TECHNICAL MEMORANDUM

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The use of profiler data at ECMWF

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January 2001

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Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Abstract

The current status of the use of wind profiler data at ECMWF is documented. The operational global four-dimensional variational data assimilation system of the atmosphere uses hourly profiles of horizontal wind in real time from the US profiler network. This observing system provides some original information about the performance of the data assimilation. Data from the European CWINDE observing network has been monitored and found to be good enough for future operational use subject to the appropriate data selection. The reporting of wind observations at high resolutions raises some concerns about the performance of the data assimilation system and a theoretical analysis of the problem is attempted.

1 Introduction

ECMWF (The European Centre for Medium-Range Weather Forecasts) uses a real-time global data assimilation system for the production of its medium-range global meteorological forecasts. Since December 1997 the core of the data assimilation procedure is a four-dimensional variational data assimilation system (4D-Var, documented in Rabier et al., 2000) for the free atmosphere, at spectral resolution T63L31 i.e. roughly 200km horizontal resolution. The vertical resolution has been enhanced to 60 levels in October 1999 with a resolution of at least 40hPa in the troposphere. The assimilating model has a higher horizontal resolution of T319 i.e. about 50km. The 4D-Var analysis is incremental, i.e. observations are compared to a previous forecast at T319 resolution, and the departures are used to generate a correction at T63 resolution, which is added to initiate a new high-resolution forecast. This process is repeated every 6 hours; the interpolation in time of the observations has a maximum error of 30 minutes. This system has been designed for the optimal analysis of large-scale atmospheric features which are important for the quality of medium-range forecasts at ranges from 5 to 7 days.

The 4D-Var data assimilation system uses a wide variety of observation types and variables as summarized in table 1. Most of these data are gathered through the Global Telecommunications System (GTS). Satellite data account for the largest volumes. Observing system experiments have been carried out in order to assess the usefulness of most of these data types (Bouttier and Kelly, 2000). In the tropical regions and in the Southern Hemisphere, satellite data are the most important, although the impact of conventional data is not negligible. Over most areas of the Northern Hemisphere including North America and Europe, the forecast quality has a similar sensitivity to the presence of radiosondes, of aircraft and of TOVS/ATOVS radiances. The general trend is for radiosondes to have a diminishing availability in time and space, whereas the relative weight of satellite data (mainly radiances) and aircraft data is expected to increase in the next few years.

Satellite data have a good coverage over the oceans and the poles, but they are little used over land. Western Europe and the USA are rich in conventional data when seen from a global perspective. Most of these data are synoptic reports, and vertical profile information is limited. Thus, profiler data are believed to have a potential for improving ECMWF analyses and forecasts, because they provide frequent, high-quality information throughout the depth of the troposphere.

In the current state of the ECMWF 4D-Var system, profiler data can be used as vertical profiles of horizontal wind vectors. The ECMWF model being hydrostatic and large-scale, its representation of vertical velocity is not realistic enough for vertical profiler winds to be considered. Only the horizontal wind is studied here. As a first step, the observation error variances (that include instrumental and model representativeness errors) are set to be the same as for PILOT reports. When available, the whole vertical profiles can be used with hourly frequency (using a suitable interpolation in time and space for comparison with the forecast wind). Since 4D-Var analyses are centered around synoptic times (i.e. observations from 09UTC to 15UTC are used to generate the 12UTC analysis), used profiler information can be up to 3 hours more recent than conventional radiosonde reports.

Since European and US profilers have been studied independently and they are in different implementation stages at ECMWF, they are described separately below. A few profilers that report over the GTS as conventional PILOT messages (such as Aberyswyth or Christmas Island) have been used as PILOTs for many years in operations at ECMWF, and are not considered here.

In the sequel, the process by which a large network of profilers (the US network) is validated and introduced in an operational data assimilation system is described in section 2. The converse process by which this network is used to understand and improve the data assimilation system is explained in section 3, which highlights some advantages and drawbacks of using a four-dimensional variational data assimilation algorithm. The introduction of a smaller network (the European CWINDE network) is more difficult to assess, although some potential can be shown in numerical impact experiments, as described in section 4. The conclusions are summarized in section 5.

2 The impact of US profilers

After several years of monitoring, the use of US wind profiler reports available in real time over the GTS started in the operational ECMWF data assimilation system in July 1999. For information on the US wind profiler data, see Martner et al (1993) and references therein. The data were not used before because it was felt the assimilation system did not have enough resolution in space and time to benefit from profiler data at the time. In particular, there were worries about the global model's ability to correctly handle fine-scale wind information.

Like any other data type, profiler wind measurements are subjected to many quality control checks before they are allowed into the analysis (Järvinen and Undén, 1997): poor data must not be used because they could compromise the quality of the forecasts. The most stringent check is a monthly manual monitoring of the data, by which observations that do not usually compare well with the ECMWF short-range forecasts are located and subsequently withheld. This may happen because of weaknesses in the ECMWF model itself; in this case, one needs to decide whether it is wise or not to use the observations in the hope that they will force the model towards a more realistic state through the assimilation procedure. A first check is the comparison of profiler data with other independent data such as aircraft wind observed at similar times and locations, and with some interesting short-range model forecasts, such as in figure 1. This figure shows a lee cyclogenesis to the East of the Rockies; the analysis of this weather system was crucial to the correct forecasting of a damaging storm over Denmark 5 days later. In this particular case it can be seen that the profiler data supported the ECMWF analysis in the area, and the depiction of the wind field is further supported by the available aircraft observation, which suggest that profiler winds provide sensible information on weather systems that can be important for the ECMWF forecasts.

Cases like this are important in building up confidence in the data: in the operational ECMWF

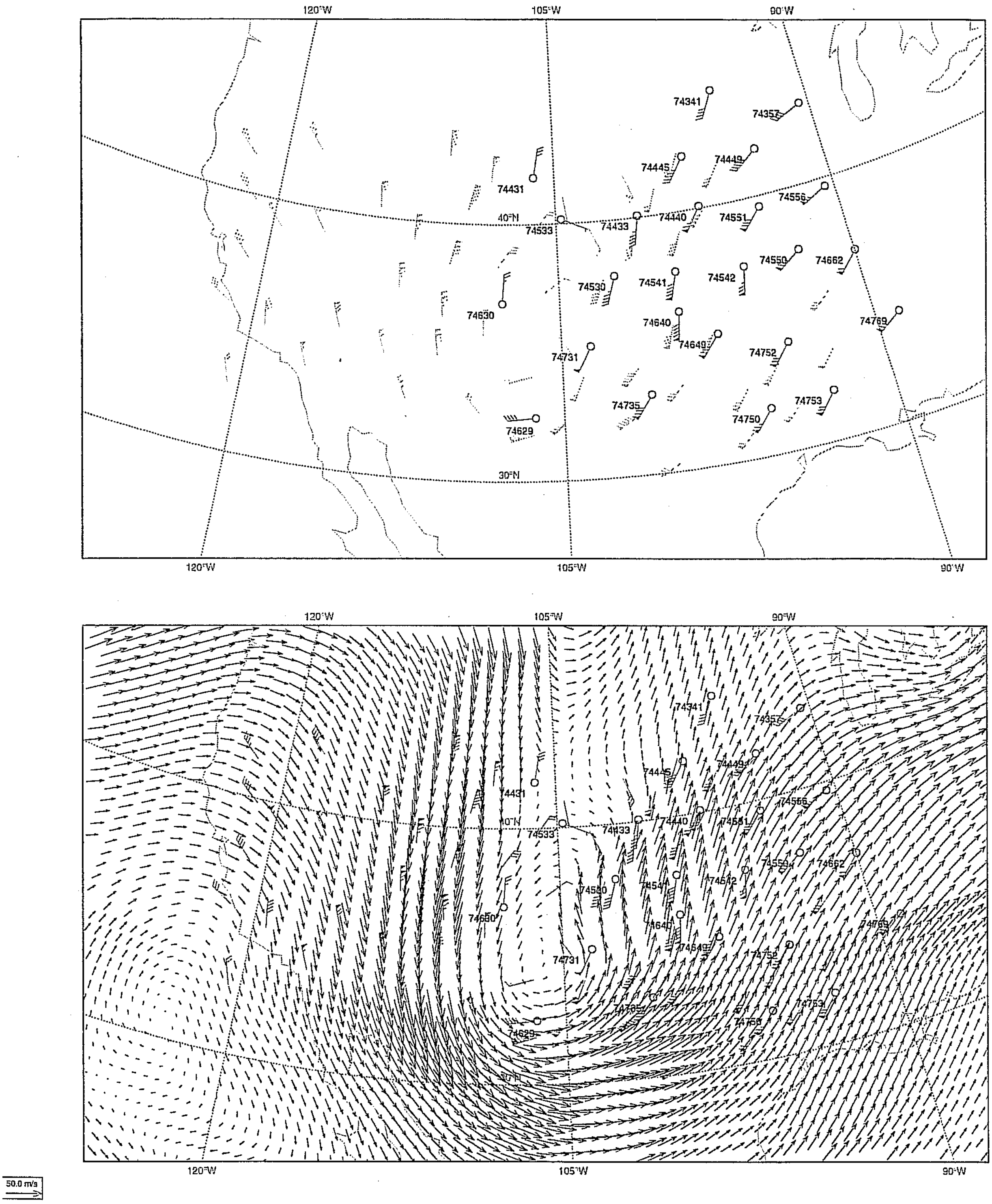

Figure 1: Top: comparison between winds observed around 4 Dec 1999, 06UTC, by aircraft (wind symbols without numbers) and the available US wind profilers (wind symbols with white circles and station IDs) near the 300hPa level. Bottom panel: comparison between the same observations and an ECMWF short-range forecast started 6 hours earlier. The model wind scaling is defined by the arrow in the bottom left corner (50m/s).

system it is usually not possible to react in real time if the quality of a station decreases suddenly. Therefore only data with a long history of quality and reliability is allowed. The monitoring of US profiler data (personal communication by Antonio Garcia-Mendez, ECMWF) has revealed inconsistencies with short-range forecasts below 700hPa and over 400hPa, so that most stations are disabled at these levels. This is thought to be a combination of data reliability problems and lack of realism of the model, in particular the structure of the surface boundary layer, the influence of orography on wind, and the outflow at the top of convective clouds near the tropopause. For instance, the ECMWF model has a known deficiency in the simulation of lee cyclogeneses near the Rockies. These considerations have led to a conservative data selection list that relies on station ID and reporting level. This list is revised every month, for operational use during the following month. Profilers that are not explicitly in the list are not used, because it has sometimes happened that new (e.g. Alaskan) stations start reporting without warning. An example of list is given in table 2.

In addition to this monthly selection list, a number of real-time quality checks are applied which may lead to the rejection of additional horizontal wind observations: data checks according to WMO rules (e.g. the wind must have reasonable values, it must be at levels that are consistent with the station height), first-guess check (each wind vector must not be too different from the wind in the previous forecast), variational quality control check (each wind vector must not disagree too strongly with its neighbours).

Once the selection list and the checking system has been set up, the last step before operational use is a global test of the impact of profiler data. Hence, a real-size numerical experiment is run in which profiler data is assimilated, everything else being kept identical to operational practice. This is an expensive test, requiring several weeks of experimental 4D-Var data assimilation and medium-range forecasts, but it gives a precise estimate of the value of the data, which is measured objectively (for ECMWF purposes) by the forecast scores over limited areas. These scores measure the quality of the numerical forecasts following WMO conventions. They have been examined over two periods (in Autumn 1998 and Spring 1999) and their average is shown in figure 2. One can see that the forecast errors over several areas are reduced in average, meaning that the impact of using US profilers is small but beneficial. The main impact is found over Europe (statistical testing shows that the impact seen in the tropics is less significant). Of course, this approach does not measure other indirect benefits that are obtained from using profilers, such as regional improvements to the analyses, as well as the feedback of monitoring information to the data producers.

3 Diagnosing the data assimilation using observations

The power of data assimilation lies in the exchange of information between the meteorological model and the observational data (Daley, 1991). In the previous section it was explained how the model fields are used to gather information about the quality of the data. Conversely, data that are used in the data assimilation system provide useful information about the quality of various observing system, of the assimilating model, and the data assimilation algorithm. Profiler data are particularly interesting because they are believed to have a very high quality (after quality control checks) and a regular distribution in space and time, unlike most other observing systems.

The most basic diagnosis is the comparison between the observed values and the model values. Any piece of observational data (each wind vector component in the case of profilers) can be compared

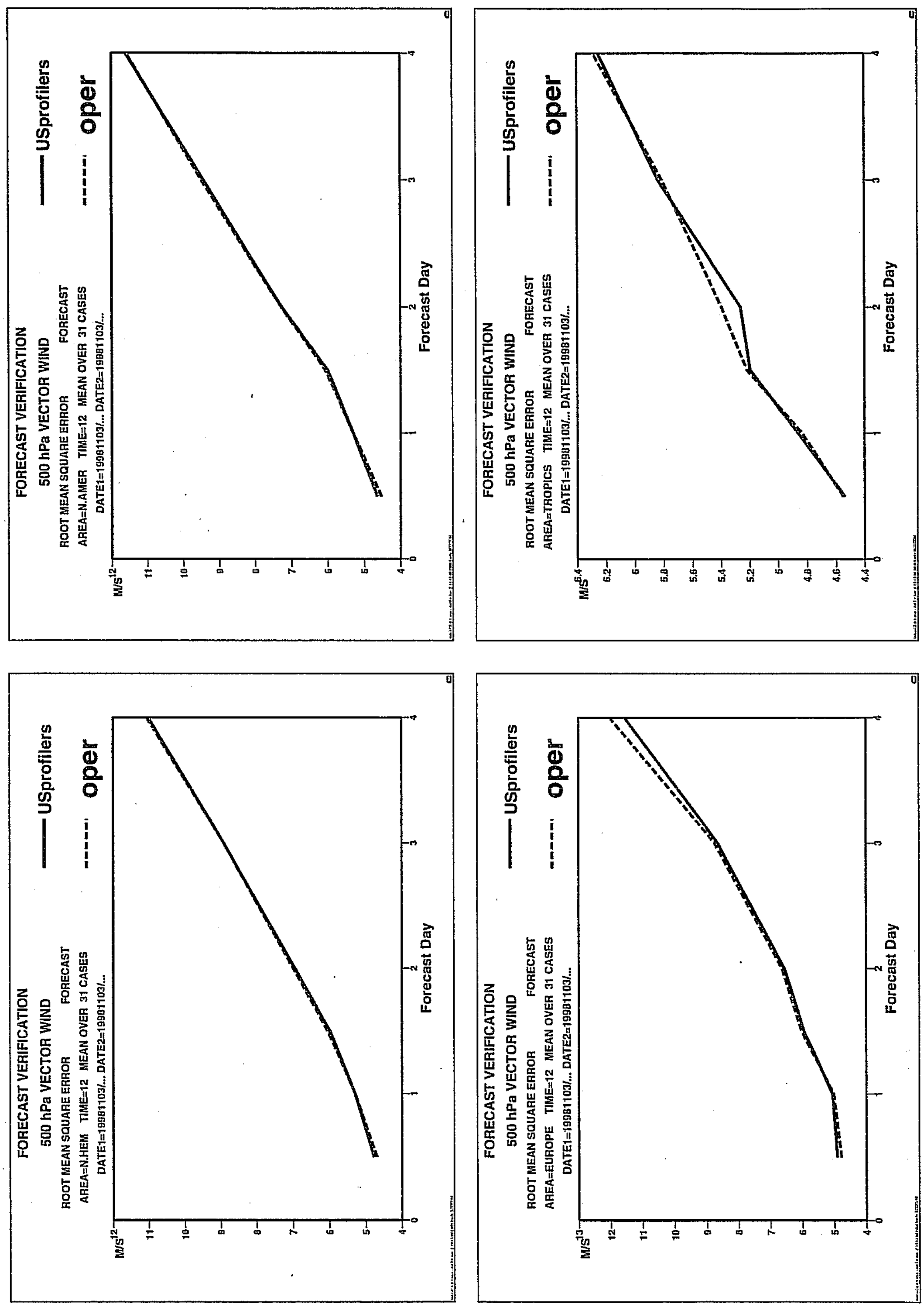

Figure 2: Impact on the ECMWF forecast performance of using US profilers, in average over 31 cases spread over two independent periods. 'oper' stands for the reference system that does not use profilers, 'USprofilers' is the same system, plus US profilers activated.

to two kinds of model fields interpolated at the same time and place:

- the analysis itself, which was prepared using the observation. The closeness to the analysis is a measure of the realism of this field, which in 4D-Var depends on the quality of the T63L60 model. In the limit of a perfect analysis, the rms average background departure amplitude is equal to the observation error standard deviation.

- the so-called background field, which is the most recent short-range forecast. The 4D-Var algorithm produces the analysis as a correction to the background, which is a linear function of the departures of the observations from the background field. The closeness of the observations to the analysis, relative to the background, is a measure of the weight given by 4D-Var to each observation. This weight may appear small if observations are believed to be poorer than the background field, or if there is disagreement with nearby observations. The absolute departure from the background is the sum of the observation error and of the quality of the background field, which is itself a function of the quality of the previous analysis, and of the growth of errors in the forecast. In the ECMWF assimilation, background fields correspond to a forecast range of 3 to 9 hours, depending on the time of observation.

The background and analysis departures can be regarded as random variables that are distributed in a situation-dependent way (Daley, 1991). Their statistics over large samples give some useful information about the performance of the data assimilation system. Figure 3 shows the mean and root mean square departures, in average over the set of observations used by the ECMWF operational assimilation system during ten days. The statistics have been computed using radiosondes (TEMP and PILOT, denoted RAOB on the plot), the US profilers themselves, and aircraft (denoted AIREP), on the part of the USA that is densely covered by the US profilers. Only zonal wind components that were used in the analysis (with a significant weight) have been considered. The statistics are stratified against pressure bins. One can see that the bulk of the profiler data is in the mid-troposphere. It nicely complements the aircraft data which is most abundant near the tropopause. In these respective layers, profiler and aircraft data are ten times more abundant than radiosonde data. The rms background departures are about the same for these three observing systems, which shows that they have a similar level of quality. The mean background departures are mutually consistent, which indicates that the observed bias is mainly made of forecast errors, not observation errors.

The analysis departures tend to be smaller (relative to the background departures) for profilers than for aircraft and radiosondes. This is not due to the assumed observation error, since it is specified as being the same for profiler and radiosonde winds. The reason is that all reported levels are used, so that many more wind vectors are used from each profiler message than from each radiosonde message. The observation errors being assumed to be uncorrelated in this version of 4D-Var, a larger effective weight is given to profilers. It may seem wrong to trust more one kind of observation because it is denser than another. In theory, this is a desirable feature of 4D-Var which aims to reduce the analysis error at each point by averaging together all the available observations in the vicinity. In practice, this can be wrong, because observation errors (including model representativeness errors) tend to be correlated for small separations, so that they should not be fitted too closely. For profiler data it is even possible to estimate mathematically the vertical part of the observation error correlation and its approximate effect on the analysis. A demonstration is given in the Appendix. Another aspect of observation error is the presence of observation error correlation in time, which can be large for hourly reporting profilers when the model error is large; this could be accounted for in 4D-Var using the scheme of Järvinen et al. (1999).

Over ten days the usage of the US profiler data can be broken down as follows: there were 242500 wind vectors received in real time at ECMWF, of which 117000 were actually used, 124000 were disabled in the selection list, 1000 failed the automatic quality checks. The background rms departure was 4.2m/s for the whole dataset, the used data set had 2.8m/s rms background departure and 2.1m/s rms analysis departure.

The good coverage and the even quality of the profiler data give an opportunity to take a closer look at some more advanced characteristics of the 4D-Var algorithm. First, the 4D-Var is incremental (i.e. it uses a low-resolution simplified, linearized model): as explained in Courtier et al. (1994), it computes a statistically optimal correction to the background field, but the full high-resolution forecast model does not necessarily react as intended to this correction. Discrepancies between the behaviour of the simplified and high-resolution model are going to degrade the quality of the analysis. The seriousness of this can be measured by looking at the ratio between the effective perturbation of the high-resolution model and the optimal correction computed by the low-resolution model in 4D-Var: this ratio should be as close to one as possible. Figure 4 shows the historgram of the distribution in time of the difference between this ratio and one (i.e. the relative error), in rms average over many 4D-Var analyses. Each 4D-Var has a 12-hour window length, the time windows extend from 03UTC to 15UTC and from 15UTC to 03UTC every day. The statistics have been averaged over 11 days i.e. 22 4D-Var analyses. The histogram does not include the observations for which the ratio (of the perturbations of the high- and low-resolution models) is ill-defined.

Thus, the histograms in figure 4 measure the amplitude of the errors due to the incremental formulation of 4D-Var. This quantity is plotted for two versions of the linearized model used in 4D-Var. It is apparent that the discrepancy between the high-resolution model and the linearized model increases in time during the 4D-Var window, meaning that the latest observations are used less accurately by 4D-Var, with linearization errors reaching 100%. The errors can be somewhat reduced by improving the linearization of the physics, but this problem is clearly going to limit the scope of four-dimensional data assimilation schemes.

The previous paragraph has shown how profiler data helps to identify inconsistencies between the two model formulations used in the incremental 4D-Var algorithm (Courtier et al., 1994). They can also be used to highlight model errors inside 4D-Var itself. 4D-Var uses the simplified model to relate observations in time. Profiler data being all given the same weight over time, 4D-Var should be able to fit all of them equally well if the model were perfect. If there is a discrepancy between the model equations and the true evolution of the atmosphere, this will show up as a non-constant fit to the data. This result has been predicted for some time by theoreticians (Ménard and Daley 1996), and this is the first opportunity to verify it in a realistic 4D-Var NWP system.

The signal is most visible when the 4D-Var time window (the period of the 4D-Var intermittent assimilation system) is extended from 6 to 12 hours. The distribution in time of the background and observation departures (i.e. observed minus model values) is shown in figure 5. The distribution of background departures shows how wind errors grow over the central USA during a short-range forecast. One can see that on this area the doubling time of wind errors is about 24 hours. The errors are not simply advected because the central USA are inside a data-rich region. They grow because of local atmospheric instabilities that amplify small analysis errors, erroneous propagation of large-scale atmospheric wave energy, upscale transfer of errors (Bouttier 1994), and errors in the

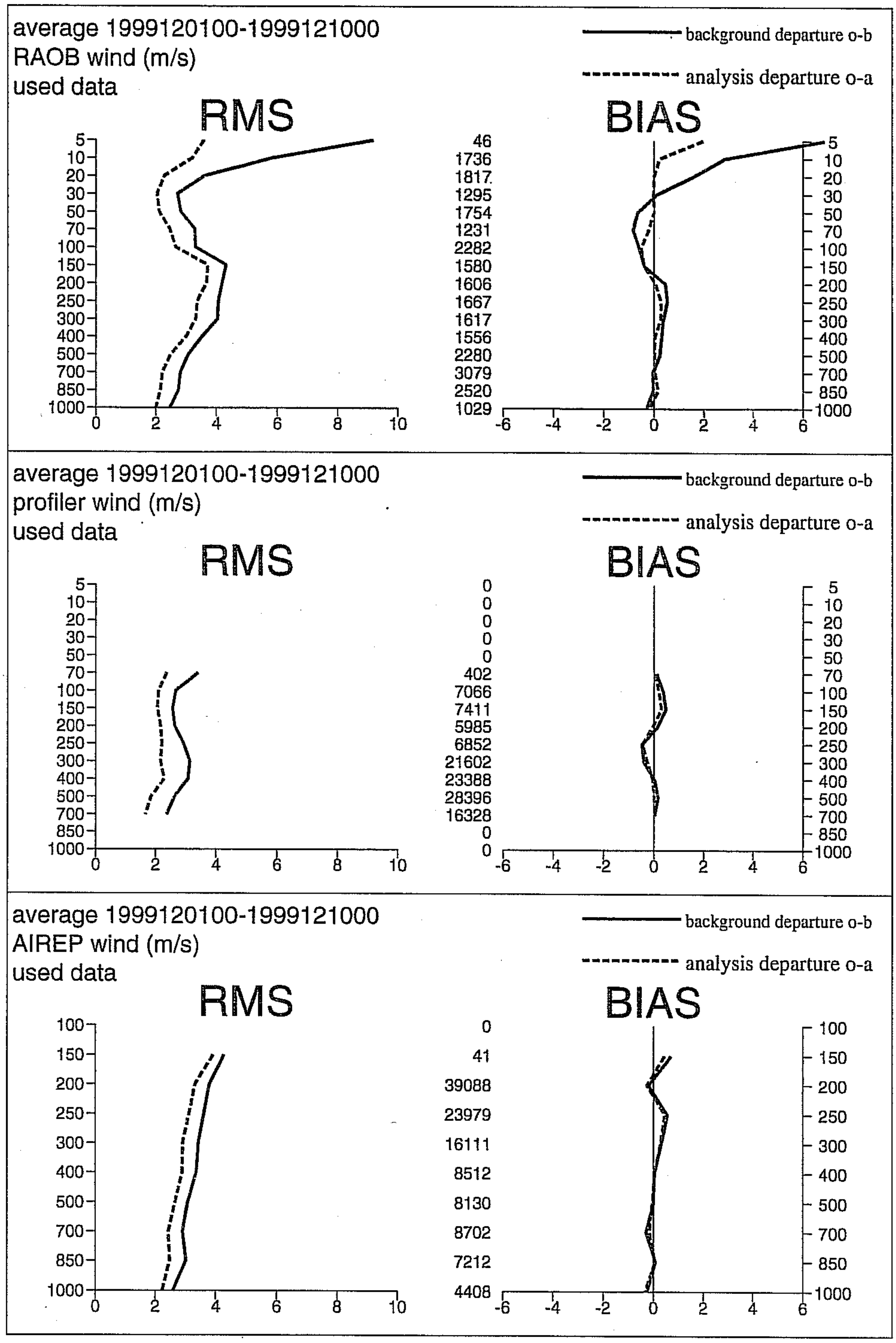

Figure 3: Statistics of the departures (i.e. differences) between the observed zonal component of the wind, and the background and analysis fields, for radiosondes (RAOB), US profilers and aircraft (AIREP). The departures have been accumulated over 10 days of operational ECMWF assimilation, over the area of the continental US profiler network. They are expressed as rms and average ('bias' i.e. observation minus model) departures, stratified according to pressure (in hPa). Only data that was actually used is considered. The column of number in the middle gives the sample size for each pressure bin.

Observation type	Used variables
radiosondes TEMP, PILOT, dropsondes	temperature, wind, humidity
aircraft (AIREP, AMDAR, ACARS)	temperature, wind
US wind profilers	wind
surface reports (SYNOP, SHIP)	pressure, humidity, wind over sea
drifting buoys (DRIBU)	pressure, wind
TOVS/ATOVS (MSU/AMSU radiances)	cloud-cleared brightness temperature
atmospheric motion winds (SATOB)	wind
Australian pseudo observations PAOB	surface pressure
SSM/I retrievals	total water content, surface wind speed
SCAT scatterometer	ambiguous surface wind

Table 1: The list of observation types and variables used operationally by the ECMWF data assimilation and forecasting system in Spring 2000.

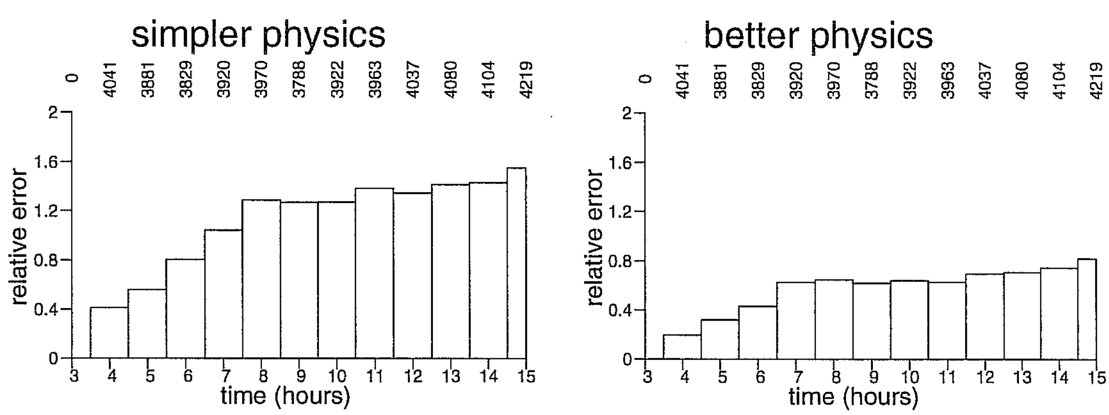

Figure 4: Distribution in time of the errors due to the incremental formulation of 4D-Var, as seen in terms of the US profiler winds, in rms average from 1 December 1999, 06 UTC to 11 December 1999, 00 UTC. Two versions of the linearized model are used in 4DVar, one with very crude physics (left panel), one with more accurate physics (right panel). The horizontal coordinate is the time coordinate inside the 4D-Var window, in hours (see text). The numbers above the bars indicate the number of data in each hourly bin. The ordinate measures the relative error, i.e. a value of 1 means that the rms average of the discrepancy between the linearized model used in 4D-Var and the high-resolution model is 100%.

lat	lon	station ID	levels used
65.50	-144.68	70197	none
62.31	-150.42	70252	above 700hPa
62.11	-145.97	70268	above 700hPa
44.67	-95.44	74341	above 700hPa
43.22	-90.53	74357	from 700 to 400hPa
41.90	-106.18	74431	above 700hPa
40.08	-100.65	74433	above 700hPa
42.90	-101.69	74437	above 400hPa
40.08	-97.31	74440	above 400hPa
42.20	-97.79	74445	above 700hPa
41.90	-93.69	74449	above 700hPa
37.77	-102.17	74530	from 700 to 400hPa
40.18	-104.73	74533	none
37.65	-99.11	74541	above 400hPa
37.30	-95.60	74542	from 700 to 400hPa
38.30	-97.29	74546	above 700hPa
37.52	-92.70	74550	above 700hPa
39.57	-94.18	74551	none
39.65	-90.48	74556	above 700hPa
32.40	-106.34	74629	none
36.84	-107.90	74630	above 700hPa
36.07	-99.21	74640	above 400hPa
36.69	-97.48	74647	none
35.68	-95.86	74648	above 700hPa
34.97	-97.51	74649	above 400hPa
36.88	-89.97	74662	above 400hPa
35.08	-103.60	74731	above 400hPa
33.01	-100.98	74735	above 700hPa
31.77	-95.71	74750	none
34.11	-94.29	74752	from 700 to 400hPa
31.89	-92.78	74753	above 700hPa
34.08	-88.86	74769	above 700hPa

Table 2: The data selection file for US profilers used operationally at ECMWF in December 1999. The reporting pressure is the one implied by the model background at the reporting height.

physical parameterizations of the model.

The distribution of analysis errors is U-shaped, which is a sign of model error (Ménard and Daley 1996). The order of magnitude of this error is given by the amplitude of this U-shaped variation (about 0.4m/s), which can be compared with the average analysis departures (about 3m/s) and the assumed observation error (about 2.5m/s). This shows that model errors inside the 4D-Var window are small. A possible interpretation is that most of the model errors in the ECMWF system are slow-growing, so that they show up as situation-dependent biases in the background field. In figure 5 they would only contribute to an overall degradation of the analysis fit, not to an identifiable time-dependent pattern.

4 Experimentation with European wind profilers

The acquisition and archiving of European wind profilers from the CWINDE network has recently started at ECMWF. This was delayed because of the technical effort required to implement a specific BUFR observation encoding template which is incompatible with the US profiler network. The following study has been performed using an arbitrarily selected period (7 to 15 February 2000) during which US profilers were used as indicated in the previous section, and most technical problems had been solved. During that time 12 European profilers were regularly available in real time, as shown in figure 6. This network is very small in comparison with the resolution of the ECMWF data assimilation system. To put things in perspective, a very expensive observation impact study has recently been run with the ECMWF system in order to measure the impact of about 50 conventional radiosondes and 120 aircraft platforms from the European operational observing network (Eumetnet/E-SAT/Eucos study for observing network planning purposes, see Cardinali, 2000). The impact of these changes on the regional forecast scores was found to be small and of little statistical significance. The only significant impact was found in the analysis fields themselves and in a few selected forecasts. This suggests that the current European profiler network does not contain enough stations to produce a significant change in the medium-range forecast quality. It may however be important for the quality of analyses and short-range forecasts and this should be investigated in the future. Profiler data can also be used to diagnose weaknesses in numerical weather prediction models, for instance in the representation of the surface boundary layer of the atmosphere.

In a first step the European profilers have been passively allowed (i.e. with zero weight) into the ECMWF data assimilation system, in order to gather statistics on the comparison with model fields. This yields the same kind of departure statistics as for the US profilers. The statistics in figure 7 show that the background departures are much worse than for radiosonde and aircraft winds, which suggests that some data are corrupt and a selection needs to be done.

When these statistics are broken down according to station ID, wide variations are found. The quality usually varies a lot in the vertical and from station to station. For several stations the quality seems good at low levels and poor above, although it can be the reverse. Some stations compare very well with the background fields. Indeed, there are more good-quality observations at low levels than in the whole US profiler network. There may be variations according to the profiler frequency, but this was not investigated here, and the only distinctions were made based on the reported station ID.

A problem of the study was its rather short time span of 8 days. In ECMWF operational practice, at least one month of statistics is required before taking the decision to use a station or not. Shorter

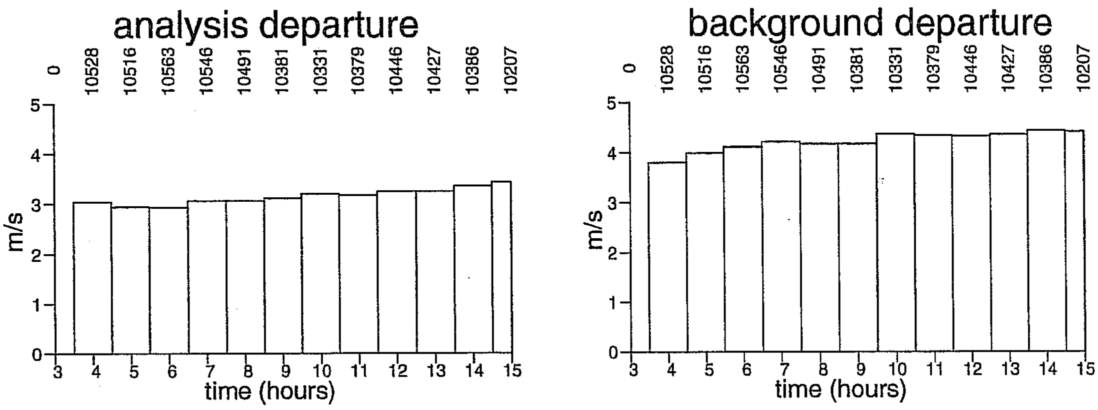

Figure 5: Distribution of the rms background (left panel) and analysis (right panel) departures from US profiler observations, as a function of the time coordinate inside the 4D-Var window, as in fig.4. The unit of the ordinate is ms^{-1}.

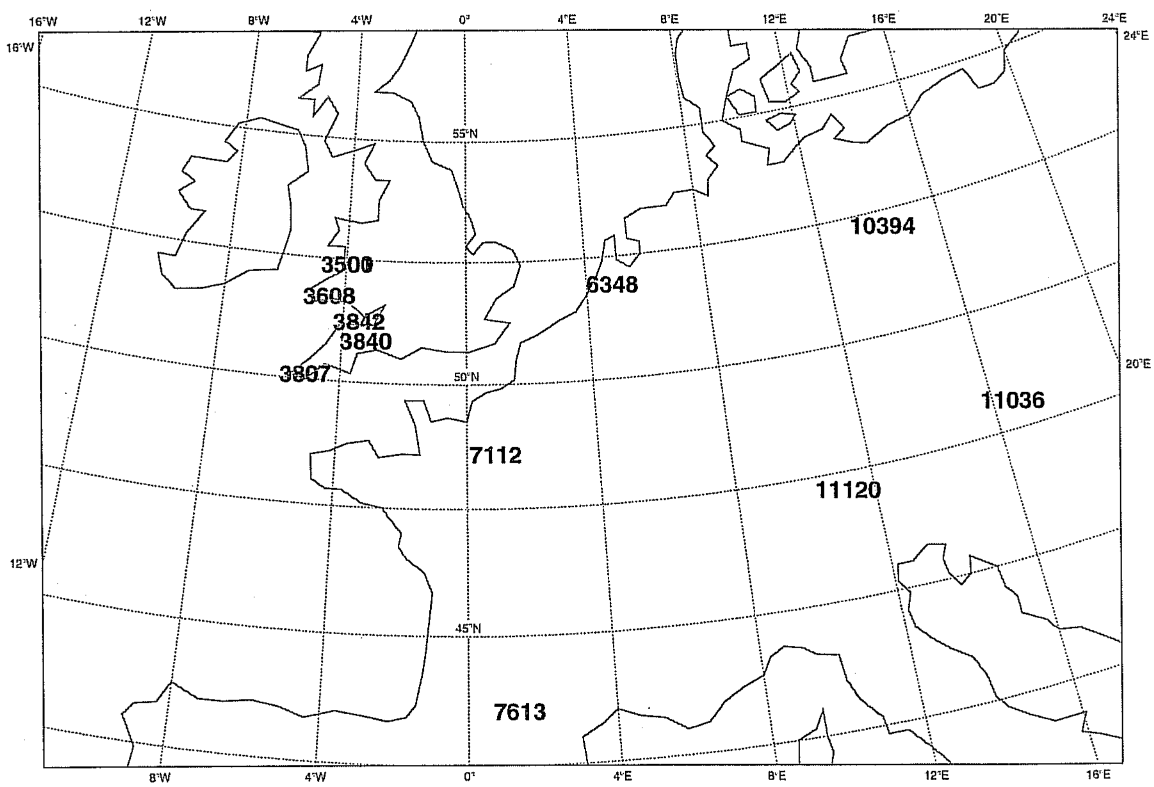

Figure 6: Network of European 12 profilers received in real time at ECMWF on 8 February 2000. The numbers are the WMO station IDs.

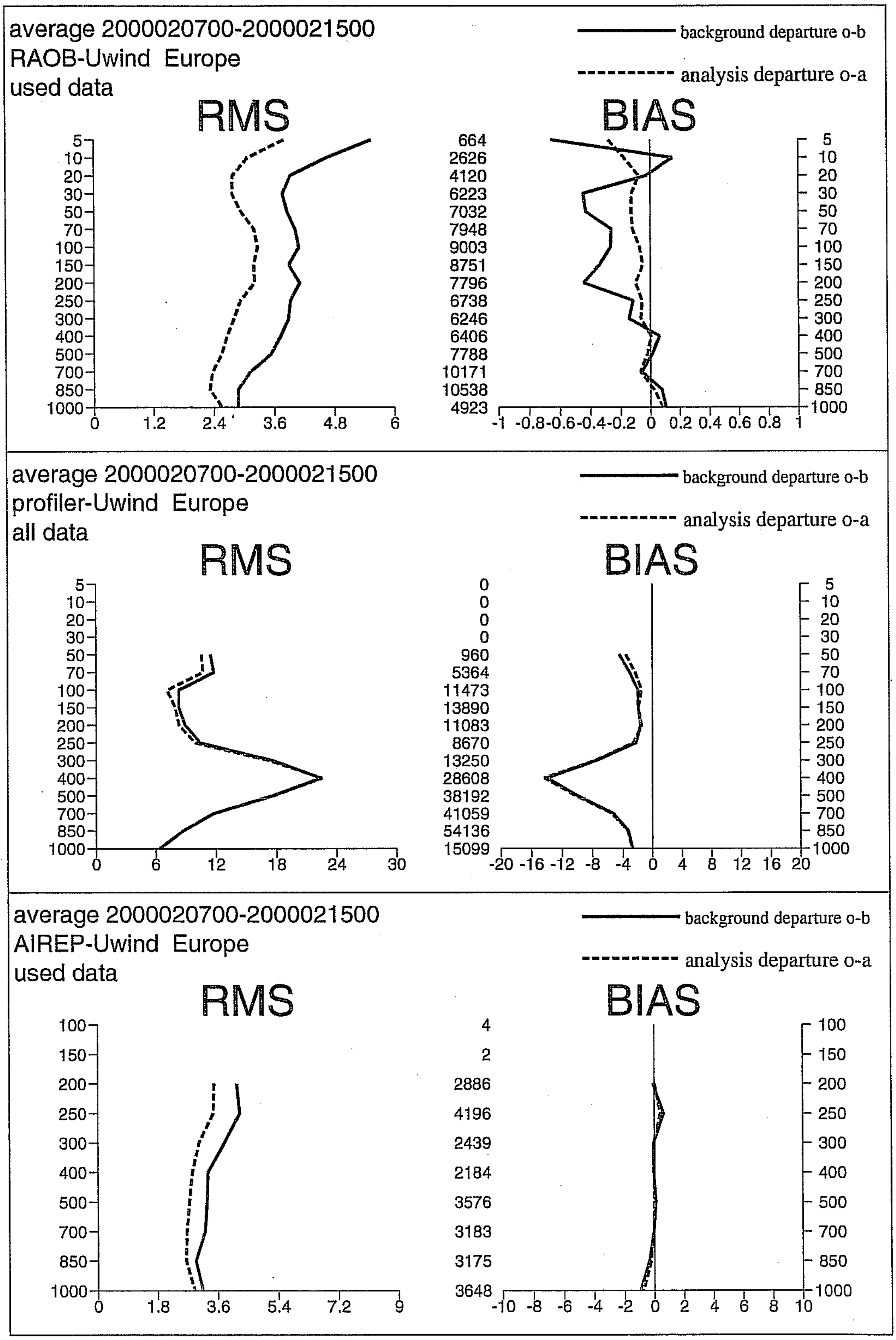

Figure 7: background and analysis departure (observation minus model) statistics on all European profiler data, averaged over 8 days as in figure 3.

lat	lon	station ID	name	levels used
43.56	1.36	07613	Toulouse (F)	below 400hPa
47.16	11.23	11120	Innsbruck (AU)	below 700hPa
48.10	16.60	11036	Wien (AU)	below 850hPa
48.61	0.87	07112	La Ferte Vidame (F)	all
50.13	-5.10	03807	Camborne (UK)	none
50.87	-3.23	03840	Dunkeswell (UK)	none
50.97	-3.45	03842	Liscombe (UK)	none
51.75	-4.52	03608	Pendine (UK)	below 850hPa
51.95	4.88	06348	Cabauw (NDR)	all
52.21	14.13	10394	Lindenberg (D)	from 700 to 400hPa
52.42	-4.00	03500	Aberystwyth (UK)	all
52.42	-4.00	03501	Aberystwyth (UK)	all

Table 3: Data selection of European wind profilers, based on the monitoring in mid February 2000.

periods leave the door open to special meteorological events giving a poor picture of a station, simply because the model did not perform well in these cases. Two examples are given in figure 8: the meridional wind from Toulouse exhibits substantial departures which can be related to high winds across the Pyrenees Mountains: independently of any possible instrumental problems, much of the discrepancies can be attributed to a poor representation of mesoscale orographic interactions with wind in the ECMWF model. The zonal wind from Aberyswyth exhibits a large bias on 9 February 2000, because the ECMWF short-range forecast misplaced a storm development in the area. Together with the generally more active weather in this part of Europe, this makes the Aberyswyth profiler compare rather poorly with the ECMWF background field, although experience shows that it actually is a very valuable and reliable station.

A subjective examination of these pieces of evidence has led to proposing the data selection list in table 3 for the European profiler network, leaving 9 stations to be used at least partially.

The next step is the running of a data assimilation and forecasting experiment in which these profilers are activated on top of the operational ECMWF data selection. This was done on the same period as the above monitoring exercise, which is not the same as the operational practice in which the monitoring would be done in real time over several months, before setting up a data selection list. An additional criterion would be safety: a station that behaves generally well, but reports erroneous values from time to time would not be allowed because it would endanger the overall quality of the forecasting system.

The first analysis of the impact experiment uses the same background as the operational ECMWF system, therefore the difference in analysis fields shows how 4D-Var uses profiler data. Two selected levels are displayed in figure 9. The picture shows how 4D-Var is able to extrapolate the observed information in a physical flow-dependent way. 150hPa is above most profiler data, but 4D-Var inferred a rotational correction at this level over the Atlantic, in a dynamically active area. The impact of additional data is usually larger over data-poor area, which means that stations on the fringe of the continent (such as over Cornwall and Wales) are more useful for synoptic-scale analysis than stations in data-rich areas. At 850hPa the corrections are very different: 4D-Var has flow-dependent, baroclinic structure functions. It is interesting to note the correction to wind over the Adriatic Sea and Slovenia: 4D-Var has used the Innsbruck and Vienna profilers to correct wind structures forced by orography, to the extent permitted by the T319 model. The analysis differences are locally significant, in excess of 4m/s at low levels, which suggests that profilers have good potential for improving regional short-range forecasts.

The impact on forecast performance is small (figure 10). It is weakly positive, and localized to specific areas of the Northern Hemisphere: Europe, Asia and the North Pacific, in accordance with the predominantly eastwards propagation of forecast errors. No impact could be seen over North America and the Atlantic, probably because analysis and forecast differences did not have time to propagate far enough during this short experiment. These forecast impacts are probably affected by sampling errors, but they indicate that it is safe to activate European wind profilers in the ECMWF assimilation scheme if a reliable data selection can be set up in real time. Only experience will tell whether this is the case.

5 Conclusions

Wind profiler data can only be used in a real-time forecasting system if enough confidence has been built into its quality, and if the data assimilation system is realistic enough to extract value from this additional data. It has been found in section 2 that 4D-Var is well suited to assimilating frequent wind profiler data, and a positive impact of using the data has been shown on forecast performance. Unfortunately, it has been demonstrated that there are limits to the quality of the data assimilation, as can be seen from the data selection list and from the statistics presented in section 3. Several explanations can be given: the model resolution and the physics are not yet sufficiently accurate to make use of all the available data, notably the winds at low levels and near the tropopause if there is deep convection or orographic drag in the vicinity. In the mid-troposphere, American and European wind profiler observations generally compare very well with short-range forecasts. This suggests that, if one is interested in instrumental quality, American and European wind profilers seem to be at least as good as conventional radiosonde and aircraft data. In the context of data assimilation, however, data monitoring is necessary to eliminate those stations and levels that should not be used because of data or modelling problems.

Profiler data have a uniform quality in time, which makes them ideally suited to investigating the behaviour of the 4D-Var assimilation algorithm. Some examples of relevant diagnostics have been shown in section 3, which provide some useful insights into the characteristics of incremental and linearization errors, model errors, and short-range forecast error growth. In the future it is hoped that the systematic comparison of profilers with the ECMWF model state will help to monitor and to improve the model physics as well, such as the depiction of the planetary boundary layer.

In conclusion, there are notable benefits from monitoring and assimilating wind profiler data in the ECMWF forecasting system. Profiler data disseminated as conventional PILOT reports have been used for a long time, but with a low time frequency. More recently, American wind profiler data have successfully been used as such (i.e. with hourly frequency and specific monitoring) in ECMWF operations since summer 1999. European wind profilers will start being monitored in real time in summer 2000, with a possible operational implementation at the end of 2000 if the data quality is consistent enough.

Appendix: The effect of observation error correlation

In most operational data assimilation schemes, it is assumed that observation errors are uncorrelated. This is surprising as the historical tendency is for observing systems to provide data with increasing density in space and time. As we shall demonstrate, there is evidence that observation errors are correlated to some extent. These correlations tend to increase for small separations, meaning that the weight given to dense datasets should be adjusted accordingly. Some problems linked to observation error correlation have been explored in Hollingsworth and Lönnberg (1986), Seaman (1977) and section 4.8 of Daley (1991), a simpler and more practical approach is adopted here.

An example is given in figure 11, where two vertical profiles of observed zonal winds are compared for virtually collocated stations (a radiosonde and a wind profiler). The separation between these stations (about 30km) is negligible compared to the resolution of the ECMWF 4D-Var analysis. The profiles have been observed independently with different instruments, so they can be regarded as observations of the same atmospheric profile with mutually uncorrelated observations errors. Indeed they are very much alike, but there are differences which are necessarily caused by observation errors in one or the other instrument. Of particular interest is the difference around 300hPa, where the wind maximum is sharper in the radiosonde profile, suggesting that there is a spurious smoothing of jets in the profiler data.

If both instruments had vertically uncorrelated observation errors, the difference would have a white noise structure. This is clearly not true; a study of the autocorrelation of differences between such profiles shows that there is a substantial autocorrelation for small vertical separations. Since it is unlikely that all the error correlation is in the radiosonde profile, one has to assume that there is a significant vertical observation error correlation in profiler data (this could be further proven using a third source of data such as aircraft profiles at Denver airport). At the average 14hPa vertical resolution of reports from this profiler, the apparent correlation is 80%. Even if the data were thinned to half this resolution, there would still remain a correlation of 25%. It means that despite their good average quality, profilers tend to smooth out features of the atmosphere which may be important for numerical weather prediction.

A way of dealing with this problem would be to model the observation error correlation explicitly in the analysis system. This may be technically non trivial to implement. We are going to use a simple analysis problem to suggest an approximate solution: let us consider two observations of two variables (e.g. two consecutive component observations in a wind profile). For simplicity we will assume that background errors are mutually fully correlated — it does not fundamentally change the results and it simplifies the algebra. This hypothesis is justified insofar as the vertical wind background error correlation length (Derber and Bouttier, 1999) is much larger than the spacing between two profiler observations.

For simplicity, we will also assume that the background and observation error variances are the same for the two variables. Using the notation from Ide et al. (1997), the background error covariance matrix for this analysis problem is (in the limit of small separations):

$$\mathbf{B} = \begin{pmatrix} b & b \\ b & b \end{pmatrix}$$

whereas the observation error covariance matrix is

$$\mathbf{R} = \begin{pmatrix} r & r\rho \\ r\rho & r \end{pmatrix}$$

Where b, r and ρ are respectively the background and observation error variance, and the observation error correlation. If each variable is directly observed by each observation, the observation operator is equal to the identity and the optimal analysis weight matrix is

$$\mathbf{B}(\mathbf{B}+\mathbf{R})^{-1} = \begin{pmatrix} b & b \\ b & b \end{pmatrix} \frac{1}{(b+r)^2-(b+r\rho)^2} \begin{pmatrix} b+r & -(b+r\rho) \\ -(b+r\rho) & b+r \end{pmatrix}$$

If d_1 and d_2 are the background departures for the two observations, the analysis correction for each variable is

$$\frac{b}{2b+r(1+\rho)}(d_1+d_2)$$

i.e. it is a rescaled average of the two background departures, a kind of "super-observation" (Lorenc, 1986). For small separations one expects the observation error correlation ρ to be positive, which means a reduction in the analysis fit to the observations. If ρ is not explicitly modelled in the analysis algorithm, the optimal weight can still be obtained by inflating the modelled observation error variance by a factor $(1+\rho)$.

This very simple calculation suggests that although the profiler data appears to have about the same quality as the radiosonde winds, consecutive profiler winds seem to have an observation error correlation of about $\rho = 0.8$. This means that the profiler wind standard error should be inflated by a factor $\sqrt{1+0.8}$ i.e. 34%. A more rigorous study would have to account for correlated interpolation errors (which are a function of model resolution and can be large near local extrema of the wind profile) and the presence of more than two pieces of data in the genuine analysis problem: this would lead to a further reduction of the weight of profiler wind observations.

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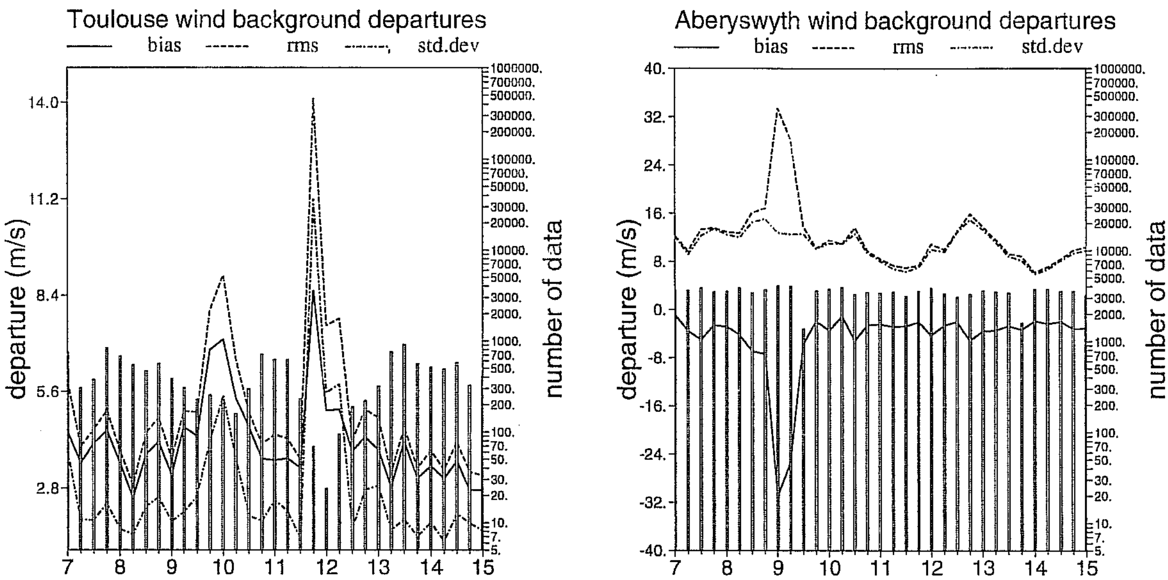

Figure 8: Examples of variation in time of the background departure statistics for the profiler wind in Toulouse (left panel, meridional component) and Aberyswyth (right panel, zonal component). The scale of the departures in m/s are on the left vertical axes, the full, dashed and dot/dashed curves give the vertical average, rms mean and standard deviations in the vertical profile of wind departures. The vertical grey bars give the number of observations available in each 6-hour period, as indicated by the right vertical axes.

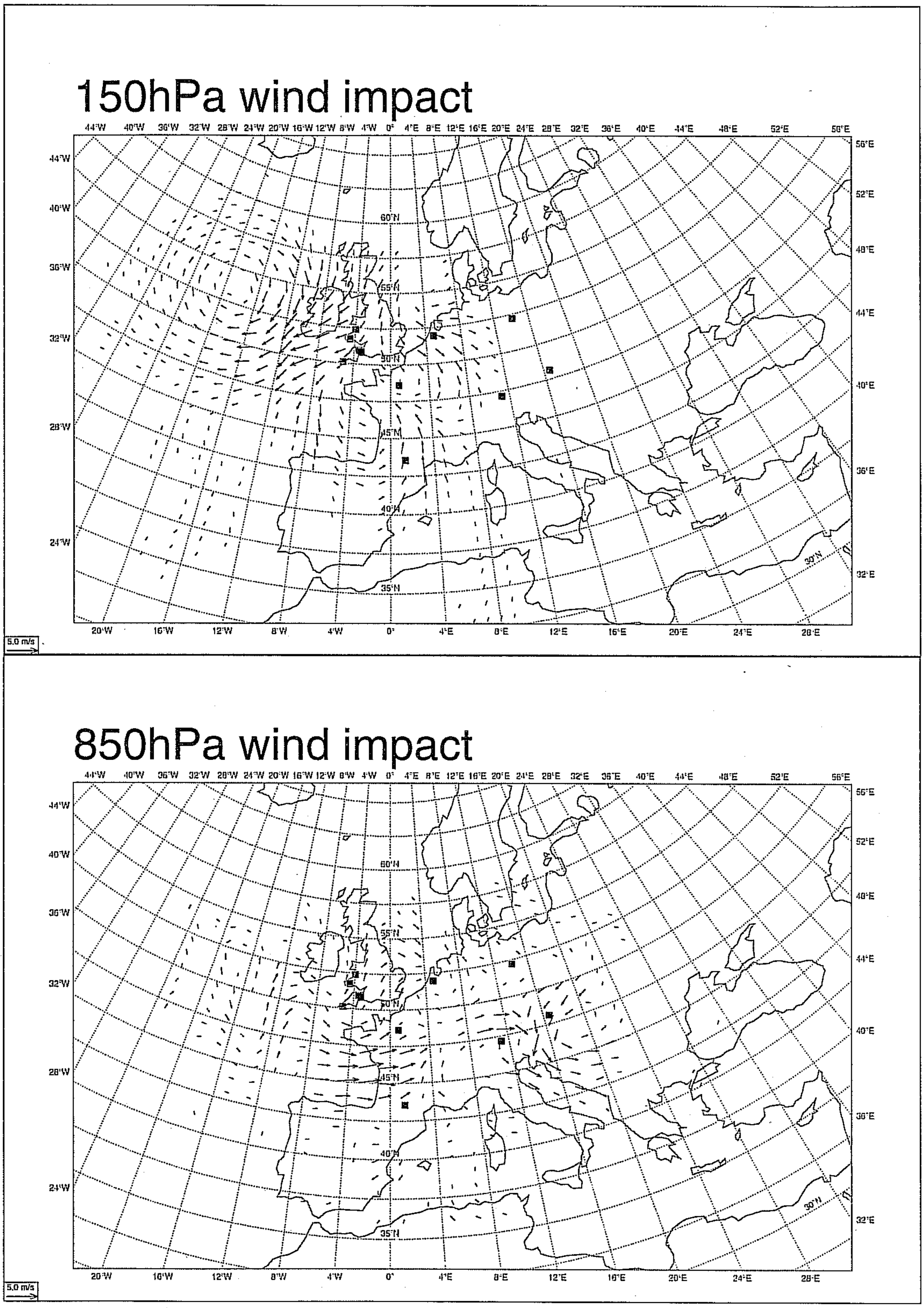

Figure 9: 4D-Var wind analysis differences caused by using profiler data, at 150hPa (top panel) and 850hPa (bottom panel) on 7 February 2000 at 00UTC. The wind scaling is given by the lower left arrow of 5m/s. The black dots indicate the location of the used profilers.

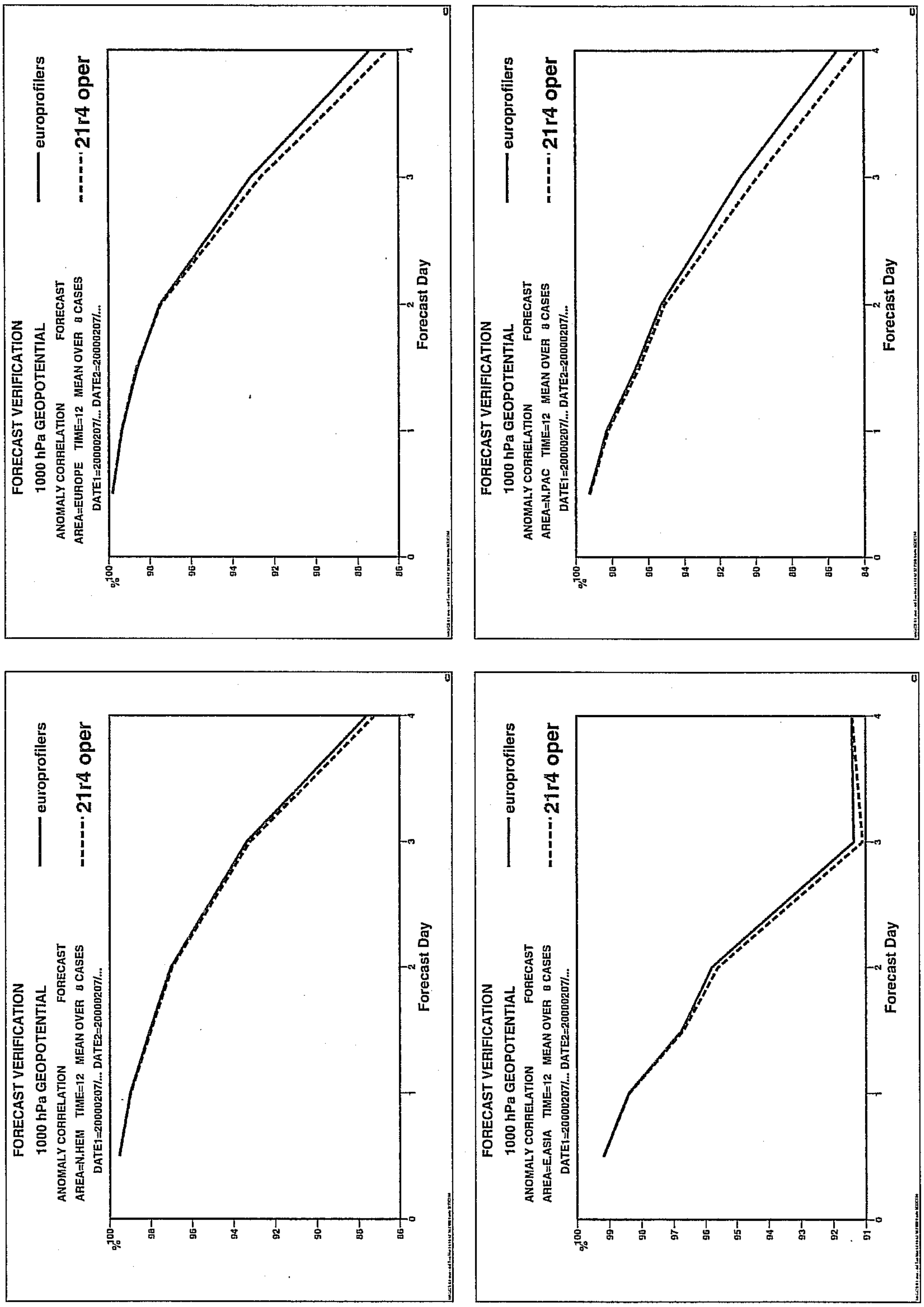

Figure 10: Objective forecast scores showing the impact of activating European profiler data during 8 consecutive days in February 2000. The forecasts are verified against the ECMWF operational analysis. '21r4 oper' (dashed) is the operational ECMWF system, which did not use European profiler data.

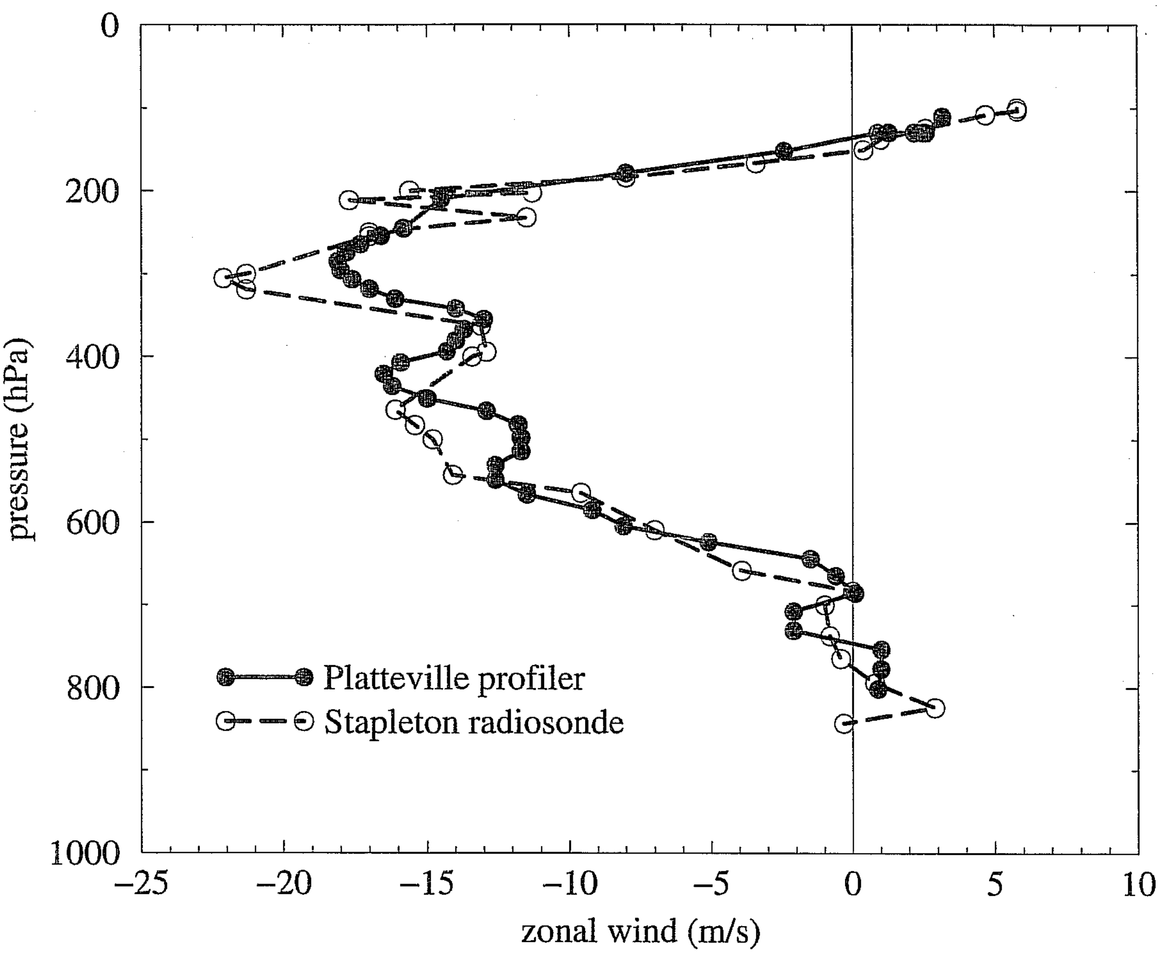

Figure 11: Observed profiles of the zonal wind component at Denver on 1 May 2000, 12UTC, by the local radiosonde (Stapleton) and profiler (Platteville) stations. The circles and disks show the actual values reported over the Global Telecommunications System.