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THE USE OF AN OPERATIONAL DATA ASSIMILATION SYSTEM TO INFER THE QUALITY OF RADIOSONDE OBSERVATIONS

C D Hall

Meteorological Office, Bracknell, UK

1. INTRODUCTION

The data assimilation systems in operational use today provide global analyses of wind, temperature, geopotential, humidity and surface pressure. The availability in real time and general high accuracy of these analyses together with the associated short-period forecasts or background fields make them well suited for use in the regular monitoring of the quality of observations. In most instances they provide reliable reference values which may be used to compare observations separated in space or time and from which systematic departures may be noted. Errors in the model fields, which may be large in data-sparse areas, are a limiting factor on the success of such monitoring methods.

Hollingsworth et al (1986) have described some studies of data quality made at ECMWF. In the last few years an archive has been set up at the Meteorological Office containing, for each observation used by the UK operational global data assimilation system, its departure from the value of the model analysis and background at the observation position as well as information on the flags raised by the objective quality-control scheme. Some of the methods of estimating the quality of radiosonde observations using this archive will be described with particular reference to the measurement of wind.

2. THE DATA PROCESSING AND ASSIMILATION SYSTEM

All observations have to undergo objective quality-control checks and preprocessing before being used by the data assimilation system. Checks may be performed on the message format, excess over climatological extremes, internal consistency, temporal consistency, closeness to background values, and spatial consistency. Quality control is performed in two stages: checks made without reference to model values (stage I), and checks made using model values (stage II). In the case of radiosonde observations, stage I checks are made for excessive wind shear, superadiabatic lapse rates, hydrostatic inconsistency between geopotential and temperature, and inconsistency between the data reported on standard levels and those reported on special levels.

Before passing onto stage II, the observed radiosonde profiles are converted to values on the sigma levels of the model. Layer-mean values are evaluated between the half levels using only data passing the stage I checks. In stage II the check against background requires that the inequality

$$(o-b)^2 \leqq N_1 \; (E_o{}^2 + E_b{}^2) \qquad (1)$$

is satisfied; o and b are the observed and background values on a sigma level, E_o and E_b are estimates of the observation and background errors and N_1 is an adjustable factor which in the case of radiosondes equals 12. The final check in the quality-control procedures ensures that there is consistency between neighbouring observations. It requires that an inequality of the type

$$(o-a)^2 \leqq N_2 \; (E_o{}^2 + E_a{}^2) \qquad (2)$$

is satisfied; a is the analysed value at the observation position using all the observations which have passed the background check with the exception of the one that is the subject of the check, E_a is an estimate of the analysis error, and N_2 is another adjustable factor which in the case of radiosondes equals 12. A final quality-control flag, specifying that a value is unsuitable for use by the data assimilation system, is set on those observations failing the check against their neighbours defined by equation 2. Quality-control checks in stage II are performed separately on each derived sigma-layer value of each variable (wind, temperature and humidity) of a radiosonde observation. If a final flag is set at more than 4 levels, the observation is considered unreliable and a final flag is set on all remaining values of that variable.

The data assimilation scheme is based on a 6-hour cycle; observations falling within 3 hours of a nominal analysis time (00, 06, 12, 18 GMT) are used to create the numerical analyses valid at that time by blending the data with a forecast from the previous analysis. In this way all asynoptic observations are used in the analysis, though there will be differences of up to 3 hours between the observation time and the nominal analysis time which cannot properly be taken into account. The weights assigned to the observations are calculated using univariate optimum interpolation and assimilation is achieved by the method of repeated insertion of data. The model fields are modified at each step of an integration leading up to the analysis time by relaxing them towards the weighted observations. Noise is controlled by applying a damping term to the divergence. In practice it is found that the fields are sufficiently in balance by the end of the assimilation to be used as start fields for a forecast without the need for a separate initialization step. The data assimilation system and forecast model are described in detail in Bell and Dickinson (1987).

3. METHODS OF MONITORING OBSERVATIONS

The flags raised by the objective quality-control checks are a simple means of identifying regularly erroneous stations. Figure 1 shows the per cent of wind observations flagged at model level 11 (about 250 hPa) over an area covering much of Europe for the 3-month period July to September 1987. The number flagged is mostly very small which reflects not only the general reliability of the observations but also the limitations of the rather simple quality-control methods. The distance between neighbouring radiosonde stations is usually at least 250 km which is rather too great for equation 2 to provide a reliable check for mutual inconsistency. Figure 2 shows the rms vector wind differences from background at the same set of stations and at the same level. Mutual inconsistencies are more readily apparent and show up as values at neighbouring locations which differ by an amount larger than the likely inhomogeneities in the background error.

Background fields provide useful reference values against which observations can be compared. Being derived from cycles of data assimilation and short-period forecasts, they reflect the information contained in the observations valid at earlier times, but unlike the

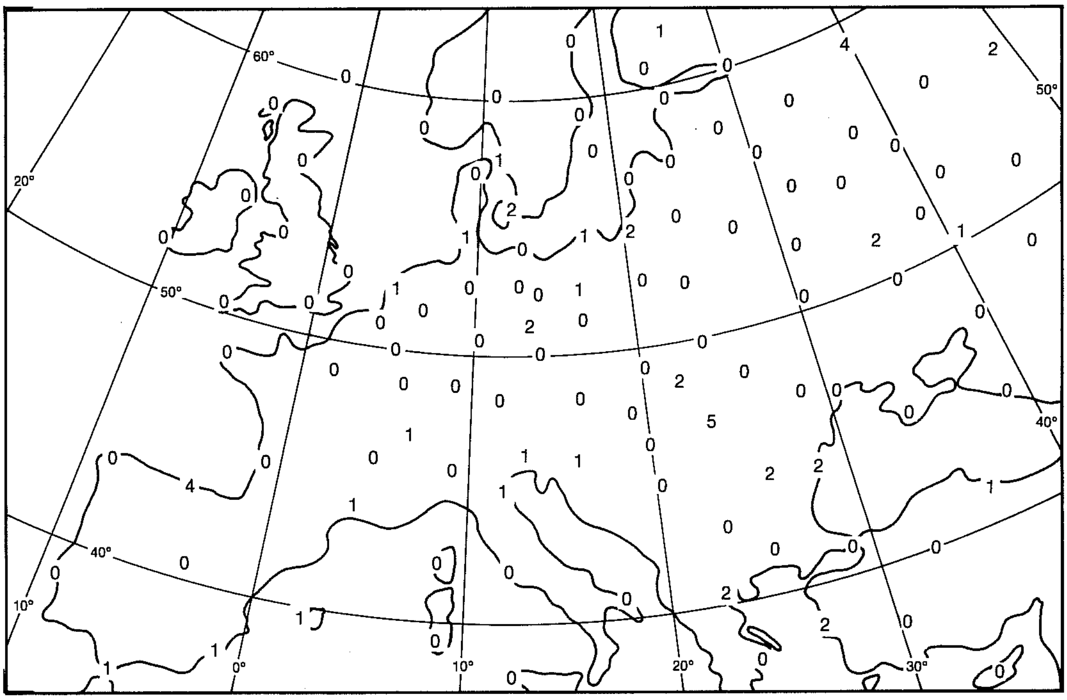

Figure 1. Per cent of radiosonde wind observations failing objective quality-control checks at model level 11 (about 250 hPa). July to September 1987.

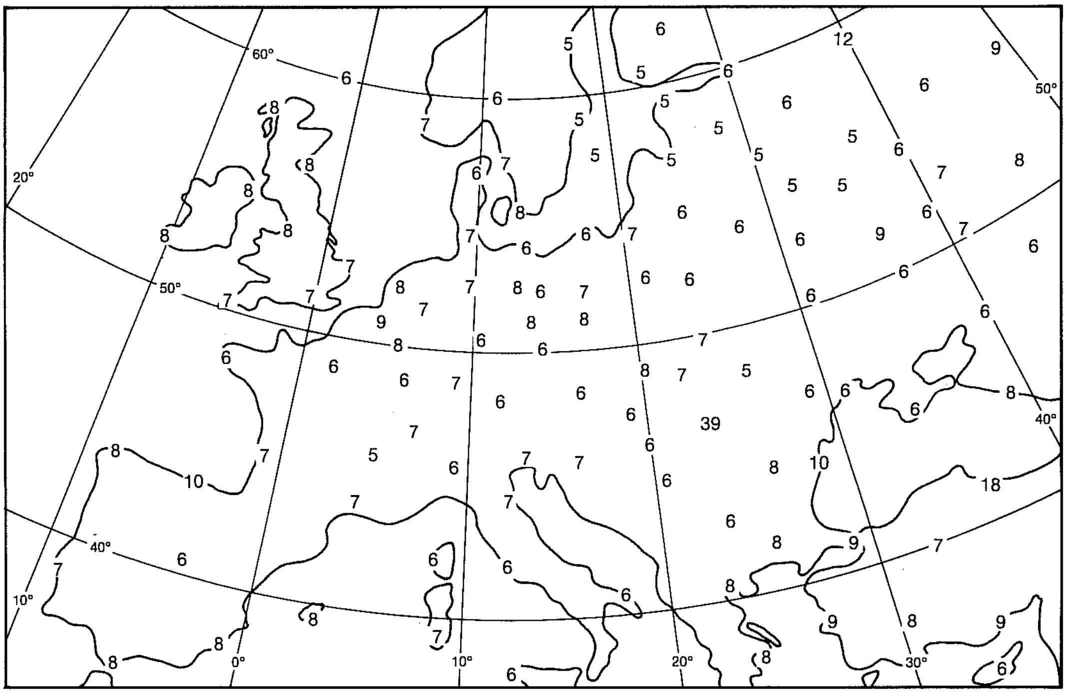

Figure 2. As Figure 1 except for rms vector wind differences from background in ms^{-1}.

analysis, are not biased towards the observation which is the subject of investigation. Differences between observation and background may be considered as arising from three sources: background error, observation error and the lack of representativeness of the observation on the scale of the model.

3.1 Observation error

Radiosonde intercomparison trials (eg Nash and Schmidlin, 1987) have shown that many systems can achieve a high degree of reproducibility; typical values are 0.2 K in temperature and 1.5 ms^{-1} in wind (except at low balloon elevation). Mean and rms differences between observation and background at Crawley (51.1°N 0.2°W) are shown in Figure 3 for the 3-month period July to September 1987. The station is in a region of locally good data coverage and the quality of the background fields is probably higher than average. Mean differences are mostly small, and the rms differences are a little over 1 K in the temperature at all levels and up to a maximum value of 4-5 ms^{-1} in the wind at 250 hPa. Clearly observation error from properly functioning instruments contributes only a small amount to the rms differences between observation and background. However, where large observation errors occur, model fields have an important role to play in their identification. The sources of such errors are manifold; for wind-finding instruments for example, the axes of the system may be misaligned, a levelling error may result in wrong elevation angles, or the pressure sensor may be biased. Wrong elevation angles in radiotheodolite systems are a source of major error in the measured wind when the elevation angle is small, which is the case in strong jets.

3.2 Observation representativeness

Radiosondes provide detailed vertical profiles of the atmosphere at point locations. For wind measurements, the vertical resolution depends on the averaging period, which in the case of the UK primary radar is just over 1 minute and for most other operational wind-finding systems is between 2 and 4 minutes. By contrast model fields represent values on a horizontal scale of at least 100 km and a vertical scale of perhaps 100 hPa. Where the vertical wind profiles are derived from 1-minute averages much fine structure may be observed (Figure 4a). In this case an almost identical profile was obtained from another radar 52 km distant tracking

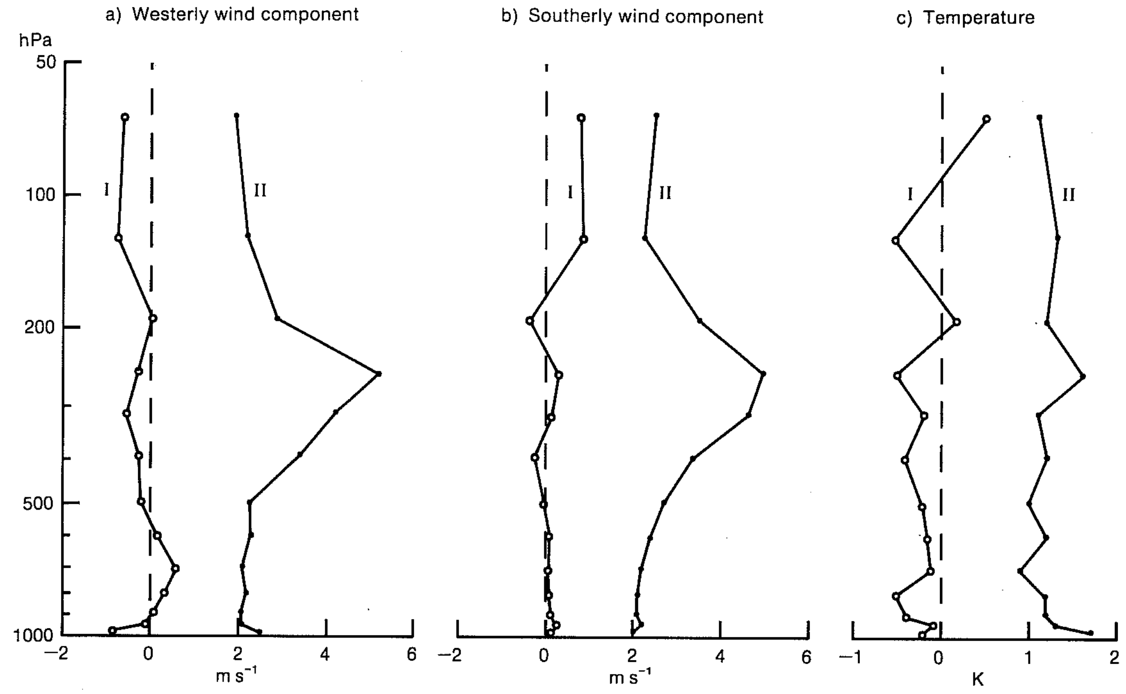

Figure 3. Mean (I) and rms (II) differences from background of wind components and temperature at Crawley (51.1°N, 0.2°W). July to September 1987. 171 cases.

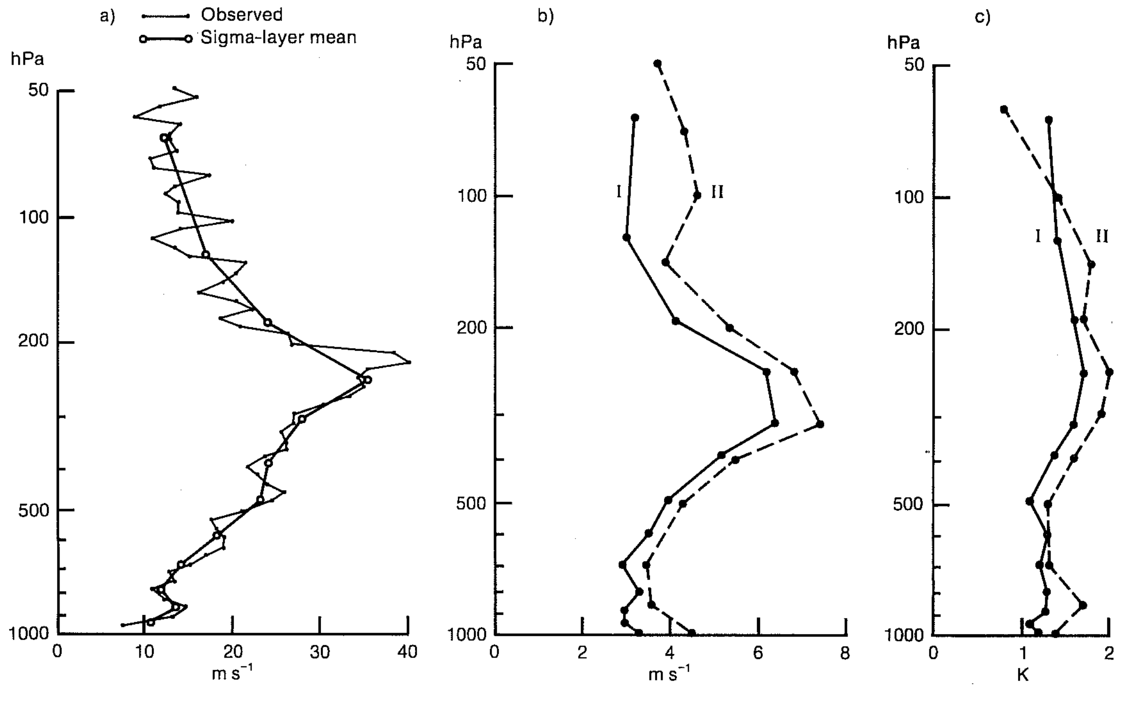

Figure 4. a) The observed wind speed at Beaufort Park (51.4°N, 0.9°W) on 20 November 1984 (1-minute averages) and the derived sigma-layer mean values. b) rms vector wind differences from background of observations meaned over sigma layers (I) and observations on standard levels (II). All UK radiosonde stations 1-8 August 1987. 166 cases. c) As b) except for temperature.

the same balloon (Kitchen and Tolworthy, 1987), demonstrating that the fine structure is real and not a characteristic of the observing system. Of particular interest is the strong wind shear around the jet and the gravity wave structure in the stratosphere. The derived sigma-layer mean values used by the data assimilation system are also shown in Figure 4a. They represent a fairly deep vertical average and give a much smoother profile. Differences from background calculated using these values are significantly smaller than differences calculated using 1-minute averages at the standard levels (Figure 4b). A similar comparison is made for temperature measurements in Figure 4c.

The degree of representativeness of radiosonde observations in the horizontal has been estimated from the UK radiosonde network by Kitchen (private communication). He arrives at values between 3 and 5 ms^{-1} for the rms differences between radiosonde observations in the troposphere and model values interpolated from a 150 km grid: the resolution of the UK model. These values relate to middle latitudes. Errors of representativeness which include all scales that the model cannot reasonably resolve will of course be larger; 3 or 4 grid points are required to represent a simple wave structure with any accuracy by finite-difference methods. There is no clear distinction between what may be attributed to errors of representativeness and what to background errors.

3.3 Background error

Background fields are short term (6-hour) forecasts from earlier analyses which in turn are a blend of observations with the previous background fields. Background errors arise from a wide variety of sources. Where there is a persistent lack of observations the analyses will be strongly reliant on forecast values over several assimilation cycles with the unavoidable build up of forecast error. In data-sparse areas the background fields will often display some of the systematic errors characteristic of medium-range forecasts from the model. This is particularly true in the tropics where the systematic errors of the UK model may be quite large. Figure 5 shows the mean differences from background of the southerly wind component at two stations 470 km apart in a data-sparse region of the equatorial west Pacific. Both stations show large but similar mean biases relative to background in the period January

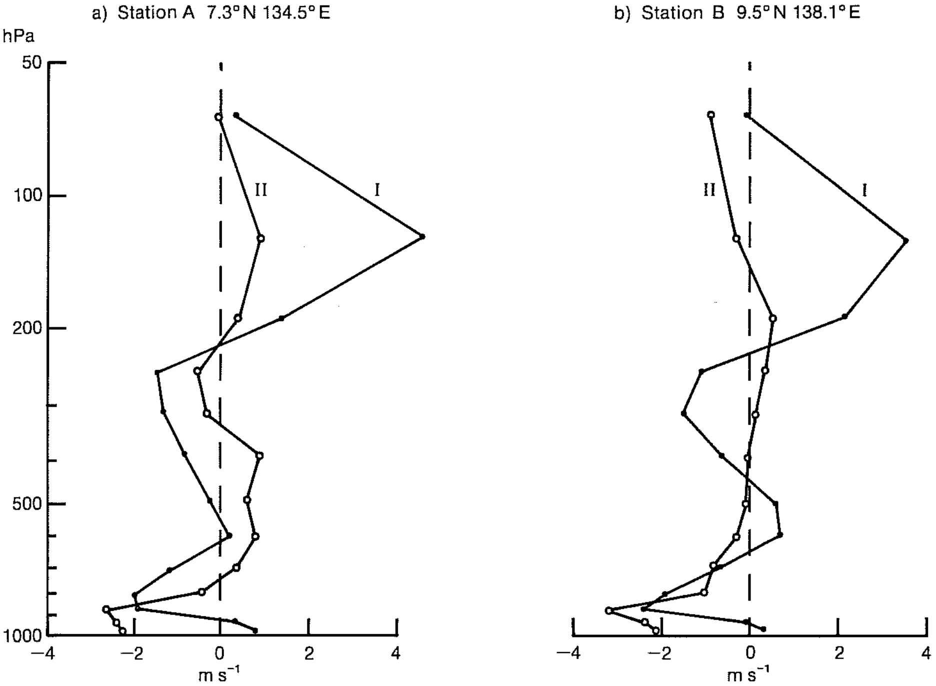

Figure 5. Mean differences from background of the southerly wind component at two stations in the equatorial west Pacific during January to March 1987 (I) and July to September 1987 (II).

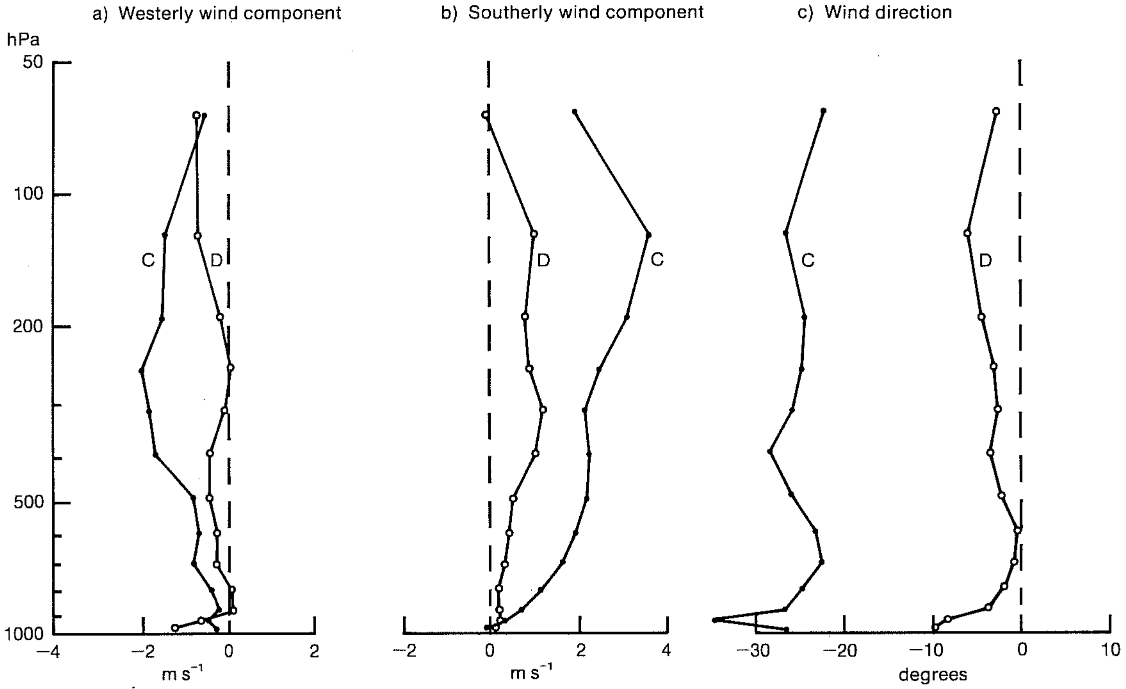

Figure 6. Mean differences from background of the wind components and wind direction at station C (59.3°N, 39.9°E) and one of its neighbours station D (57.9°N, 34.1°E).

to March 1987 when the mean flow was from the northeast; background is stronger than observation around 800 hPa and 300 hPa and considerably weaker around 150 hPa. In the period July to September 1987 when the mean flow was from the southwest a quite different pattern emerges. It seems most probable that the differences reflect changing systematic errors in the background winds.

Background errors are often large near the surface because of inaccuracies in the representation of orography and surface processes, and in the stratosphere because of insufficient resolution near the model's upper boundary. Background errors can also result from errors in observations used in previous analyses. A systematically erroneous observation which nevertheless passes the quality-control checks, may significantly degrade the analyses and subsequent background fields. Satellite observing systems often display systematic biases which may affect the background fields; satellite temperature retrievals, as used at present, contain a built-in bias toward the climatological mean state of the atmosphere; satellite cloud -track winds underestimate wind speed at jet-stream levels in middle latitudes (Kallberg and Delsol, 1987). In both these examples the problems are particularly severe since the observations are very numerous and are located primarily in regions lacking observations from other sources.

4. EXAMPLES OF MONITORING

In Figure 2 certain stations stand out as having rms differences from background considerably larger than those of their neighbours. One such station (C) is at 59.3°N 39.9°E and mean differences from background of the wind components and the wind direction are shown in Figure 6 along with similar values from one of its neighbours (D) at 57.9°N 34.1°E. In this case a bias of about 25 degrees in the wind direction clearly stands out.

Figures 7 and 8 show the mean observed values and mean and rms differences from background of the westerly and southerly wind components at two stations at the southern extremity of Africa. Though there are a number of radiosonde stations to the north, none lie to the south or west over the large expanse of ocean. Background errors are probably fairly high. The two stations are 640 km apart yet have quite different

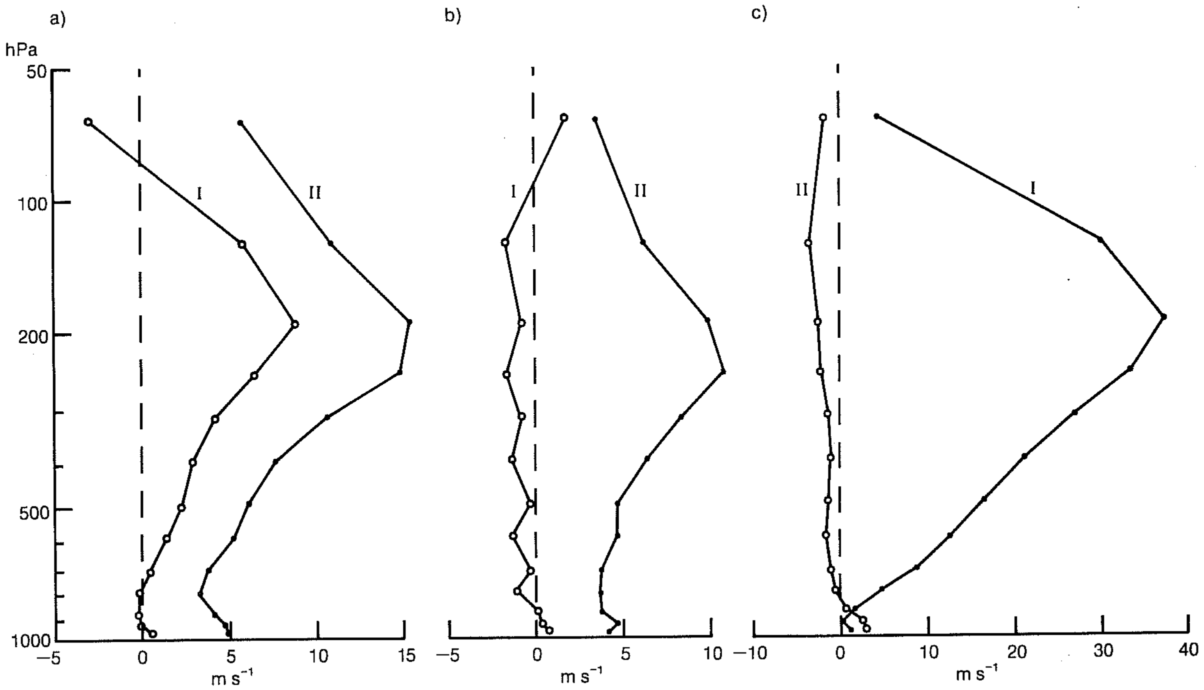

Figure 7. a) Mean (I) and rms (II) differences from background of the westerly wind component at station E (34.0°S, 18.6°E). January to March 1987. 349 cases. b) as a) except for differences from background of the southerly wind component. c) As a) except for the mean observed westerly wind component (I) and southerly wind component (II).

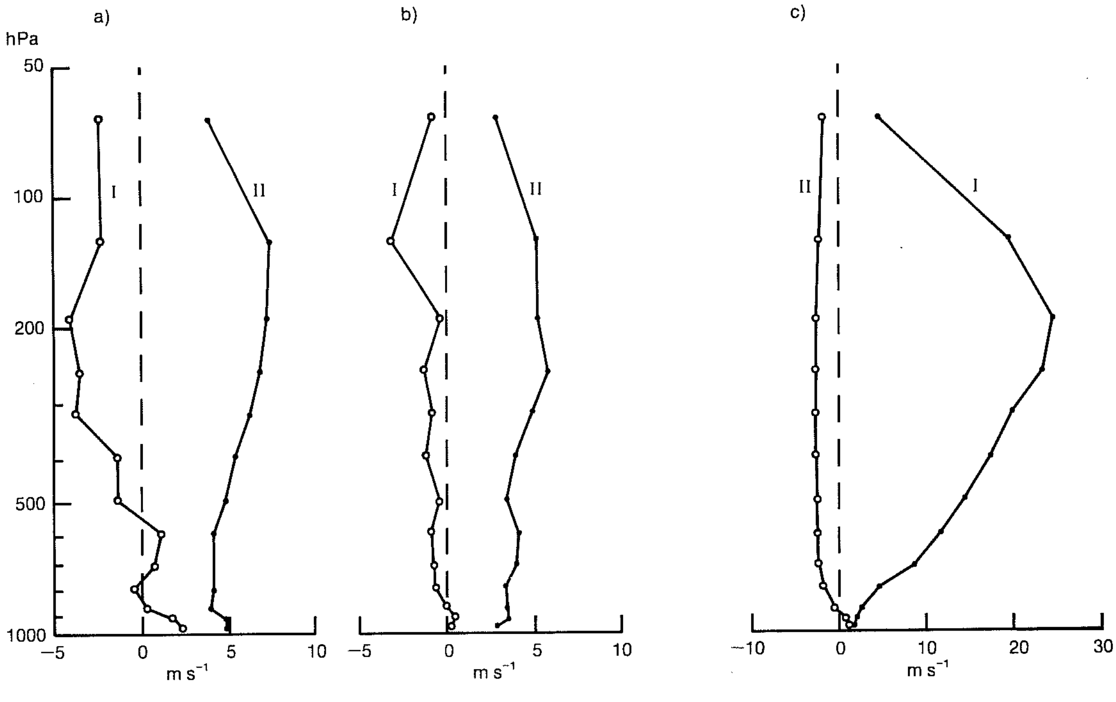

Figure 8. As Figure 7 except for station F (34.0°S, 25.6°E). 351 cases.

characteristics; the observed westerly wind component at station E is 12 ms^{-1} stronger at jet-stream levels than at station F lying due east, and the rms differences from background are much larger. It seems that the wind speed at this station is consistently overestimated, but not usually by an unrealistic amount since on only 2 of the 349 reports were flags raised by the objective quality control. The mean differences from background of the westerly wind component are as large as 8 ms^{-1} but there is no significant bias in the southerly wind component at any level. It is interesting that station F lying to the east has a 4 ms^{-1} bias in the westerly wind component relative to background in the opposite sense, which probably reflects the impact of the excessively strong observed wind from station E on earlier analyses and background fields.

The quality of the background fields in this region depends on observations from 3 main sources; the surface and upper-air measurements from southern Africa and coastal shipping, satellite temperature retrievals, and satellite cloud-track winds. The satellite based systems provide very numerous observations in the region which may be biased, as has been discussed. Figure 9a shows mean differences from background of wind speed at station E and for cloud-track wind observations within a rectangular box around the station. The satellite derived winds are some 5 ms^{-1} lighter than background at jet-stream levels and more than 15 ms^{-1} lighter than winds from station E. A similar comparison is presented in Figure 9b for an isolated radiosonde station (G) at about the same latitude lying about 2500 km to the west in the South Atlantic. Here the speed bias relative to background at the radiosonde station is of similar magnitude but opposite sign from the bias of the satellite derived winds. In this case it is quite possible that the background wind field is too light as a result of the continuous assimilation of satellite observations and the radiosonde station may be closest to the truth.

5. CONCLUSIONS

The global data assimilation systems in use today are a powerful tool in the monitoring of the quality of observations. The objective quality-control checks which are part of such systems are able to identify stations with regular gross errors in their observations. Smaller errors which show up as systematic differences between neighbouring observations can be identified using the reference values provided by background fields.

A few results from the UK operational data-monitoring system have been presented here. The methods used do not seem suited to full automation and the regular monitoring of the complete radiosonde network will probably require considerable resources.

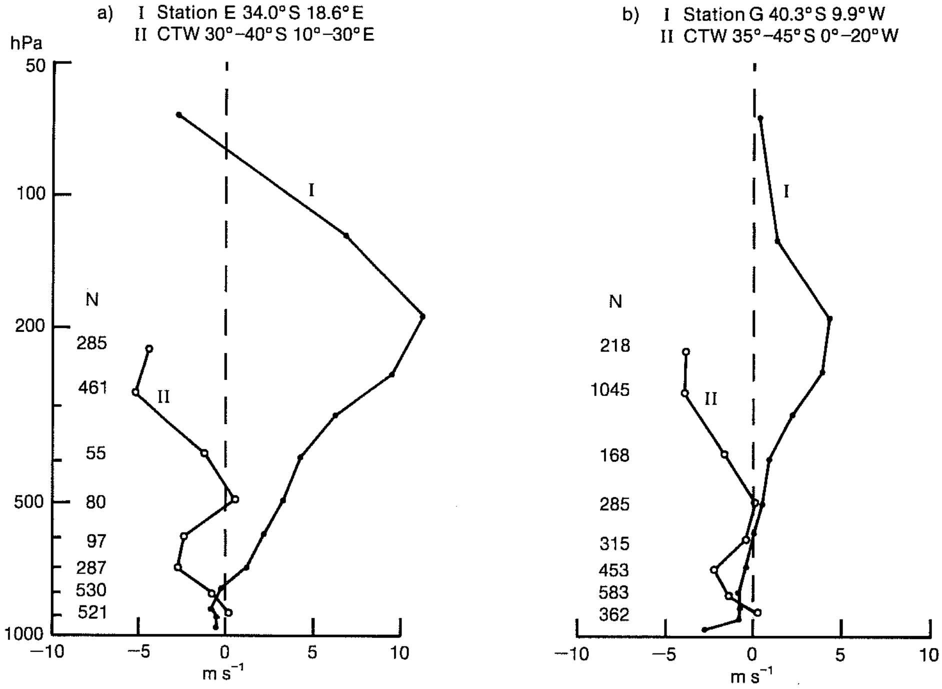

Figure 9. a) Mean differences from background of wind speed at station E (34.0°S, 18.6°E) and for cloud-track winds in a rectangular box around the station. January to March 1987. The number of cloud-track wind observations at each level (N) are shown. b) As a) except for station G (40.3°S, 9.9°W).

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