and standard deviation (std. dev.) are used for the daily verification, and bias and root mean square (r.m.s.) are used for the full period. We use std. dev. for the daily verification in order to not let large fluctuations in daily biases show up. (It also takes away differences in systematic biases from different models. The latter is not the case here, however.) Furthermore, in both cases all available data are used. That is, observations at 0600 and 1800 UTC are used as well as at 0000 and 1200 UTC, and all forecasts valid at the same times are used. ECMWF analyses are

TABLE 1. CONTINGENCY TABLE OF 12-HOUR PRECIPITATION (6-HOUR FORECAST TO 18-HOUR FORECAST INTERVAL) FOR WIF (SEE TEXT)

	O1	O2	O3	O4	O5	sum
F1	185	4	2	0	0	191
F2	299	47	9	0	0	355
F3	22	35	44	11	2	114
F4	0	0	9	14	0	23
F5	0	0	0	0	0	0
sum	506	86	64	25	2	683
%FO	37	55	69	56	0	42

F stands for forecast and O for observation. The number is the class number (see text). %FO is the percentage of the forecasted values in the same class as the observation class.

TABLE 2. AS TABLE 1 EXCEPT FOR NOF (SEE TEXT)

	O1	O2	O3	O4	O5	sum
F1	182	5	3	0	0	190
F2	286	42	17	4	0	349
F3	38	39	39	11	1	128
F4	0	0	5	10	1	16
F5	0	0	0	0	0	0
sum	506	86	64	25	2	683
%FO	36	49	61	40	0	40

used to select the observations that are accepted for the verification. Figures 3 and 4 show daily, 24 h-forecast obs-verification and full-period obs-verification, respectively, of surface parameters: T02M, m.s.l.p. and V10M, and of upper level wind (V250, V500, V850), temperature (T250, T500, T850) and geopotential height (Z250, Z500, Z850). The surface plots show a significant, positive impact on m.s.l.p. and only a small impact on T02M and V10M from the increased number of observations. The upper-level parameters have a significant, positive impact from the increased number of observations, the higher upper levels having the largest impact. (For the 48 h forecasts, we have the following relative improvement in r.m.s. scores: m.s.l.p. (5.8%), T250 (2.0%), H250 (4.2%), W250 (2.4%), T500 (5.8%), H500 (4.5%), W500 (2.2%), T850 (1.3%), H850 (3.3%), W850 (2.3%)). It can be seen from Fig. 3 that the daily verification scores show some variance both in the scores and in which model has the best performance. However, in most cases WIF has better std. dev. scores than NOF.

Contingency tables of precipitation accumulated over 12 hours (from 6 to 18 hours forecast time) are shown in Tables 1 and 2. The numbers in these tables are obtained by counting the numbers of observed and predicted precipitation amounts in each of five classes for 25 Danish stations. The five precipitation classes are (precipitation amounts in mm): $P1 < 0.2$; $0.2 \leqslant P2 < 1.0$; $1.0 \leqslant P3 < 5$; $5 \leqslant P4 < 10$ and $P5 \geqslant 10$. P is either F (forecast) or O (observation) in Table 1. The 'sum' rows and columns are the sums of numbers in the given observation classes and forecast classes, respectively. It is evident that WIF has better scores than NOF. Note that the model has a clear tendency to overestimate weak to moderate (<1 mm) precipitation amounts.

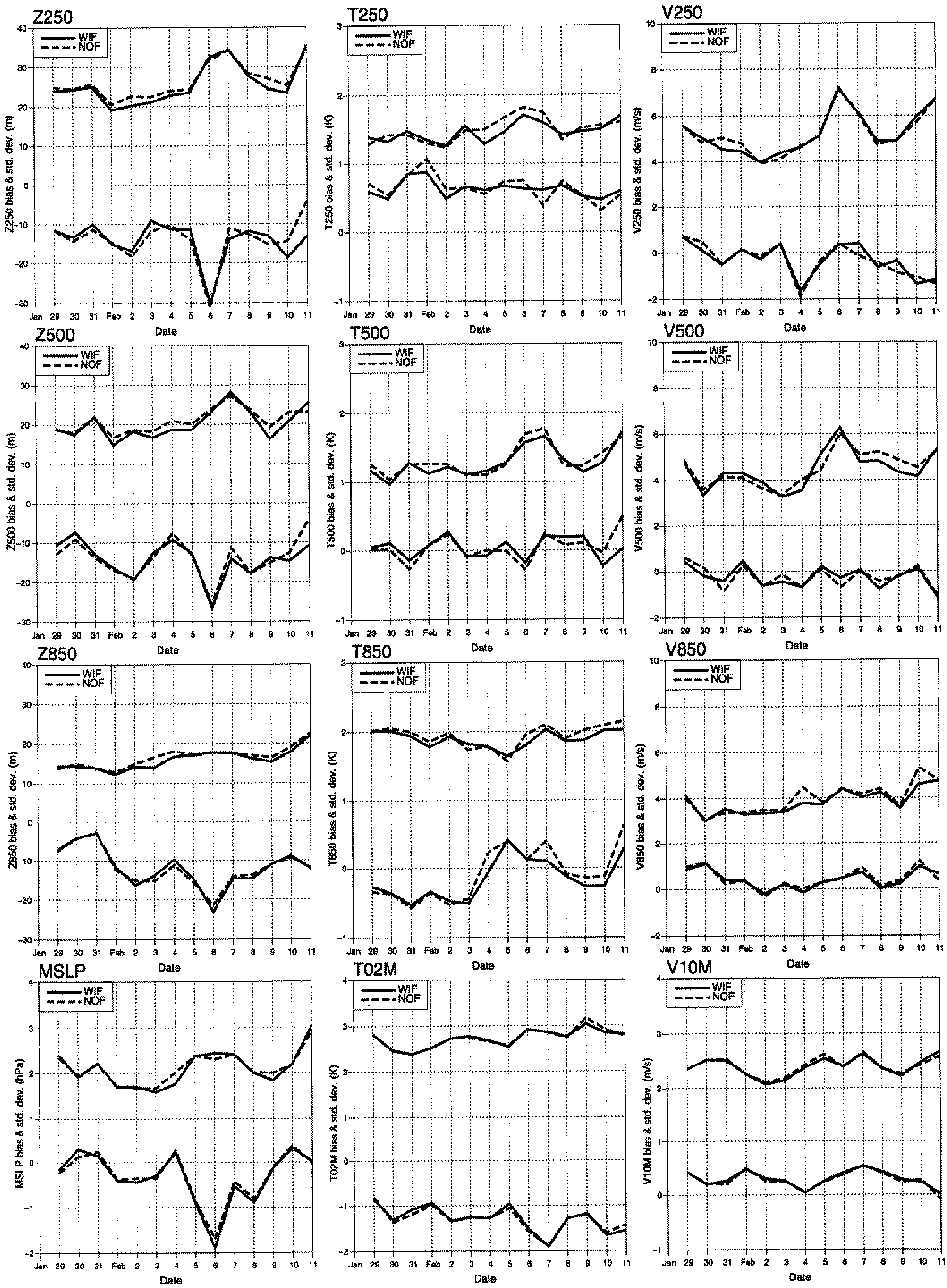

Figure 3. Daily obs-verification (bias (lower lines) and standard deviation (std. dev.) (upper lines)) of 24 h forecasts of surface parameters (mean sea-level pressure (m.s.l.p.), 2 m temperature (T02M), and 10 m wind (V10M)), and geopotential height Z, temperature T, and wind vector V all at 250 hPa, 500 hPa, and 850 hPa (Z250, Z500, Z850, T250, T500, T850, V250, V500, V850) with an extended EWGLAM (European Working Group on Limited Area-Modelling) station list. The time specifies valid date of forecasts. Results are included for the WIF and NOF experiments (see text).

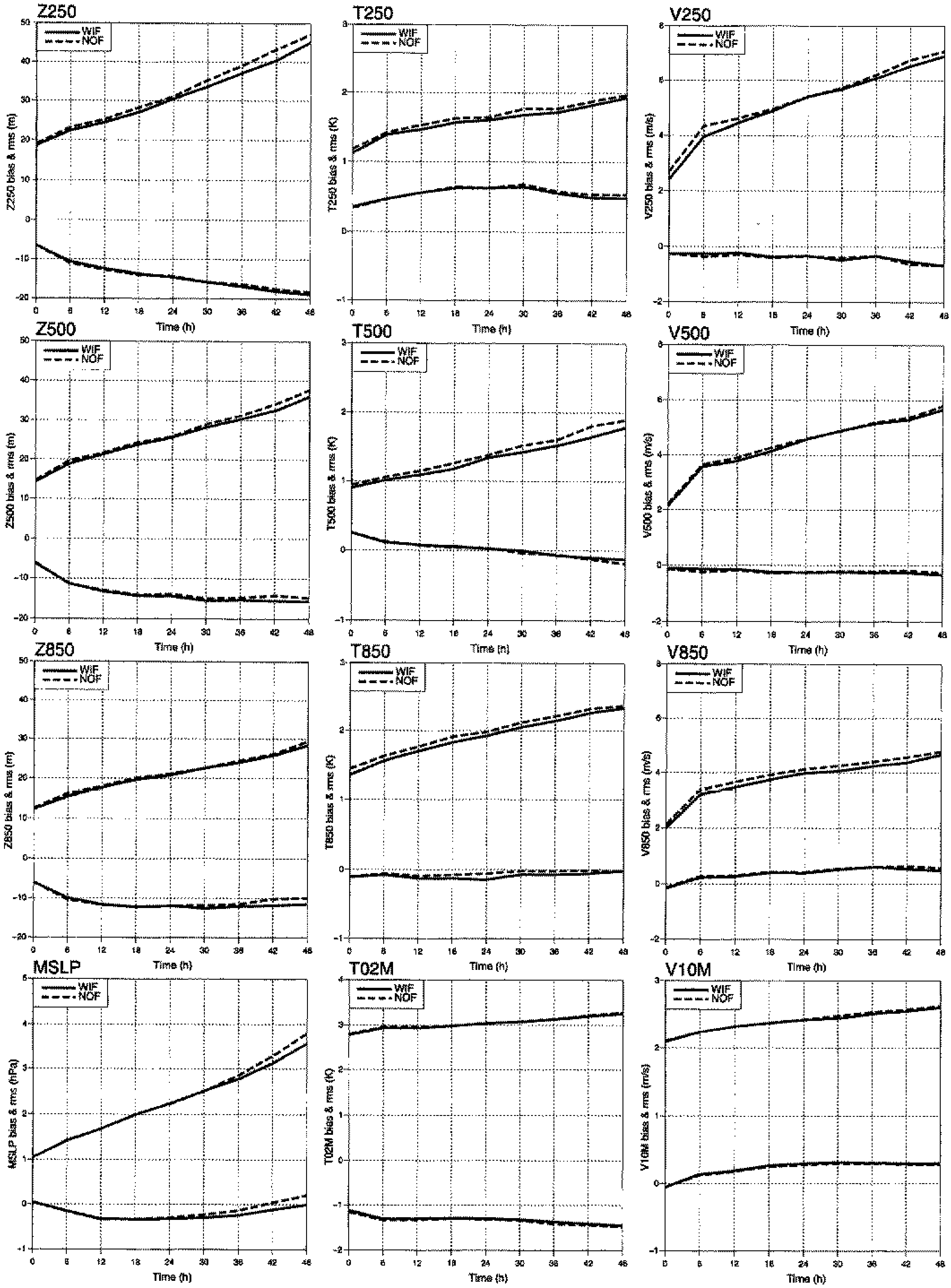

Figure 4. Obs-verification (bias (lower lines) and root mean square (r.m.s.) (upper lines)) of surface parameters and upper-level parameters as in Fig. 3. Time specifies forecast length. Results are shown for the WIF and NOF experiments (see text).

(*b*) *Results from field-verification*

Field verification is done using all available forecasts on a coarser grid (every third grid point in both directions) at the four analysis hours 0000, 0600, 1200 and 1800 UTC. The results from mean values over grid points for geopotential height and temperature are shown in Fig. 5. There is a positive or neutral impact from the extra observations depending on element. The extra radiosonde data have a positive impact on the geopotential height and m.s.l.p. as seen from the std. dev. However, the impact on the bias is very small. (For the 48 h forecasts, we have the following relative improvement in std. dev. scores: m.s.l.p.(2.9%), T250 (2.4%), H250 (5.2%), T500 (2.2%), H500 (6.0%), T850 (0.7%), H850 (3.3%)). The wind fields show a positive impact at all levels too. For the temperature the impact varies from slightly negative to slightly positive, but essentially the impact is neutral.

To illustrate the geographical distribution of the impact of the extra FASTEX TEMPs, the difference in std. dev. of 500 hPa geopotential heights from the field verification is shown in Fig. 6 for a short forecast length (24 hour) and for the longest forecast length (48 hour). It is obvious that WIF is better in the Atlantic region than NOF except for certain small regions. In comparison to these differences in the averaged std. dev., the differences between the averaged analyses (not shown) are negligible. Since there are very few stations in the obs-verification station list in the Atlantic, the differences as seen in Fig. 6 do not contribute much to the obs-verification results. The largest positive and negative differences between NOF and WIF in the average of all analyses for 500 hPa geopotential height are 5.5 m and −4.7 m, respectively. The differences appear in very small areas and are not shown here. The longer forecasts show larger differences in std. dev. between WIF and NOF runs, and over larger areas. Note also the relatively large negative impact around Novaya Zemlya in the Barents Sea in WIF compared with NOF. This undesirable side effect is due to different rejections of radiosondes in the two data-assimilation runs. There is a 'grey-list' of low-quality radiosonde stations in the HIRLAM analysis version used here (see Lönnberg and Eerola (1996), and Huang (1997) for a correct figure of 'dark grey' and 'light grey' stations). In the two experiments there were some differences in the rejection of radiosonde measurements at grey-listed stations *and* stations close to these grey-listed stations in the above mentioned area in Karelia (in northern Russia). Similar effects are seen for the std. dev. of m.s.l.p. In contrast, the bias of m.s.l.p. and geopotential height does not show such differences in this area.

(*c*) *Case study*

The FASTEX period represents a 'low predictability' group of forecasts although the specific cases in the FASTEX period may have been quite well predicted by most of the major forecast centres. Despite the better objective verification scores for WIF forecasts the differences in m.s.l.p. and geopotential-height patterns in individual cases are often small. During the last part of the FASTEX period studied here, intense marine cyclogenesis took place. At 1800 UTC on 7 February a strong cyclone had a central position over the sea between Iceland and Norway and on 10 February at 1800 UTC a strong cyclone (LOW34 (one of a series of numbered Atlantic low-pressure systems occurring during the two-month FASTEX period), IOP12) had a central position just west of Iceland. In such extreme cases, the chances of finding differences between forecasts are higher than in other cases. Since both NOF and WIF have very bad 36 h and 48 h forecasts in the 7 February case, like some of the models in Nielsen *et al.* (1998), we haven't used this case. Instead we have chosen 10 February for a case study. The daily verification scores show that it is also a good choice for seeing some positive

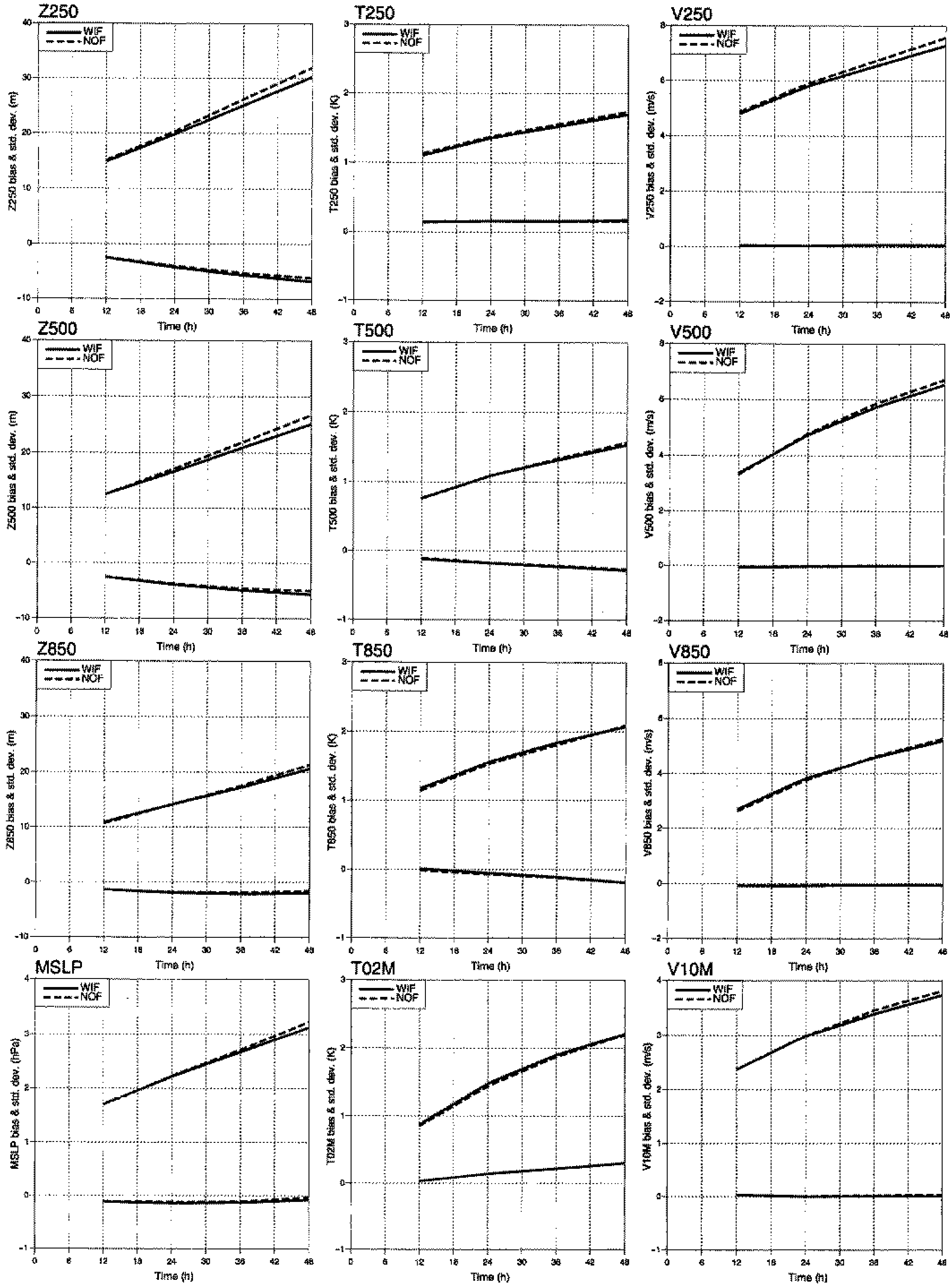

Figure 5. Field-verification (bias (lower lines) and standard deviation (std. dev.) (upper lines)) of surface parameters and upper-level parameters as in Fig. 3. Mean value over all grid points on the reduced grid. Time specifies forecast length. Results are shown for the WIF and NOF experiments (see text).

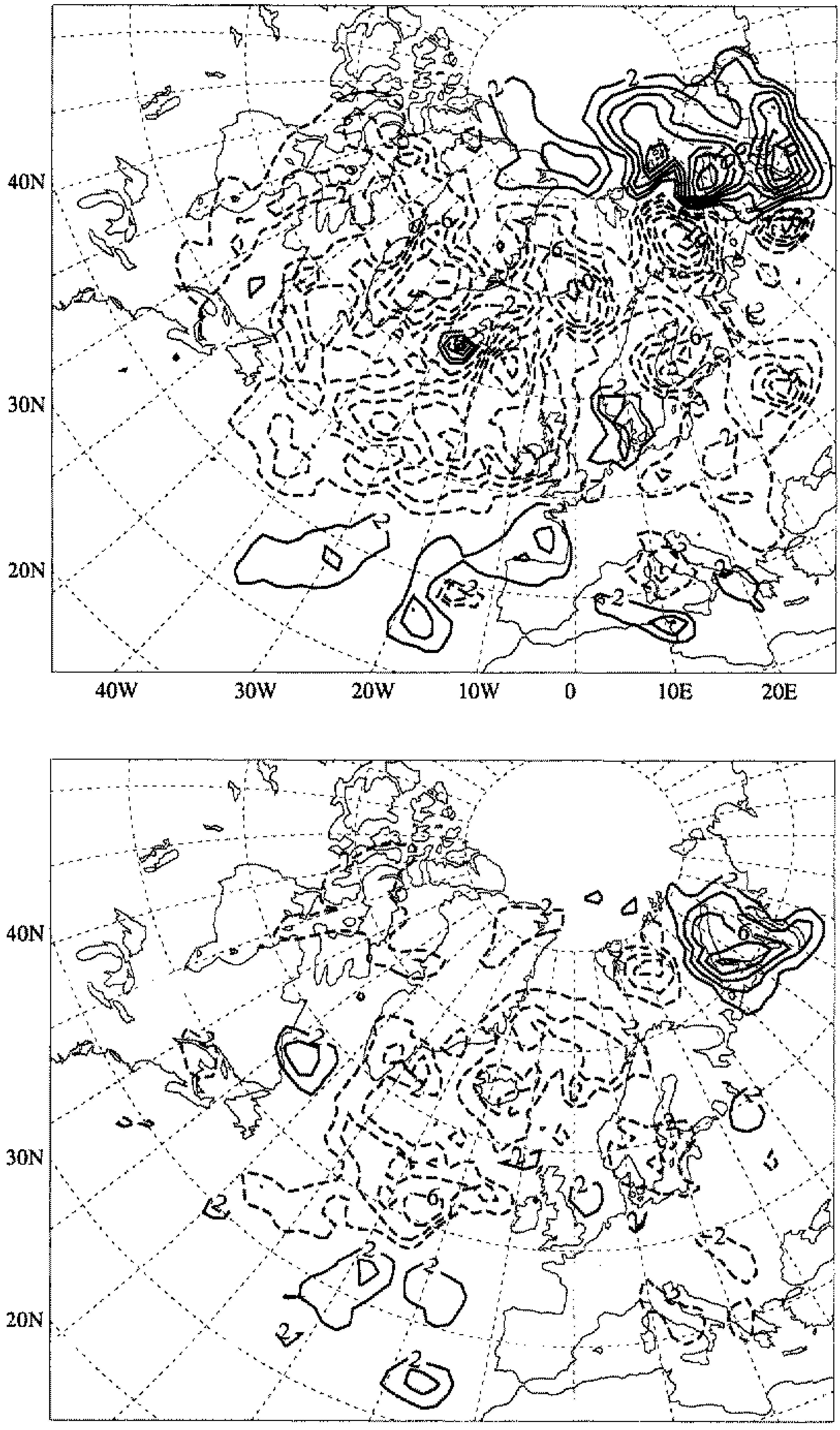

Figure 6. Difference in standard deviation of the 500 hPa geopotential height between NOF and WIF (see text) for 48 h forecasts (upper) and for 24 h forecasts (lower). Full lines for areas where NOF has better and dashed lines for areas where WIF has better standard deviation scores. The contour interval is 2 m.

impact on the 500 hPa geopotential height and m.s.l.p. Undén (1997) gives an example of a positive impact on a 72 h 500 hPa geopotential-height forecast with a valid time of 1200 UTC on 7 February. This case shows a much better-developed low east of Iceland with the extra FASTEX data than without.

For the 10 February case the WIF and NOF analyses had a low of 946 hPa and 948 hPa, respectively, close to an observed value of 948.5 hPa near the analysis centre. Figure 7 shows the verifying analyses and the 36 h and 48 h forecasts of WIF and NOF for this case. It is clear that the depth, and to some extent the position, of the low are poorly predicted by the 48 h forecasts. For the 36 h forecasts WIF predicts the position of the low better than NOF. Both predict the depth poorly with NOF predicting a slightly lower value than WIF. Both models have a secondary low east of the primary low. Both models' 24 h forecasts (not shown here) have a double low around Iceland, too, and both have too high values for the low pressure, with a NOF value of 953 hPa and a WIF value of 951 hPa.

Figure 8 shows the verifying analyses and the 36 h and 48 h forecasts of WIF and NOF for the 500 hPa height. For the 36 h forecast WIF is better than NOF around the centre of the m.s.l.p. low over Iceland. For the 48 h forecasts WIF is better close to and south of Iceland and also between Jan Mayen and the North coast of Norway. NOF is better in the Arkhangelsk area (seen from difference plots not shown here).

4. CONCLUSIONS

We have made an OSE with the HIRLAM system used operationally at DMI, repeating the data assimilation during FASTEX (0000 UTC 28 Jan 1997 – 1800 UTC 10 Feb 1997). Two parallel experiments have been run. The first is a re-run of the operational set-up, but using the ECMWF analyses (instead of forecasts) as lateral boundaries. The operational database contains the extra FASTEX radiosonde data. The second experiment is a 'normal-data' run in which the extra data are removed using the analysis blacklist. On average, the number of the radiosondes is reduced by 50 at 0600 and 1800 UTC during the experiment period.

We have used both obs-verification and field (i.e. analysis) verification to compare the analyses and forecasts from the parallel experiments. On a daily basis, the extra data can have both positive and negative impacts. The case study illustrates that for corresponding forecasts there are areas with a positive impact and areas with a negative impact from the extra observations. Averaged over the whole period, the impact is definitely positive, especially on upper model levels. Our results strongly support the idea that extra radiosonde data, like those provided by FASTEX, are very useful and would be of significant benefit in operational forecasting if made available on a regular basis. We also performed a couple of OSEs with SAtellite TEMperature (SATEM) and SATellite OBservation (SATOB) data during the same period; basically no impact from those data was found.

Impact studies using extra FASTEX radiosonde data were also reported by ECMWF and Météo-France. Their results also indicate a positive impact from the extra radiosonde data. However, the impact on their data-assimilation systems was not as large as that on the HIRLAM system. The possible explanations for this difference may be found in the major differences between the data-assimilation systems: 1) HIRLAM is a limited-area system while the systems used by ECMWF and Météo-France are global; 2) we have included 0600 and 1800 UTC forecasts; 3) no satellite data are used in the HIRLAM system.

We have made a comparison of obs-verification done with 0600 and 1800 UTC forecasts only and with 0000 and 1200 UTC forecasts only. The improvements to

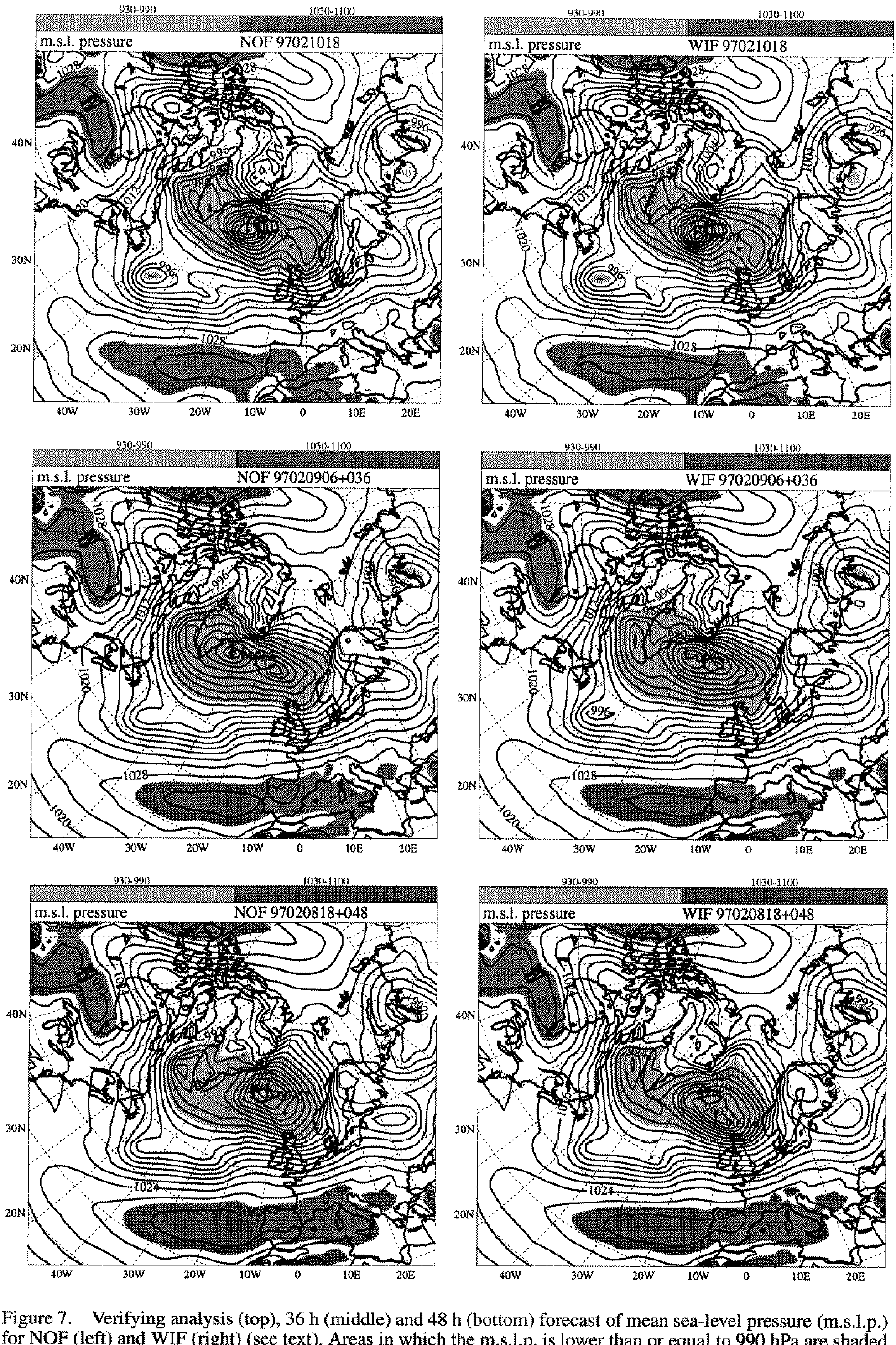

Figure 7. Verifying analysis (top), 36 h (middle) and 48 h (bottom) forecast of mean sea-level pressure (m.s.l.p.) for NOF (left) and WIF (right) (see text). Areas in which the m.s.l.p. is lower than or equal to 990 hPa are shaded light grey and areas with values higher than or equal to 1030 hPa are shaded dark grey.

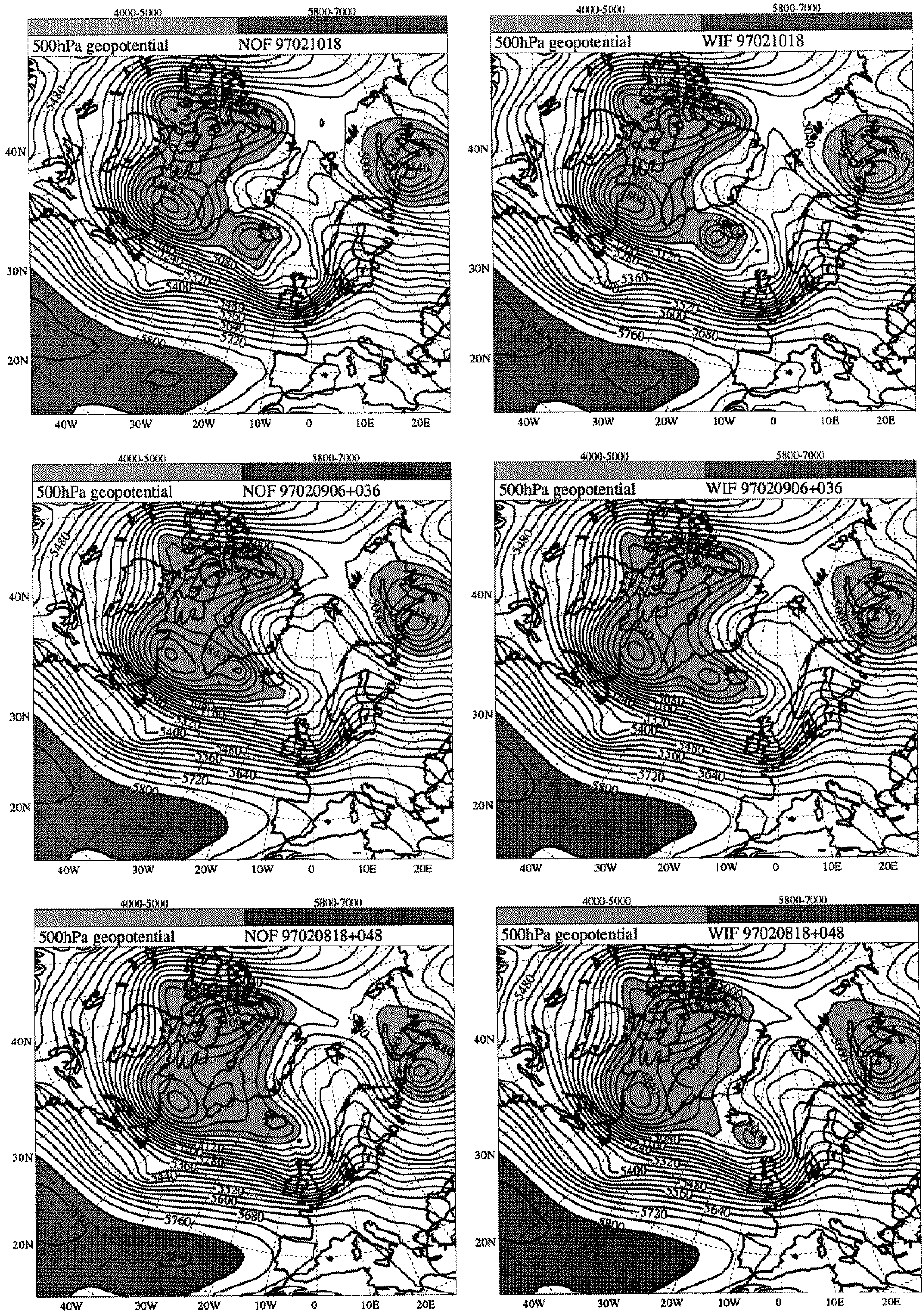

Figure 8. Analysis (top), 36 h (middle) and 48 h (bottom) forecast of 500 hPa geopotential height for NOF (left) and WIF (right) (see text). Areas in which the heights are lower than or equal to 5000 m are shaded light grey and areas with values higher than or equal to 5800 m are shaded dark grey.

48 h forecasts were indeed generally larger for the former forecasts, but the 0000 and 1200 UTC forecasts still had better scores in WIF compared with NOF. As illustrative examples, we had the following improvement in r.m.s. scores for the 48 h forecasts (0000 and 1200 UTC only, first number and 0600 and 1800 UTC only, last number): m.s.l.p. (4.3%, 7.2%), T250 (1.5%, 4.5%), H250 (3.8%, 5.7%), W250 (2.8%, 1.5%), T500 (6.5%, 5.6%), H500 (4.0%, 6.0%), W500 (0.7%, 5.5%).

It is to be expected that the impact of extra radiosondes would be smaller in 3D-VAR and 4D-VAR (3- and 4-dimensional variational data assimilation) analysis systems that can make more efficient use of other data—in particular satellite radiances and high-density ACARS (Aircraft Communication Addressing and Reporting System)/AMDAR (Aircraft Meteorological DAta Relay) aircraft data. ACARS/AMDAR data includes measurements during ascent and descent, and data are recorded very frequently along flights. Limited-area systems may have large errors close to lateral boundaries. This kind of error, if not corrected during the data-assimilation process, may propagate and amplify to cause problems in the area of our concern. In the HIRLAM system, no satellite data are used and therefore the extra FASTEX data may be of particular importance in correcting errors over the data-sparse oceans. A variational data-assimilation system is being developed for HIRLAM and this system will also be able to make more efficient use of satellite data. A requirement for extending the operational radiosonde data should be reviewed in the light of activities of this new scheme.

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APPENDIX

Blacklist used in experiment NOF

During the 0000 UTC and 1200 UTC runs the following Automated Shipboard Aerological Programme (ASAP) stations were blacklisted:

KCEJ FZVN EOGW TFTA

During the 0600 UTC and 1800 UTC runs the following radiosondes (TEMPs)/ASAPs were blacklisted:

03354	04220	04270	04339	04360	06011	07110	07145	07510	04018
03953	08508	08522	08001	03005	03026	03496	03502	03808	03240
03920	71801	71816	71906	71600	78016	72402	72208	74494	
FNOR	FNOU	FNPH	FNRS	OXVH2	OXYH2	OXTS2	V2EZ	KCEJ	FZVN
EOGW	TFTA	V2LV	V2LX	DBBH	V2GH	EHOA			

This is almost the same list as that used by Undén (1997). In addition to Undén's list, OXTS2 was blacklisted. This is a Danish ASAP operating between the west coast of Denmark and Godthaab (Greenland) that replaced OXVH2 during the FASTEX period. It appeared eight times at 0600 UTC and six times at 1800 UTC in the last part of the period studied here. One of its locations is shown in Fig. 1.

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