SOME ASPECTS OF STRATOSPHERIC DATA ASSIMILATION AT ECMWF

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1. INTRODUCTION

This paper will examine various aspects of stratospheric data assimilation. The study is aimed at a brief look at some of the strengths and weaknesses of the current operational analysis (OI) (*Lorenc*, 1986), and some stratospheric aspects and problems with the development of the newly developed three-dimensional variational analysis (3D-Var) (*Anderson et al*, 1994). One must keep in mind that the current ECMWF operational 31 level model has only four levels above 100 hPa and the top level is 10 hPa. With this stratospheric structure it is difficult to analyze the sharp vertical wind sheers frequently observed in the tropics.

2. DATA COVERAGE

Observations, or lack of them, create the major problem with stratospheric data assimilation. The situation is not improving; in the past many radiosonde stations were using large balloons and they now use smaller ones which often fail to reach 70 or 50 hPa. Examples of a typical observation wind coverage at 12 UTC on 6 March 1993 is shown in Fig 1. Note the reduction in coverage above 50 hPa particularly in the tropics.

The only other sources of real time stratospheric observations are radiances from the TOVS instrument package on-board the two operational meteorological satellites of the NOAA series (*Smith et al*, 1979). Every six hours the globe is observed by two satellites and a typical six hour coverage is shown in Fig 2. The horizontal coverage of these data is good but unfortunately the vertical resolution of these data is poor (*Kelly and Pailleux*, 1988), (*Kelly et al*, 1991) and only yields two or three pieces of information about the stratosphere. The utility of the data is also less in the tropics due to the weaker mass/wind coupling.

The regions in the atmosphere that the TOVS channels measure can be described by the temperature weighing functions (see Fig 1, *Smith et al*, 1979). The peaks of these weighing functions are shown in Table 1. Care must be taken with the use of these radiances in an analysis system in order not to smooth small scale vertical temperature structure not seen by these radiances. 3D-Var uses the TOVS radiances (cloud cleared) directly (*Anderson et al*, 1994). Prior to the OI analysis the TOVS radiances are converted to layer mean geopotential thickness using a one-dimension variational analysis method (1D-Var) (*Eyre et al*, 1993).

Analyses of radiances (16 November 1992) are shown in Fig 3 for HIRS channels 1, 2 and 3, MSU channels 2, 3 and 4 and SSU channels 1, 2 and 3. These radiance analyses are produced using a simple Cressman analysis method which requires no background. If one takes note of Table 1, then SSU 3 is the warmest and highest channel and MSU 2 is the coldest over the high Antarctic plateau, and in fact this channel is partly measuring surface temperature in this region of high terrain. MSU 4 measures the lower stratosphere. HIRS 3 peaks at a similar level but due the shape of its weighting function measures a little higher than MSU 4. By looking at all these radiance analyses, one can see the broad scale atmospheric temperature

TABLE 1. Characteristics of TOV sounding channels

HIRS Channel number	Channel central wavenumber	Central wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	668	15.00	CO_2	30 mb	*Temperature sounding*. The 15 μm band channels provide better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3 μm band channels. Radiances in Channels 5, 6 and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
2	679	14.70	CO_2	60 mb	
3	691	14.50	CO_2	100 mb	
MSU		Frequency (GHz)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1		50.31	Window	Surface	*Surface emissivity* and *cloud attenuation* determination.
2		53.73	O_2	700 mb	*Temperature sounding*. The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3 and 15 μm sounding channels.
3		54.96	O_2	300 mb	
4		57.95	O_2	90 mb	
SSU		Wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1		15.0	CO_2	15.0 mb	*Temperature sounding*. Using CO_2 gas cells and pressure modulation, the SSU observes thermal emissions from the stratosphere.
2		15.0	CO_2	4.0 mb	
3		15.0	CO_2	1.5 mb	

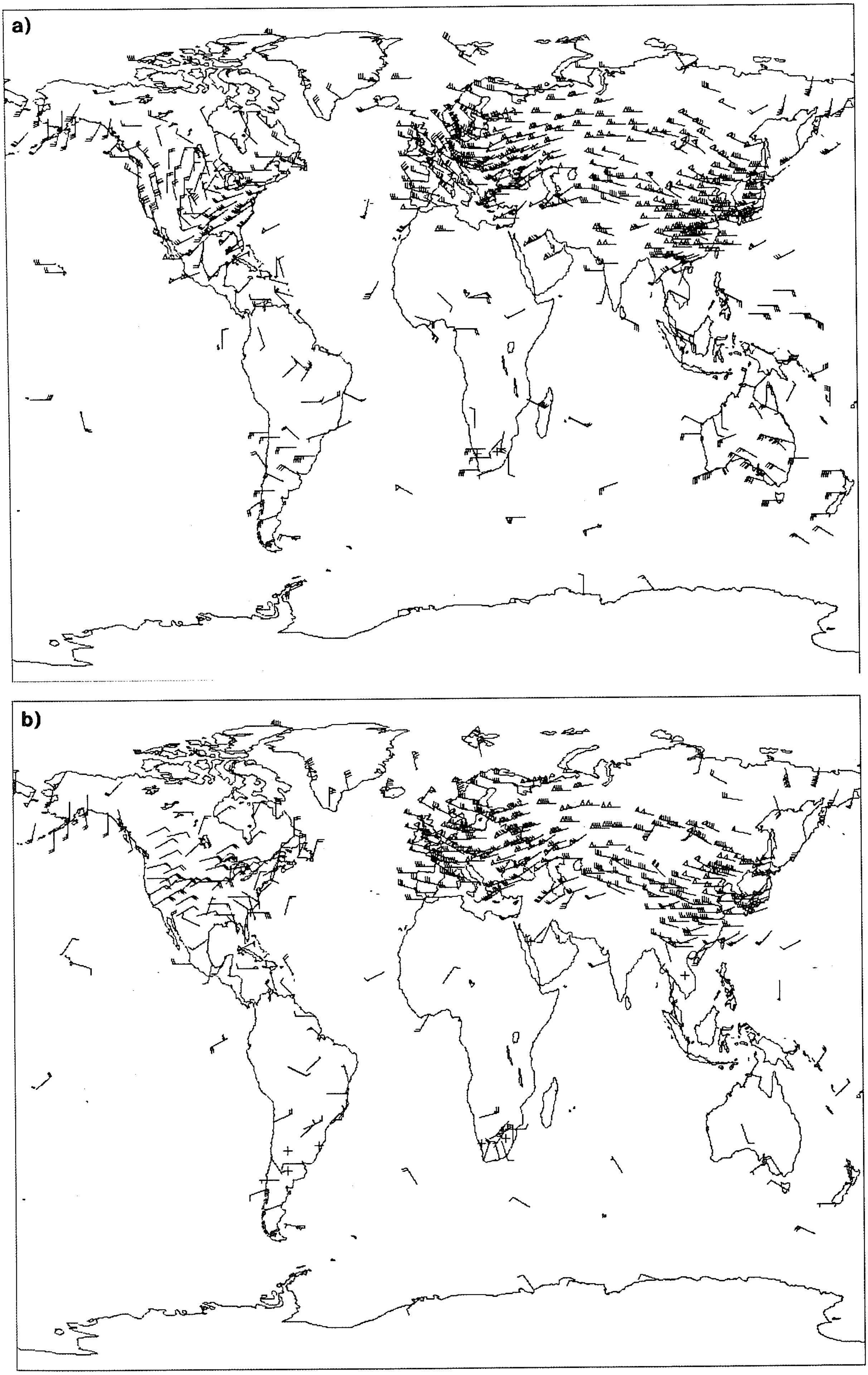
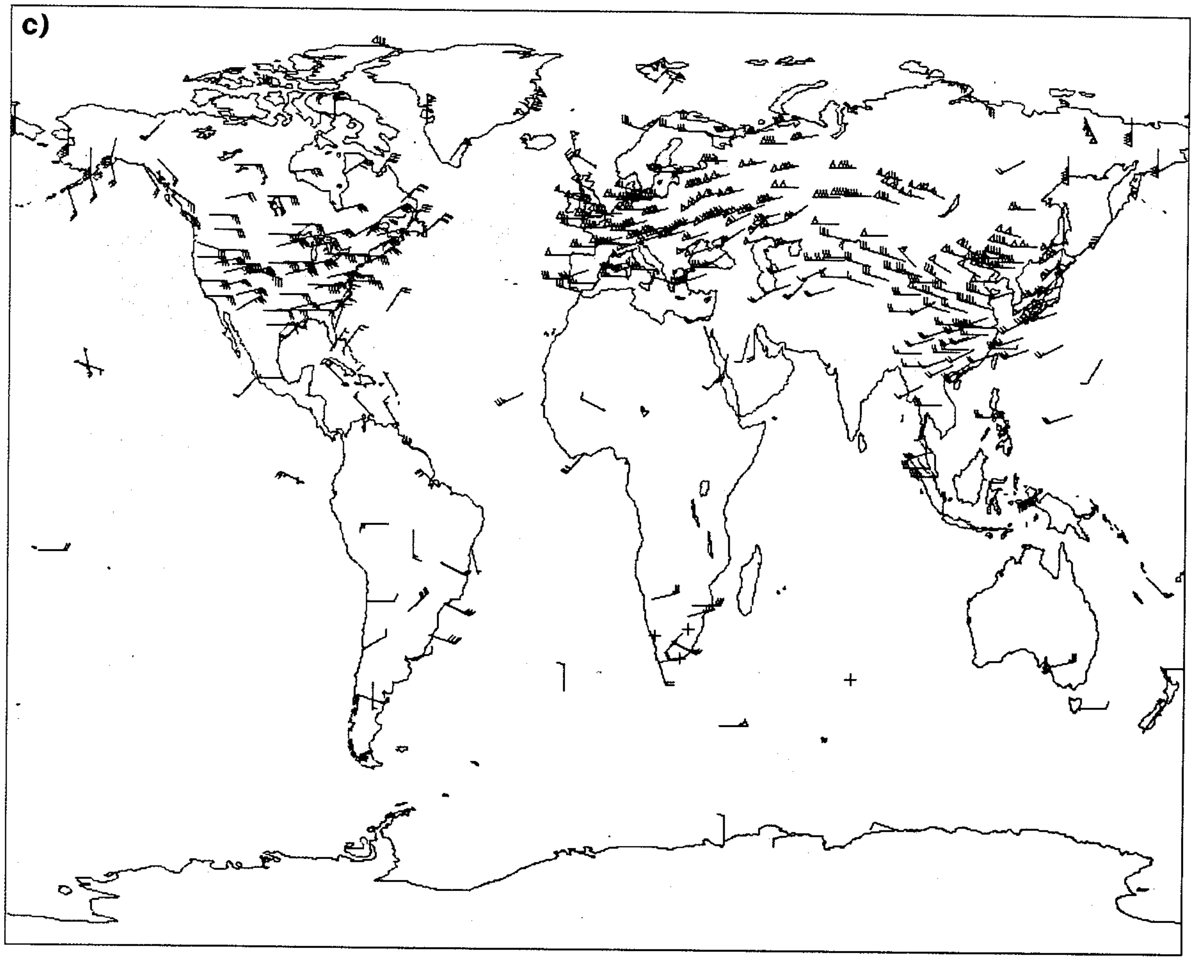


Fig. 1 Radiosonde winds for 12 UTC on the 6 March 1993. (a) Winds at 100 hPa, (b) Winds at 50 hPa



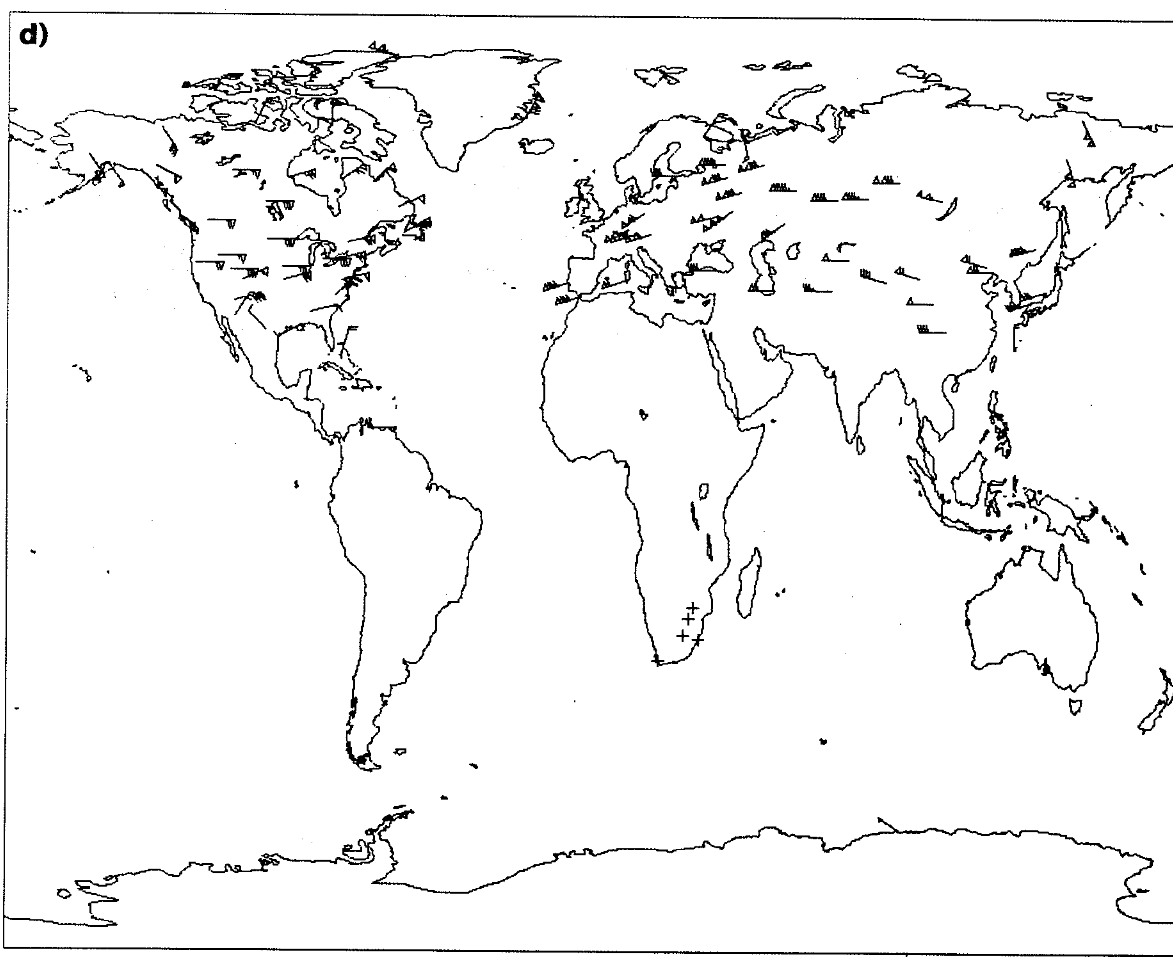


Fig. 1 cont. (c) Winds at 30 hPa and (d) Winds at 10 hPa.

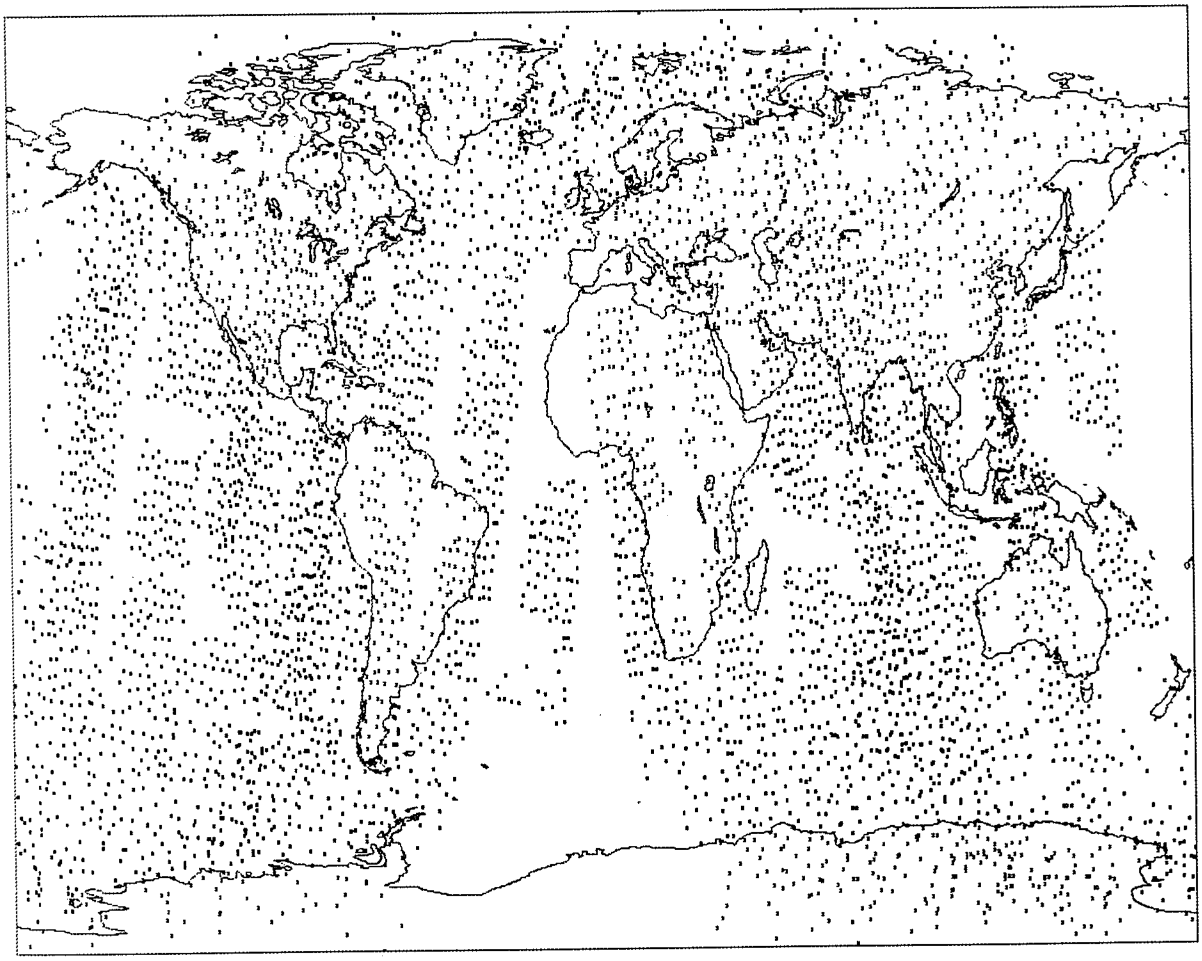


Fig. 2 TOVS temperature and humidity profiles on UTC on the 6 March 1993.

a)

b)

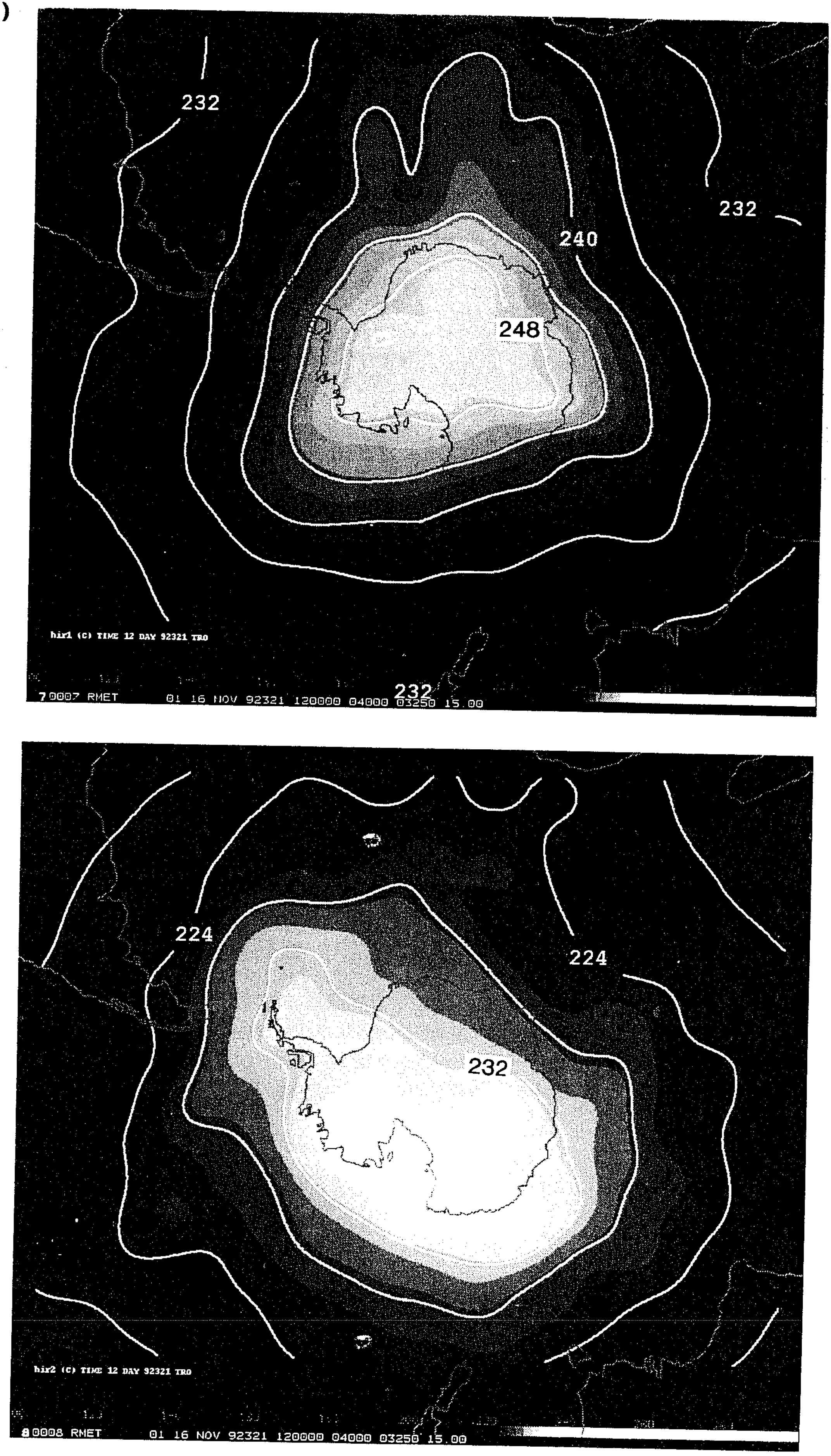
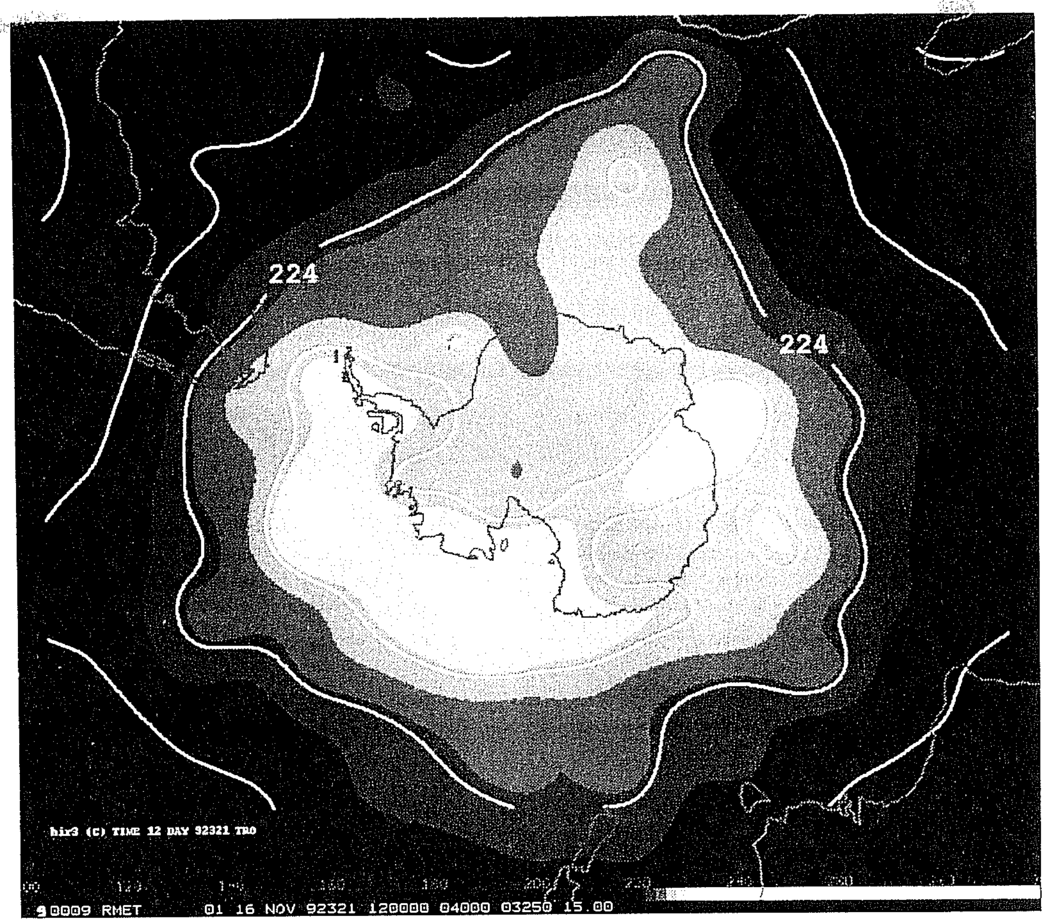


Fig. 3 Southern Hemisphere analysis of TOVS radiances 12 UTC, 16 Nov 92 (a) HIRS channel 1, (b) HIRS channel 2.

c)



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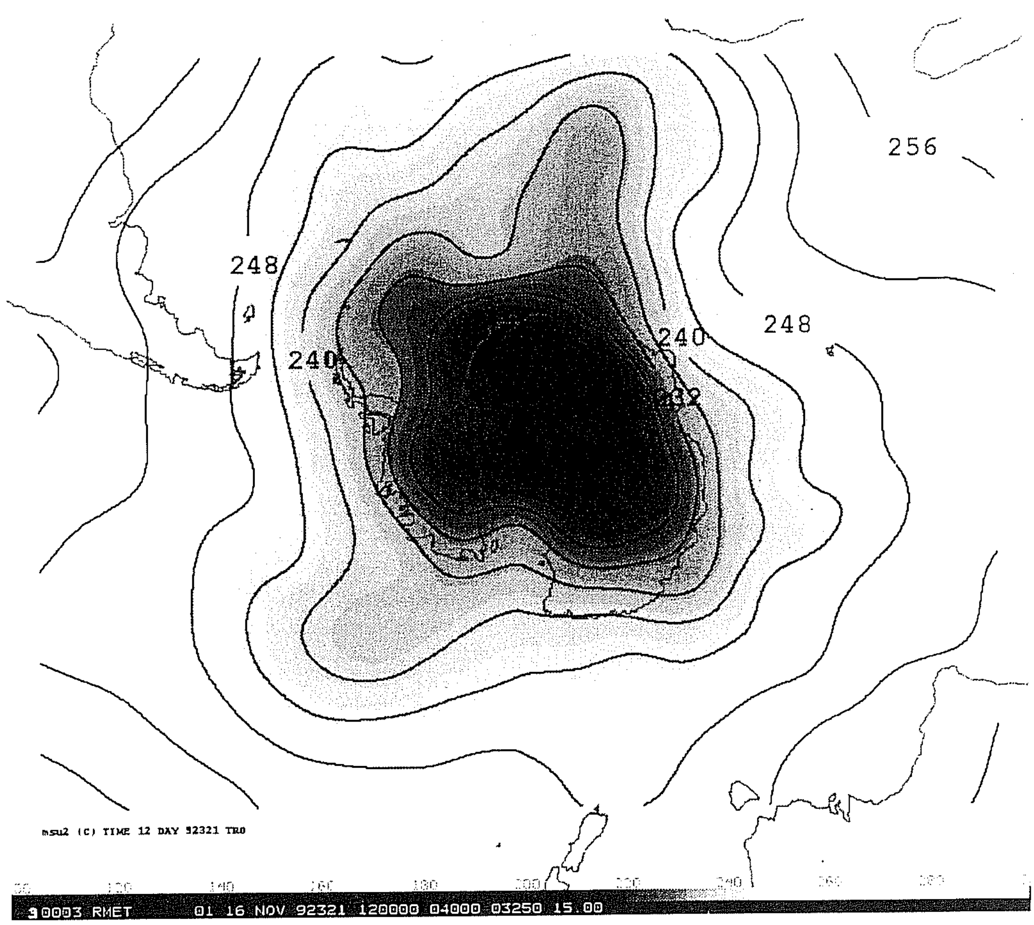
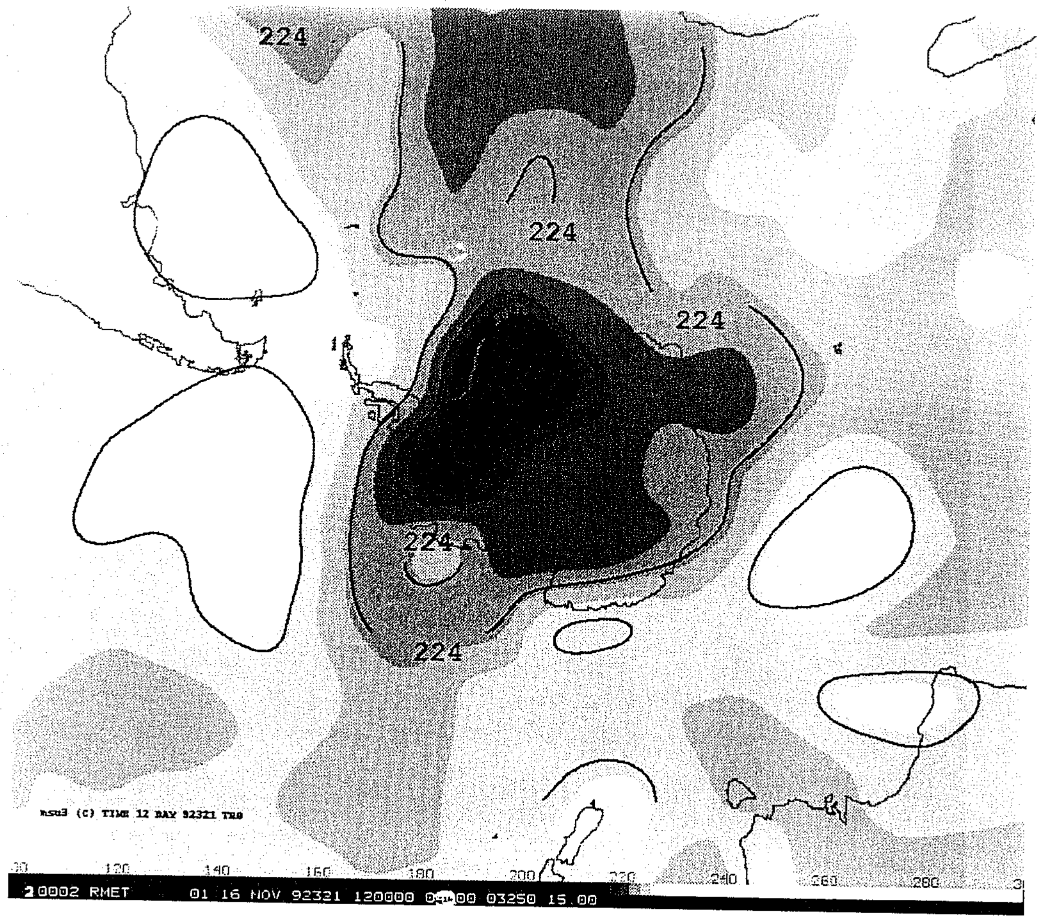


Fig. 3 cont. (c) HIRS channel 3, (d) MSU channel 2.

e)



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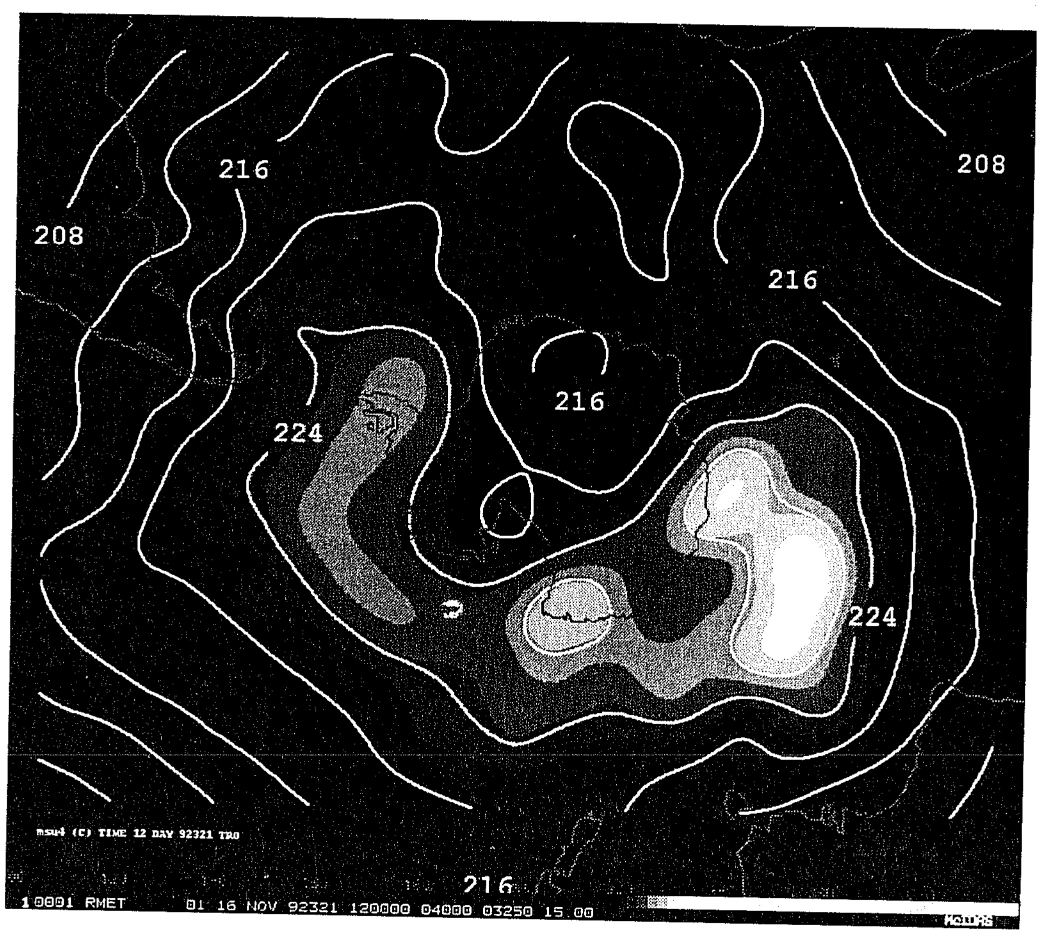


Fig. 3 cont. (e) MSU channel 3, (f) MSU channel 4.

structure but unfortunately, due the poor vertical resolution, one cannot see the strong horizontal temperature gradients associated with the intense southern polar vortex even though the strong stratospheric warming is observed.

3. DATA SELECTION AND STRUCTURE FUNCTIONS

The analysis of observations is controlled by mean, multivariate, three-dimensional forecast error covariances. For the OI analysis these covariances are obtained using radiosondes coincident with short-range forecasts (*Lönnberg*, 1989). In the current 3D-Var the forecast error covariance is obtained using the difference between the 48 hour and 24 hour forecast (*Parrish and Derber*, 1992). The analysis increments (observation minus short-range forecast) is then spread using the forecast error covariance.

3.1 Data selection

The operational OI analysis is done in two slabs, 1000-100 hPa and 100-10 hPa, and the horizontal regions of these volumes varies depending on the data density. The OI analysis requires a matrix inversion for each volume and the number of observation selected must be not greater than 700 measurements; the analyzed volumes are reduced if the data density increases (see Fig 4(a)). On the other hand 3D-Var does not have such a limitation on number of observations.

3.2 Structure functions

In order to demonstrate how the two analysis methods work in the stratosphere, some forecast error structure function plots will be discussed. In OI analysis there is a basic assumption that the forecast error can be separated in vertical and horizontal in order to simplify the calculations, these are termed 'separable structure functions'. This restriction is not necessary in 3D-Var and allows for 'non-separable structure functions'. 3D-Var also allows for its structure functions to vary as a function of level and scale unlike OI. On the other hand 3D-Var presently has only one set of structure functions for the globe whereas the OI analysis can vary its structure functions regionally to reflect forecast error.

The OI analysis varies its vertical resolution for three global regions to try to take into account average forecast error. Figs 5(a), (b) and (c) show examples of this at 30 hPa. Note that the width of the tropical wind structure function is somewhat wider and perhaps not a very desirable feature. This feature will be discussed later in relation to the observed observation structures. Fig 5(d) shows the equivalent structure for 3D-Var, its vertical correlation reflecting the average of the three OI functions. Note that, in all these structure functions, a positive correlation in wind exists between 30 hPa and 50 hPa which are two forecast model levels. This positive correlation is only true in reality at certain phases of the quasi-biennial oscillation (QBO) as will be shown in the next section.

One of the differences between 3D-Var and OI in the stratosphere is that OI only uses one horizonal scale for all levels in the analysis as shown in Fig 6(a), whereas in 3D-Var the horizontal scale varies as a function of model level, shown in Fig 6(b). Remember that these 3D-Var structure functions are computed from the forecast model itself and the upper level smoothness also reflect the amount of upper level diffusion in the forecast model.

Examples of the influence of stratospheric data at 30 hPa for both the OI and 3D-Var analyses are shown in Fig 7. Figs 7(a) and (c) are the 3D-Var increments and are considerable smoother than the OI increments in Figs 7(b) and (d). Another clear difference between the two analyses can be found in the potential

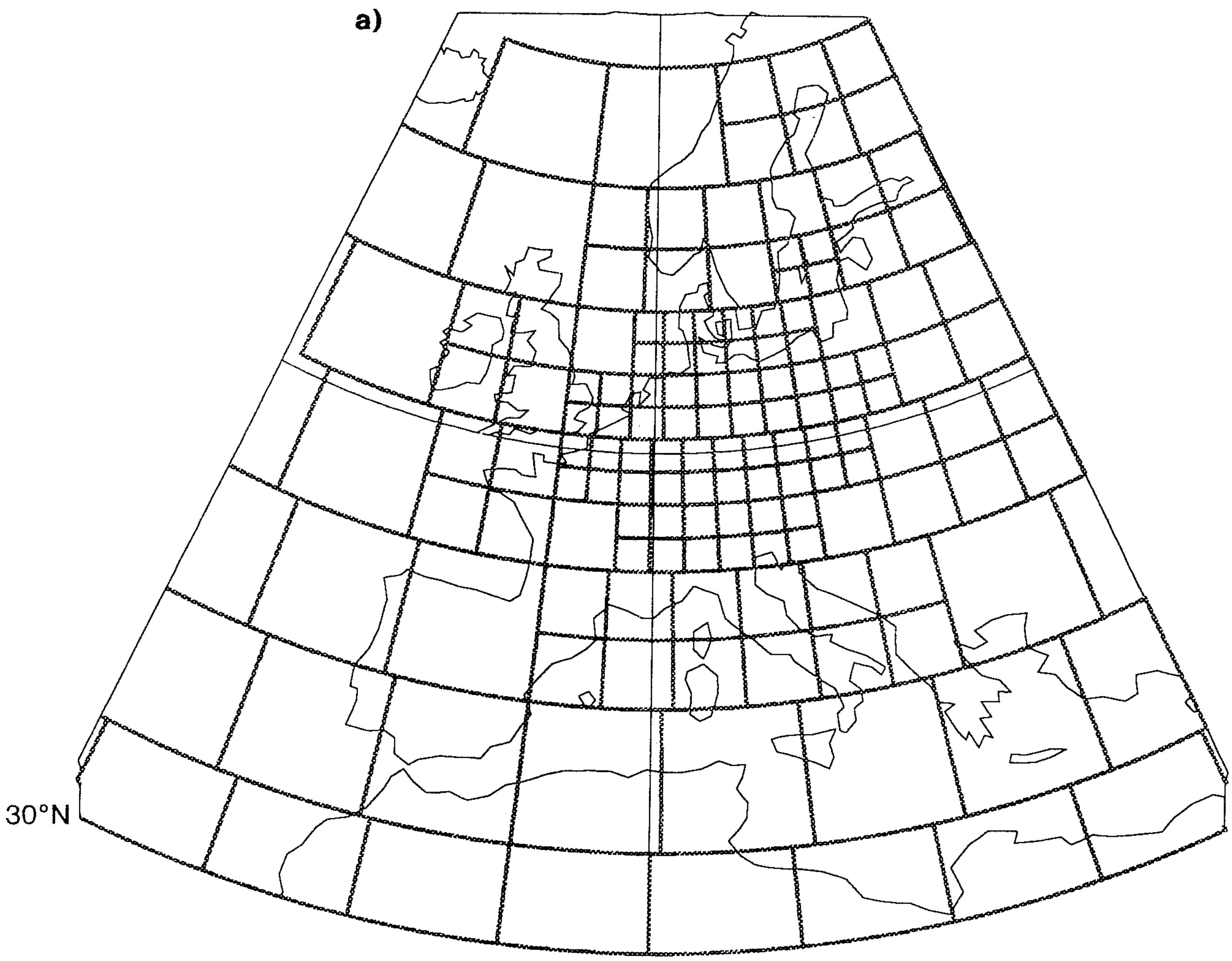


Fig. 4 (a) Analysis box structure

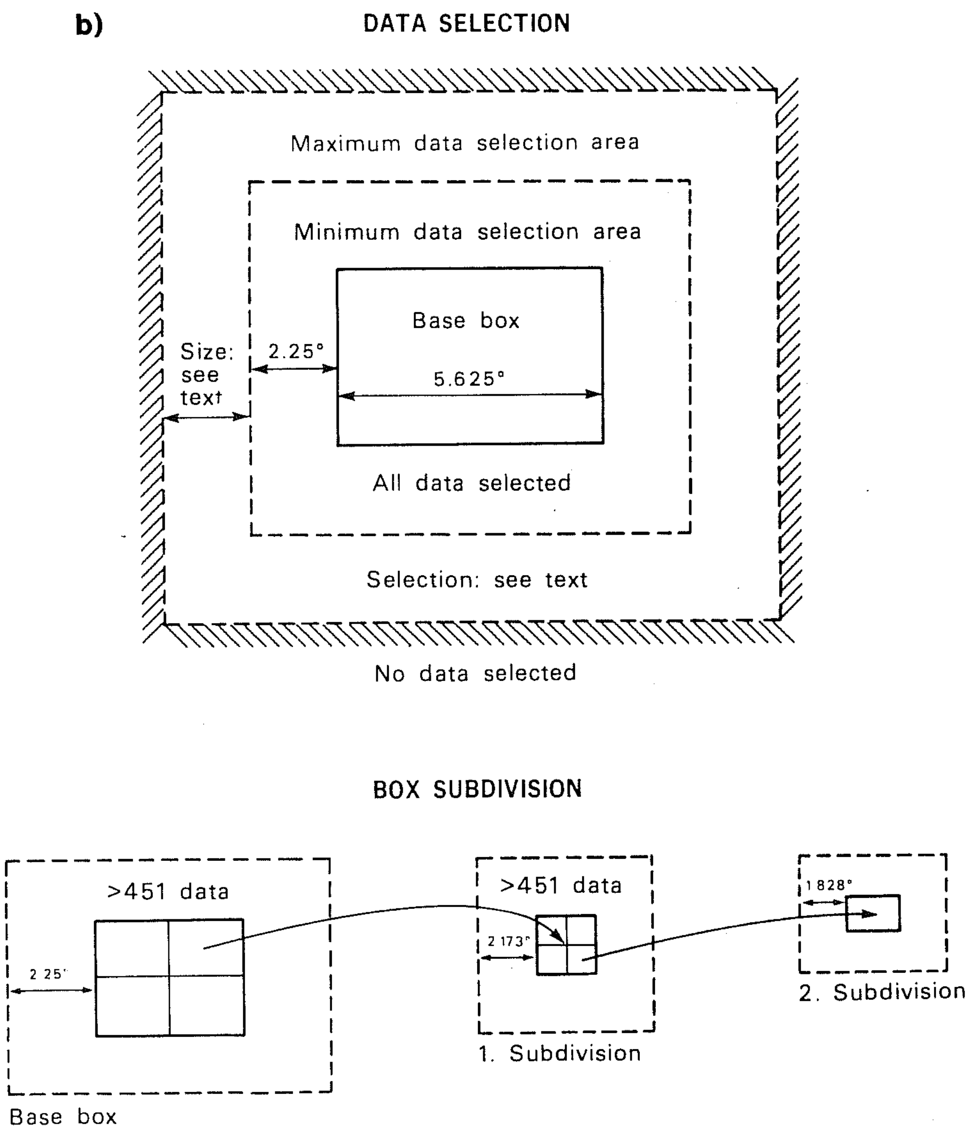


Fig. 4 cont. (b) Subregion associated with an analysis box and the sampling sequence of the regions.

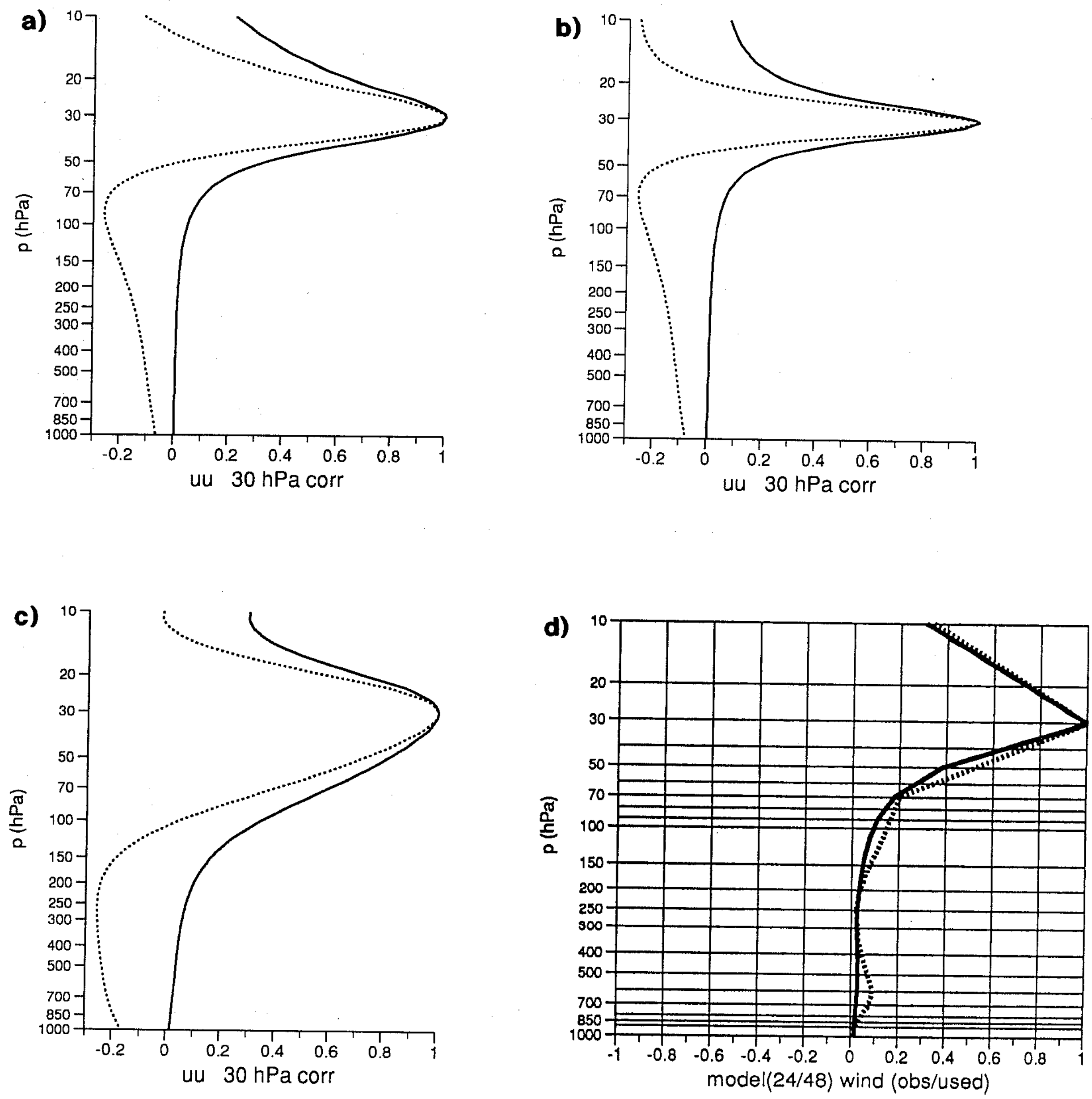
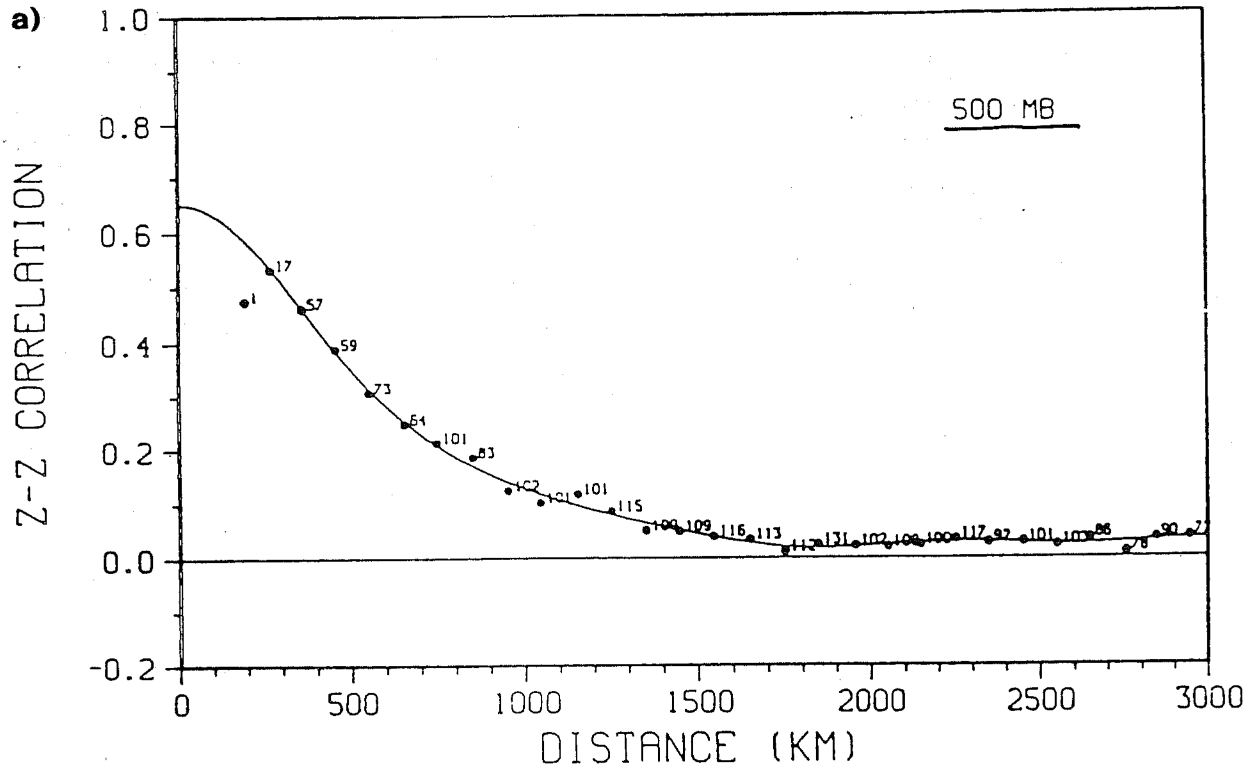


Fig. 5 Vertical correlation structure of forecast error. (a) OI structure function of forecast error for u-u component at 30hPa in the tropics, (b) OI structure function of forecast error for u-u component at 30hPa in the Southern Hemisphere, (c) OI structure function of forecast error for u-u component at 30hPa in the data rich Northern Hemisphere, (d) 3D-VAR global structure function of forecast error for u-u component at 30hPa.



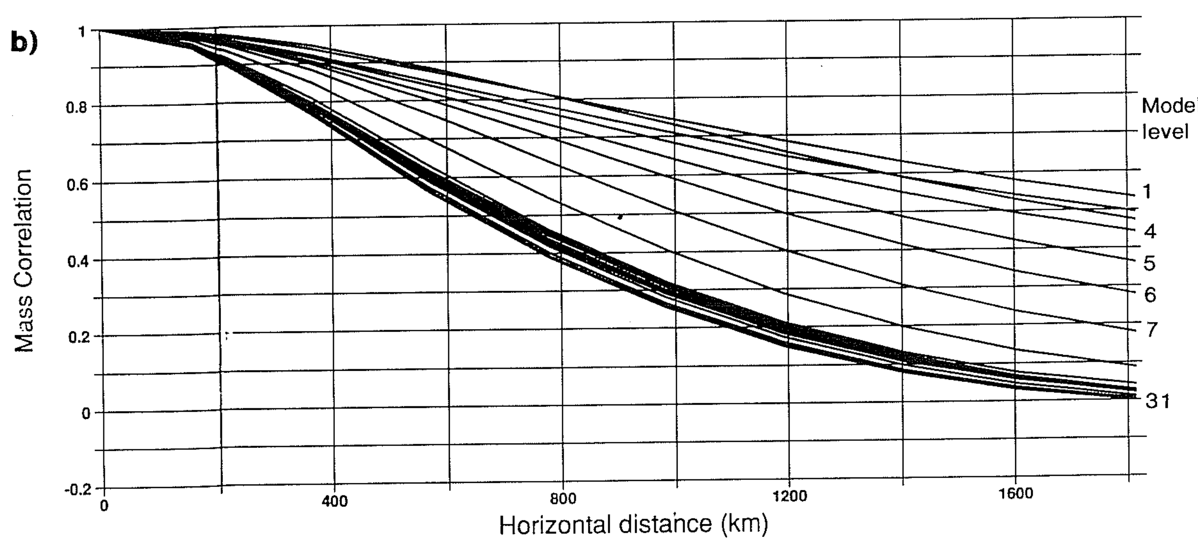


Fig 6 Horizontal correlation structure of forecast error (a) for OI fixed for all levels, (b) for 3D-Var varying for different levels.

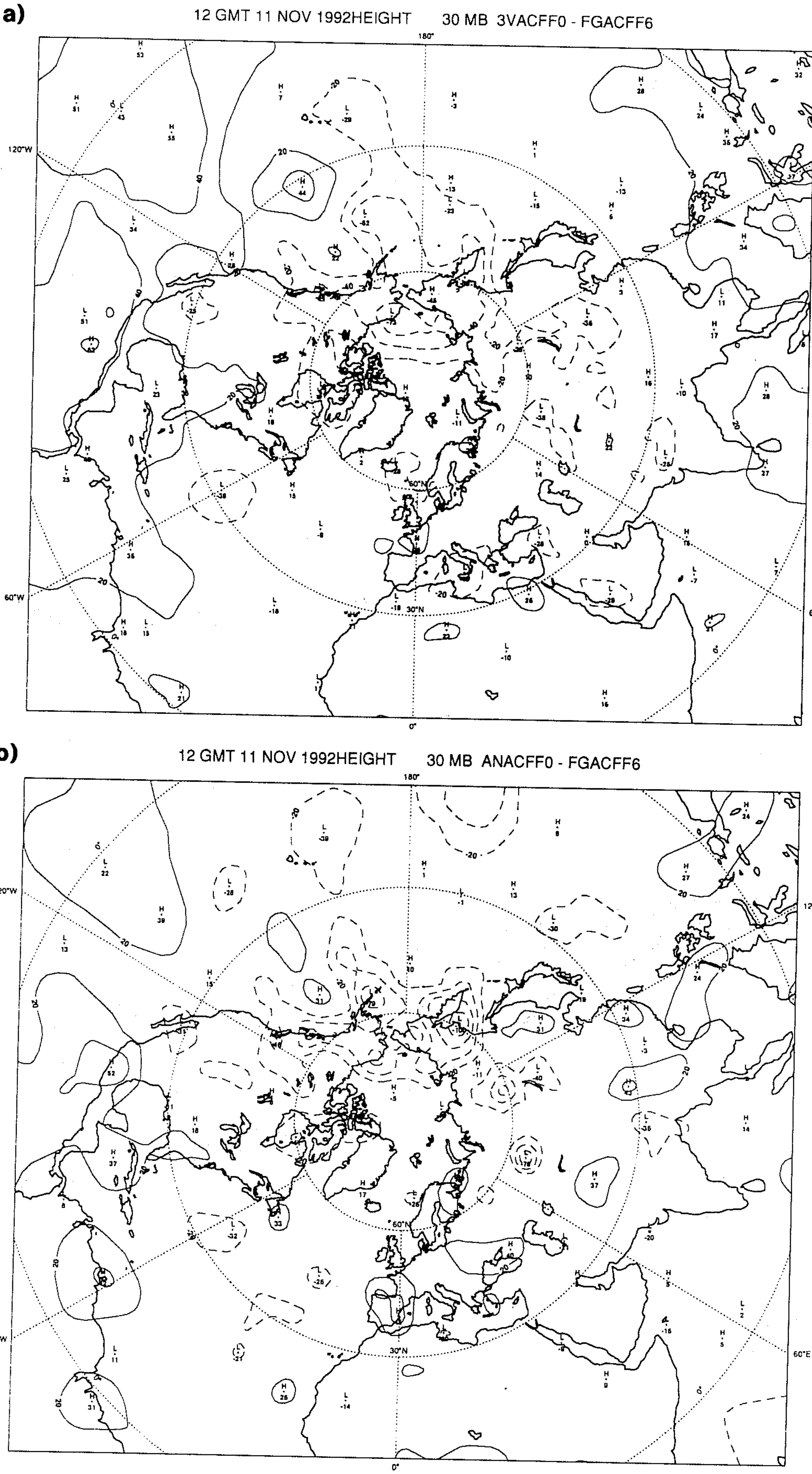
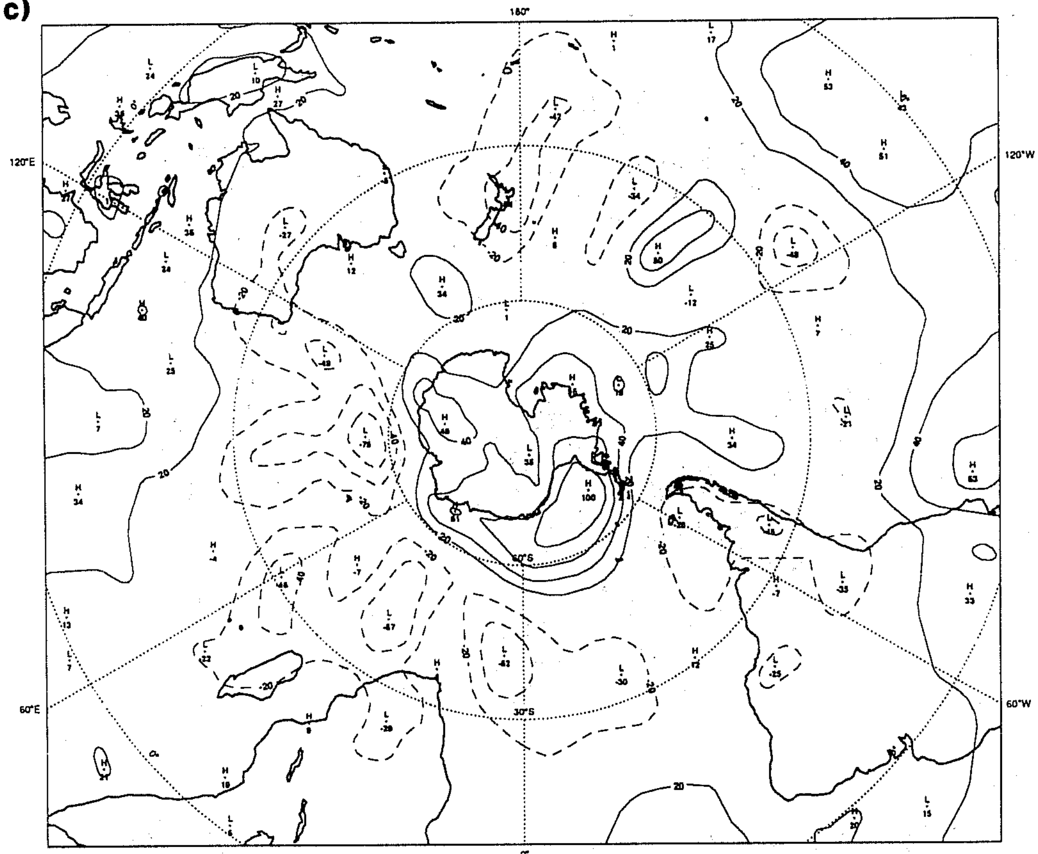


Fig. 7 30 hPa height increments. (a) Northern Hemispheric 3D-VAR, (b) Northern Hemispheric O I.

c)

12 GMT 11 NOV 1992HEIGHT 30 MB 3VACFF0 - FGACFF6



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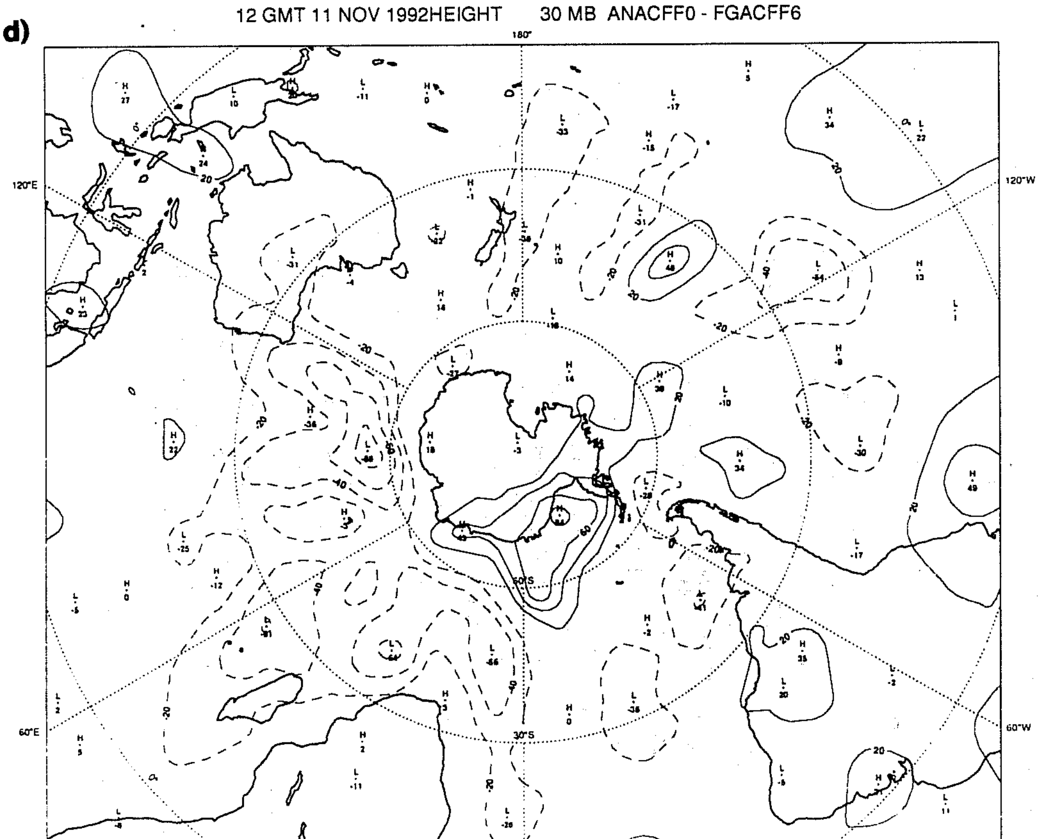
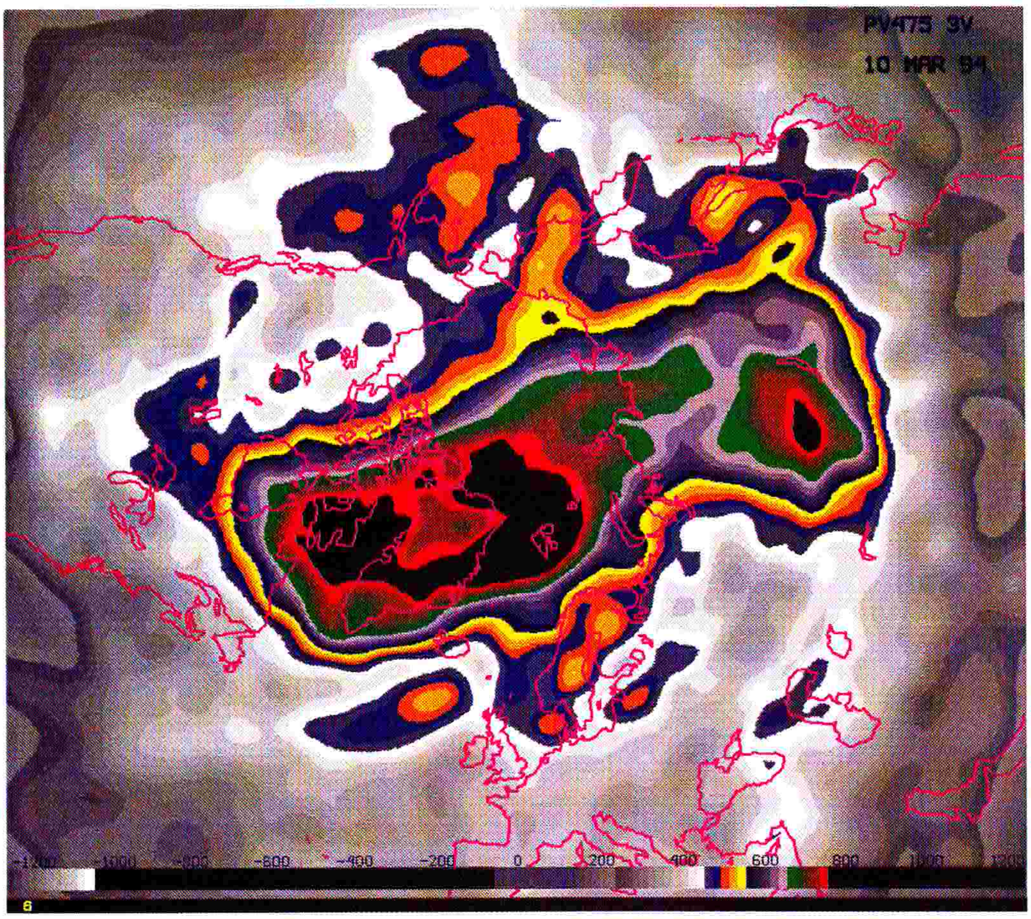


Fig. 7 cont. (c) Southern Hemispheric 3D-VAR and (d) Southern Hemispheric O I.

e)



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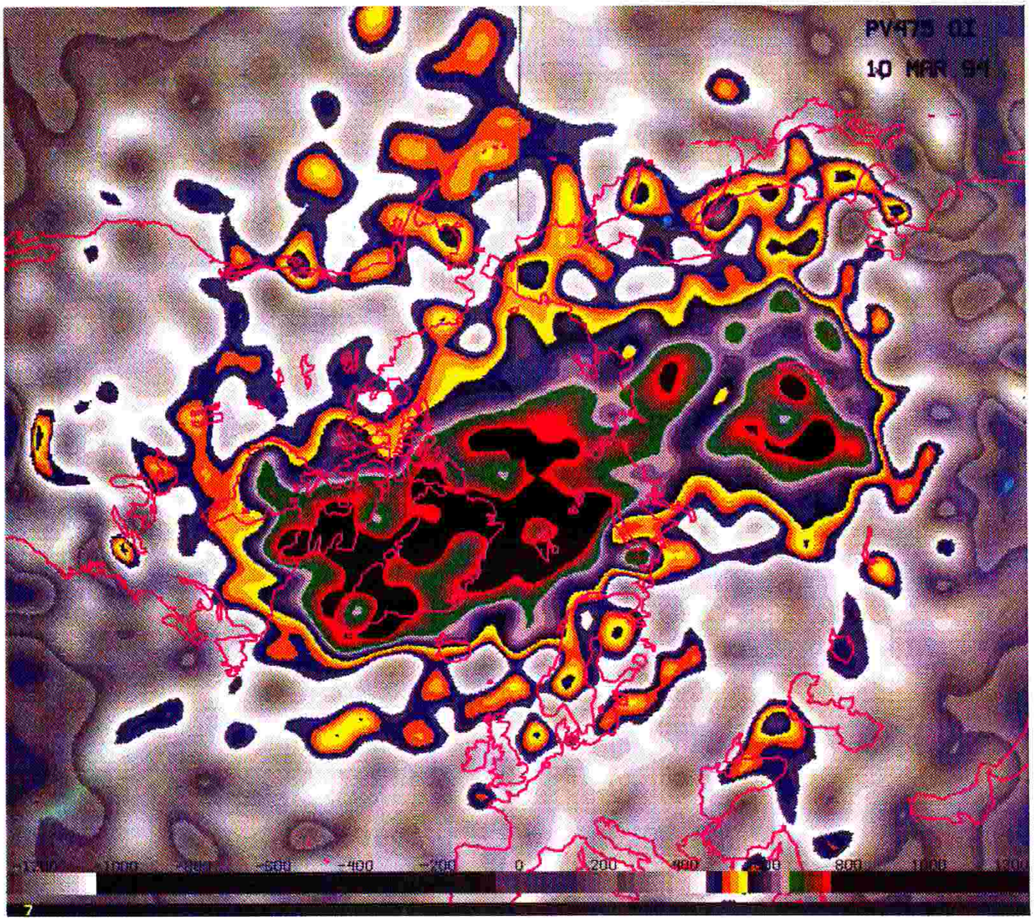


Fig. 7 cont. (e) Northern Hemisphere 3 D-VAR, (f) Northern Hemisphere OI vorticity (PV) maps (see *Hoskins et al*, 1985) computed from each analysis at 475 K (Figs 7(e) and (f)). The 3D-Var PV analysis is much less noisy than the OI PV but still contains the strong gradients across the polar vortex suggesting 3D-Var is a better analysis method.

4. QUASI-BIENNIAL OSCILLATION

Stratospheric radiosonde wind observations in the tropics show a regular wind flow pattern which is very predictable (*Andrews et al*, 1987). The wind direction reverses about every 26 months and there is a lag with height which causes a sharp 180° wind direction change somewhere between 70 hPa and 10 hPa. Fig 8 shows an example of monthly mean winds at Singapore, (*Naujokat*, 1986), together with a vertical wind profile taken from the operational ECMWF monthly mean analysis at 130°E on the equator. In the radiosonde data a 180° wind direction change often occurs over 10 hPa layer, and it is difficult to capture this in the analysis since the model only has four levels above 100 hPa. The analysis problem is even more difficult as most radiosonde winds fail to reach 10 hPa (see Fig 1), and the forecast error structure functions are used to spread the data upwards. These structure functions do not take into account the phase of the QBO. This often explains the poor correspondence between the ECMWF analysis and observations at 10 hPa. At other levels the analysis and observations are in more reasonable agreement with the Singapore time section.

5. SOUTHERN HEMISPHERIC POLAR VORTEX OF NOVEMBER 1992

In order to look at the time and space consistency of the OI analysis, a series of 12 UTC daily PV maps at 475° K are shown in Fig 9(a) - (g). The large synoptic features can be easily followed from day to day. The stratospheric vortex is generally intact and moves like an elastic membrane with occasional extensions associated with the sheering off of high PV blobs usually associated with tropospheric cut-off lows. It can be also be seen by comparing Fig 4(e) (Northern Hemisphere OI) with Fig 9(a-g) (Southern Hemisphere OI) that there is far less noise in the Southern Hemisphere. This is due to the lack of Southern Hemispheric radiosonde data. The Southern Hemispheric upper-air analysis is based almost entirely on TOVS data. Another interesting comparison can be made with Fig 9(h), a 24 hour forecast, valid at the time of Fig 9(e). One can now see a general correspondence of major features but the forecast is much smoother.

By comparing PV at other levels one can see atmospheric scales varying with height. Fig 10(a) is a repeat of Fig 9 (e) at 425° K at about 70 hPa. As you move higher to 475° K (approx. 30 hPa) the polar vortex is more intact, but down near the tropopause the PV pattern is more complex and begins to be associated with the synoptic systems of the troposphere.

6. PROBLEMS WITH THE USE OF RADIANCES IN THE POLAR VORTEX

The current operational OI analysis uses NESDIS TOVS retrievals in the Southern Hemisphere and above 30 hPa and in the Northern Hemisphere. The 1D-Var method is used in the Northern Hemisphere below 30 hPa (*Eyre et al*, 1993).

A series of experiments have been carried out to test extending the use of 1D-Var. A number of unexplained problems have occurred in the stratosphere. Fig 11(a) shows a comparison of Southern Hemispheric radiosondes south of 40°S and the OI analysis using 1D-Var. There is clearly a very large bias and rms difference in the stratosphere. A similar comparison is shown Fig 11(b) for the current operational system using NESDIS TOVS profiles. The operational system has much better statistics with the exception of the 30-20 hPa layer. The model has levels only at 30 hPa and 10 hPa and one should combine both these

a)

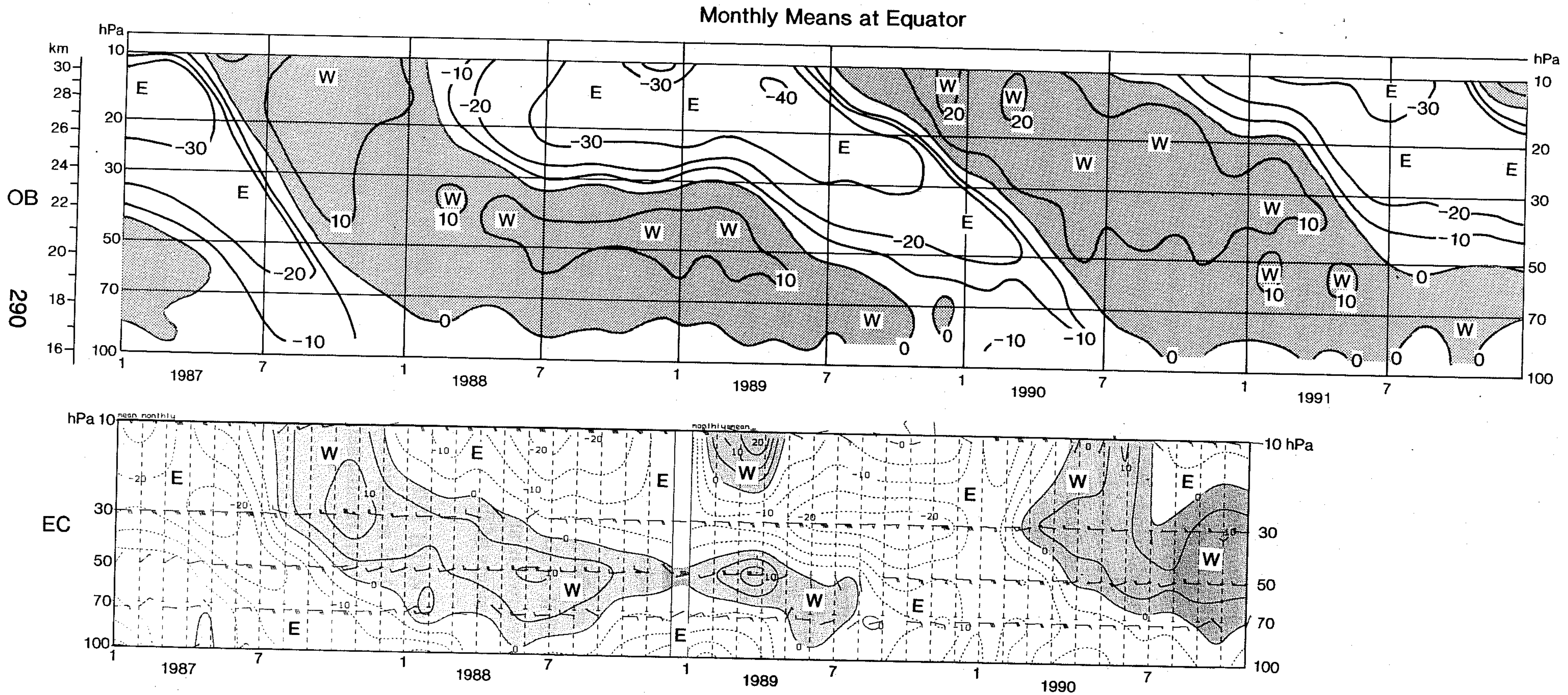


Fig. 8 (a) Stratospheric monthly mean zonal wind time sections. Top: Singapore 0°N 130°E from 1987 to 1991. Bottom: Operational ECMWF analysis at the equator at 130°E.

b)

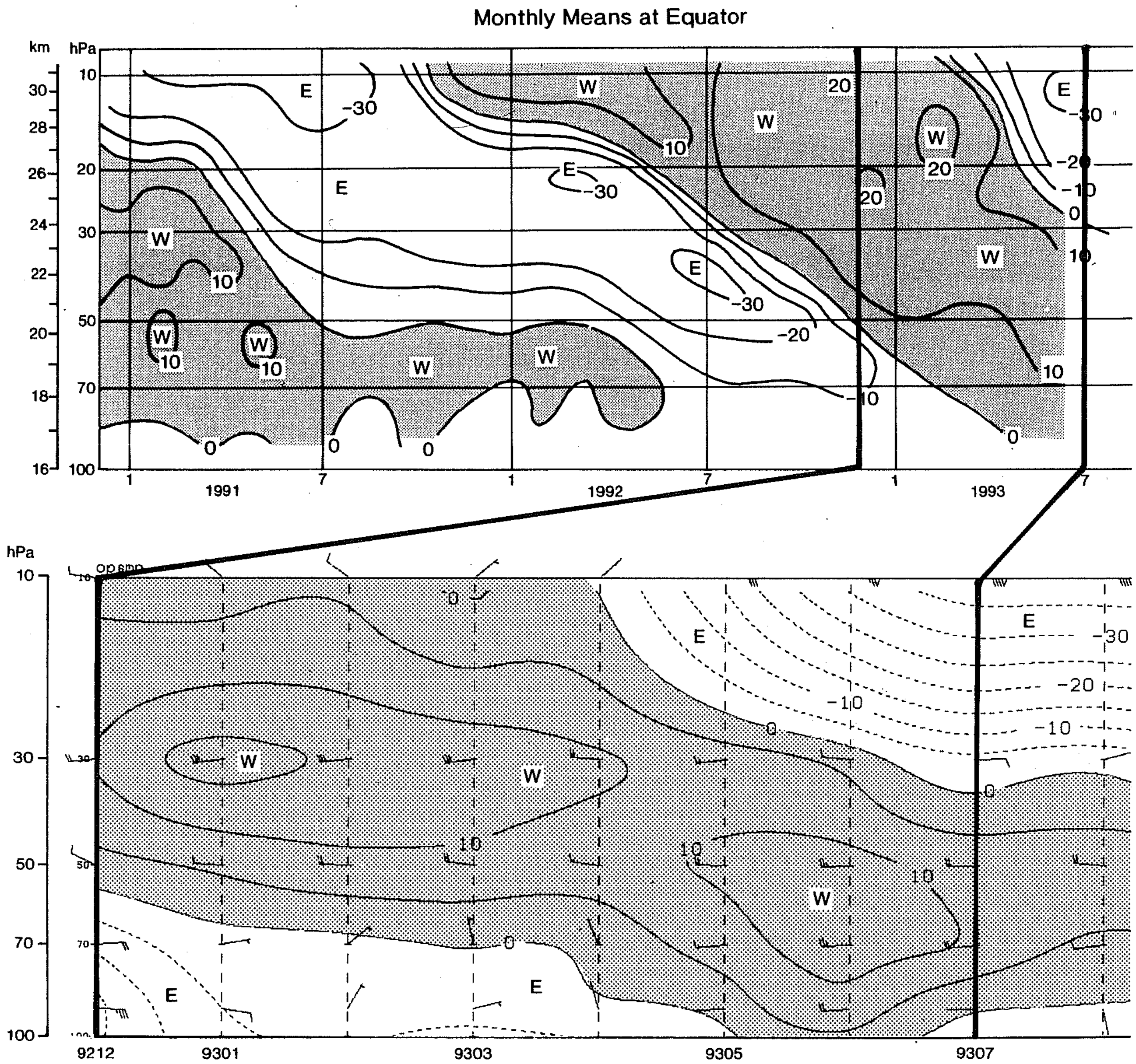


Fig. 8 cont. (b) Similar sections to (a) from December 1992 to July 1993.

a) c) b) d)

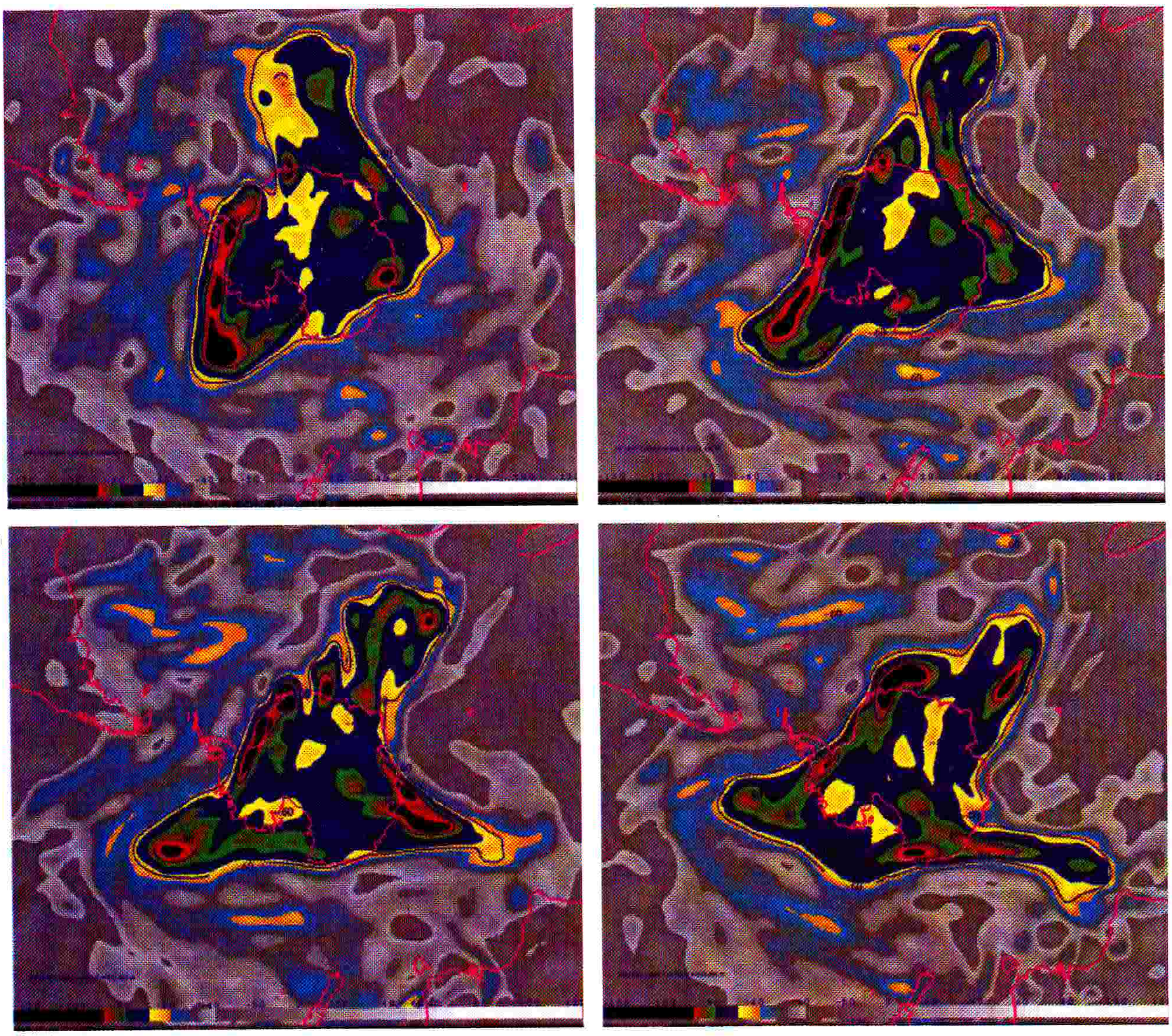


Fig. 9 Potential vorticity calculated on the 425°K surface. (a)-(g) Daily operational ECMWF analyses from 19-25 November 1992 and (e) 24 hour ECMWF forecast valid for 23 November 1992.

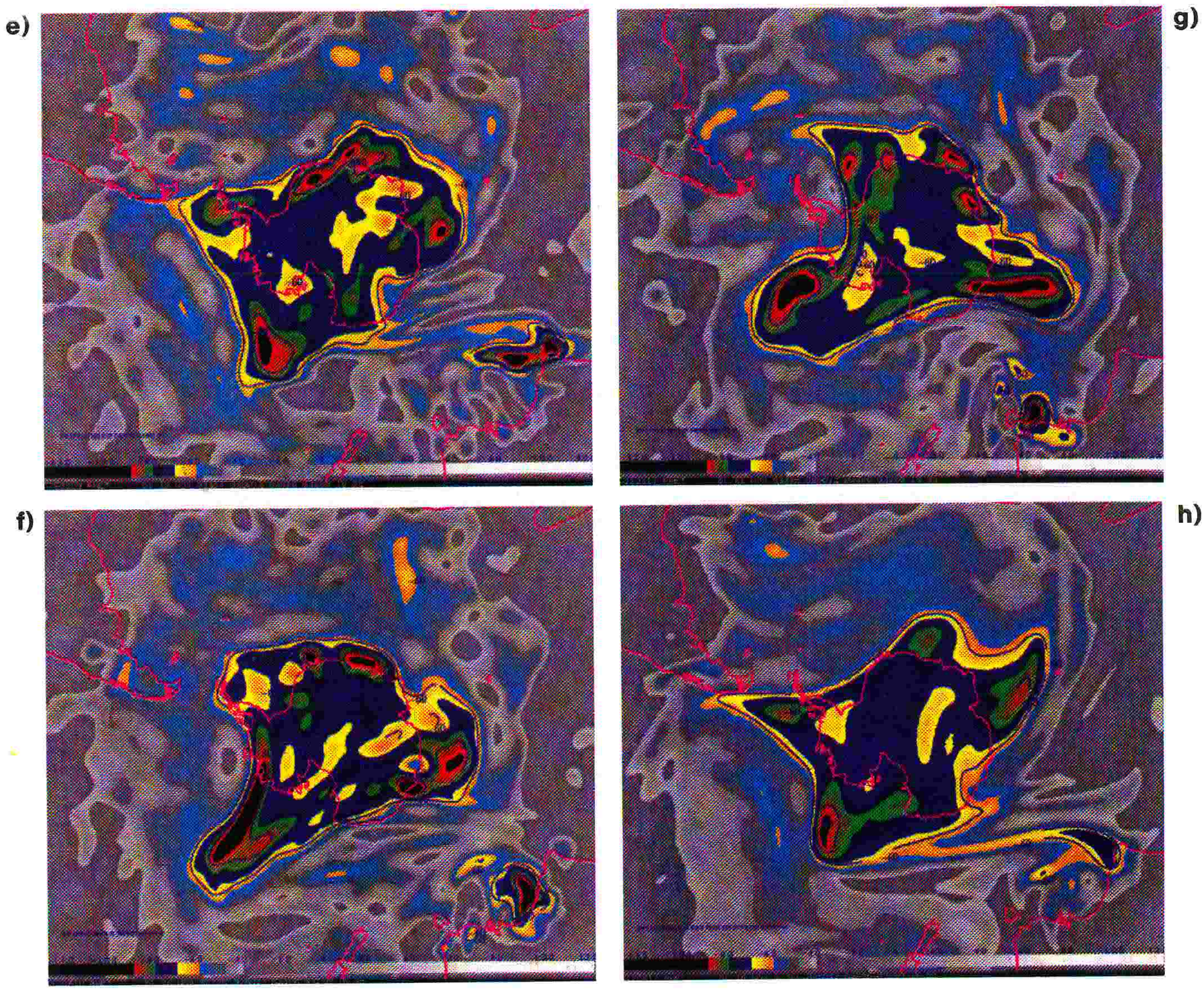


Fig. 9 cont. e),f),g) and h)

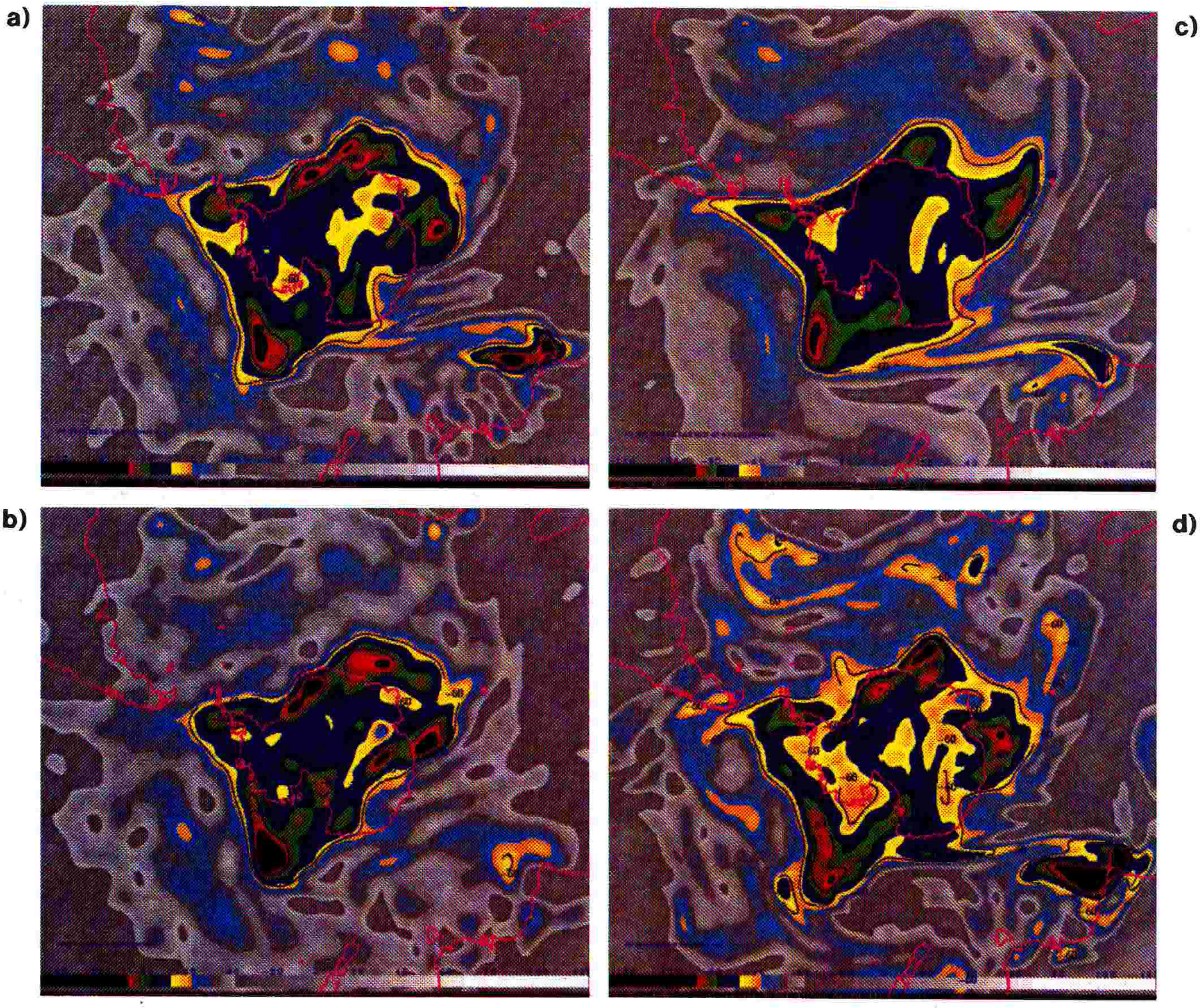


Fig. 10 Potential vorticity for 23 November 1992. (a) Operational ECMWF analysis 325°K surface, (b) Operational ECMWF analysis 425°K surface, (c) Operational ECMWF analysis 475°K surface, (d) Operational ECMWF 24 hour forecast 425°K surface.

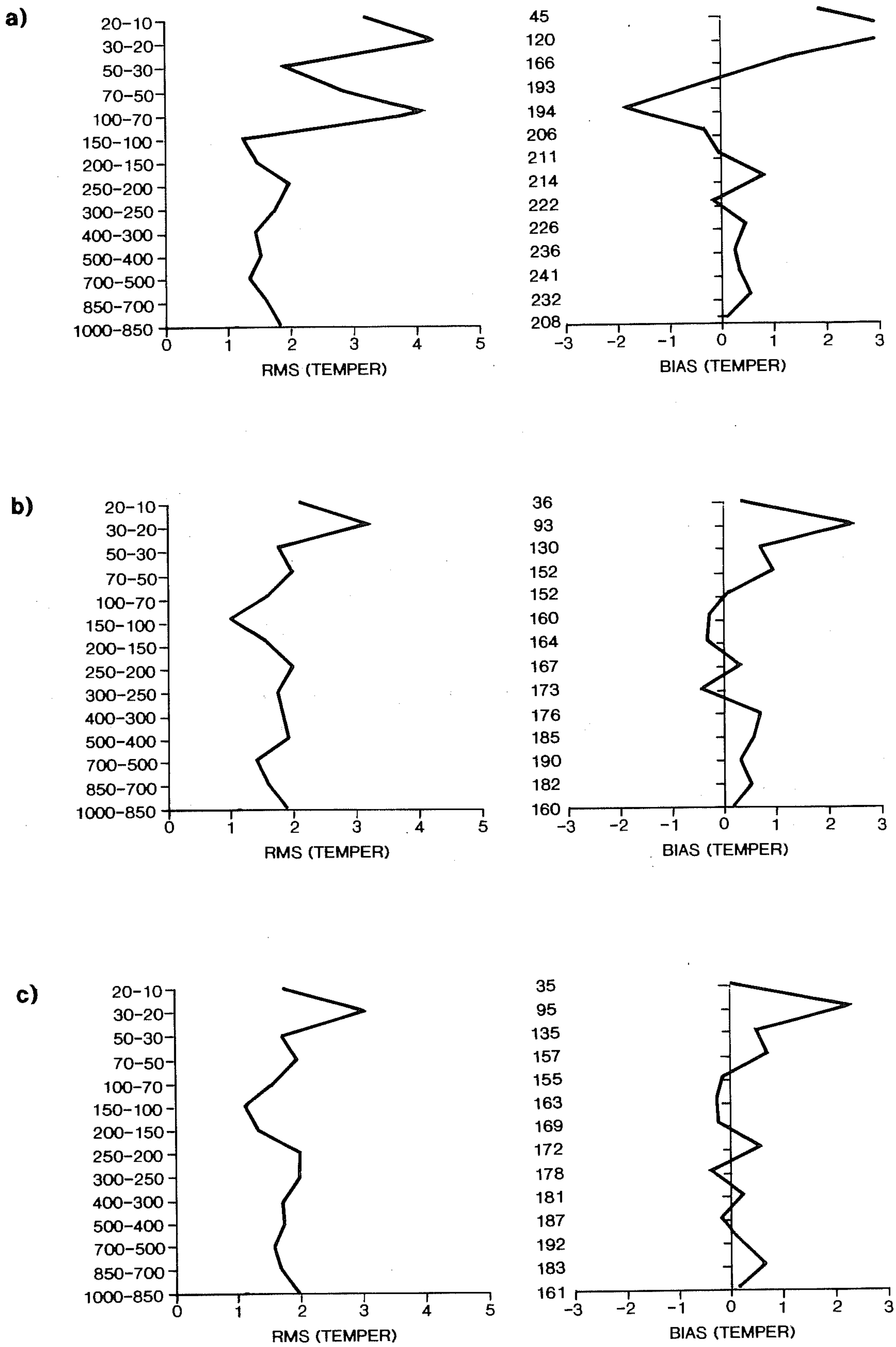


Fig. 11 Mean RMS temperature differences between 6 hour forecasts and Southern Hemispheric radiosondes for November 1992, lat 40°S-90°S. (a) 1D-VAR TOVS used in the analysis, (b) NESDIS TOVS used in the analysis, (c) 1D-VAR TOVS used below 100 Hpa and NESDIS TOVS above.

top levels for a true comparison. Fig 11(c) show the results of combining the use 1D-Var in the troposphere (below 100 hPa over sea) with NESDIS TOVS elsewhere. These results are similar to the operational configuration in Fig 11(a).

Initially it was thought that the problem with 1D-Var was only associated with retrievals over Antarctica because of the low surface temperatures and, in some places, high terrain. The 70 hPa temperatures fields from the two experiments indicate large differences (Figs 12 and 13(a)) occur in the polar regions. Stratospheric PV was computed for this situation and it was noted that the 70 hPa temperature difference pattern showed a similar pattern to the PV, as shown Fig 13.

Some vertical profiles were then plotted for the three locations indicated on Fig 13(b) from the 1D-Var and NESDIS TOVS analysis (after four days of data assimilation). One profile set, Fig 14(a), was plotted inside the polar vortex over sea and away from any radiosonde stations. On this plot there are two pairs of profiles, the NESDIS pair include the short range forecast and a 1D-Var profile using this NESDIS guess with the observed radiances. The closeness of these profiles indicates the 1D-Var retrieval and the observed radiances are in general agreement. On the other hand the second profile pair, obtained from the full use of 1D-Var actively during the assimilation both show a very unusual stratospheric structure, a strong inversion between the stratospheric model levels. This unrealistic structure has developed mysteriously during the active 1D-Var data assimilation. What is also strange is the observed radiances appear blind to this structure because the difference between the 1D-Var retrieved profile and the guess is small.

A similar set of profiles, Fig 14(d), is shown near an Antarctic radiosonde station Casey (89611). This station is also plotted separately in order to see its stratospheric structure. The OI analysis in the stratosphere has tried to draw somewhere between the strange inversion, present in the guess and the radiosonde. The result is there is the same stratospheric feature but its amplitude is weaker. The analysis in this region is more constrained by the radiosonde. If one now moves out of the polar vortex, Fig 14(b) there is now much closer agreement between the two data assimilation.

The use of TOVS radiances in 3D-Var has also showed similar problems in the southern polar region for this period.

7. PROBLEMS WITH THE USE OF RADIANCES IN THE TROPICAL STRATOSPHERE

The horizontal wind in the tropical stratosphere is very stable and only varies on a relative long time scale as discussed in section 4. Fig 15(a) shows Yap Island for six days. Between 100 hPa and 50 hPa there are 30 to 40 knot easterlies and above there are 20 to 30 knot westerlies, and this persists for the period. A similar cross-section is shown for Singapore, Fig 15(b). It is unfortunate that winds received on the GTS do not often reach 30 hPa. On the other side of the equator and in the same tropical flow regime the Darwin time section, Fig 15(c), shows a very similar wind flow to Yap Island. The observed temperature is also very slowing varying in time in the lower stratosphere except for a small diurnal tidal component.

Currently in operations no 1D-Var or NESDIS TOVS are used in the tropics. The TOVS measurements are good at measuring tropospheric moisture and it was also felt that TOVS should improve the tropical stratospheric temperatures. The data assimilation experiments described above in section 6 will be examined in the tropics. The measure of skill for these experiments will be a comparison of the short range forecast, usually six hours, with radiosonde data in the tropical region 10°N to 10°S, 80°E to 180°E.

a)

b)

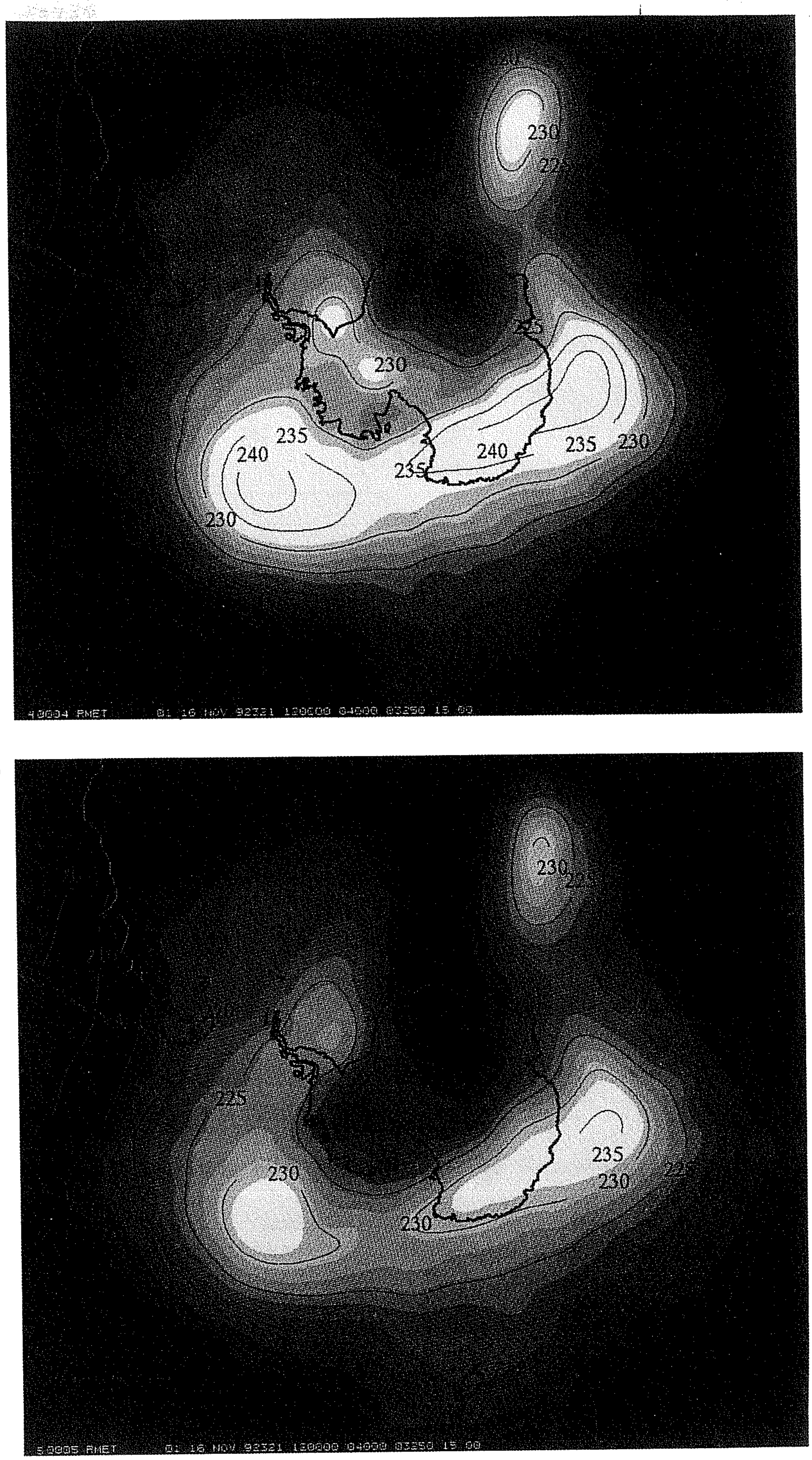
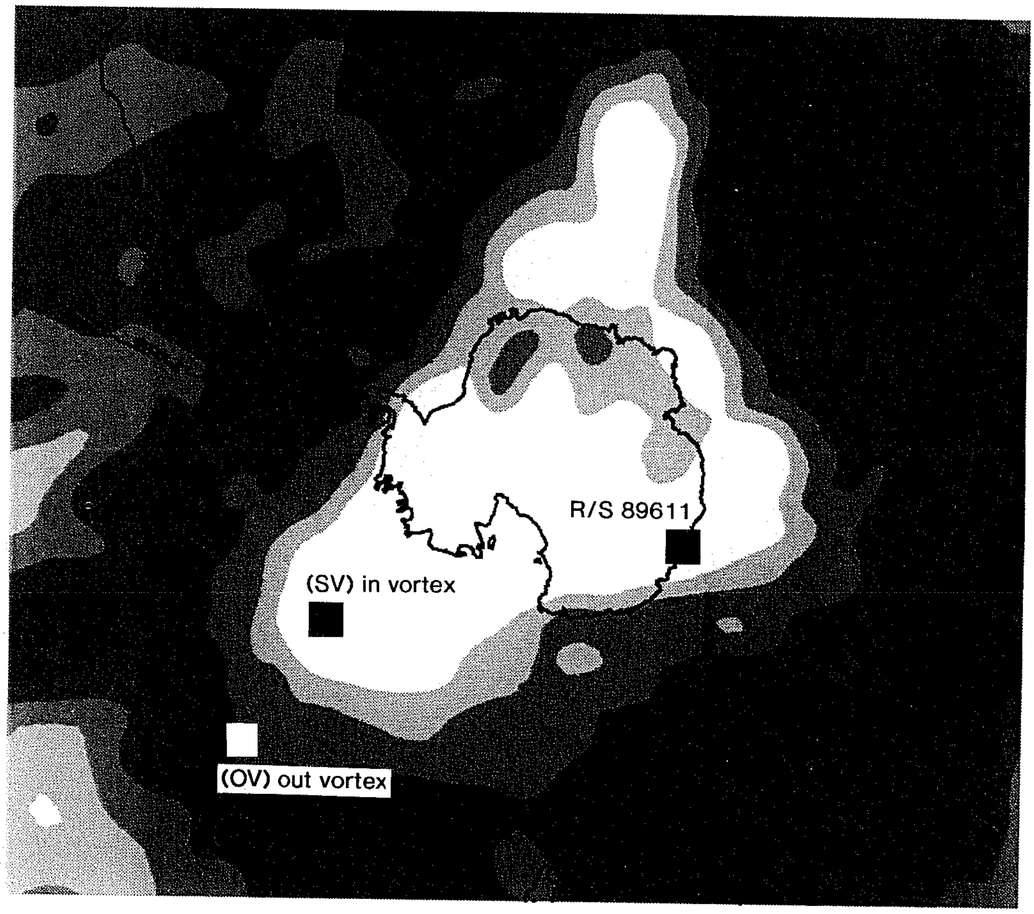


Fig. 12 Southern Hemispheric 70 hPa temperature for 16 November 1992. (a) 1D-VAR analysis, (b) NESDIS analysis.

a)



b)

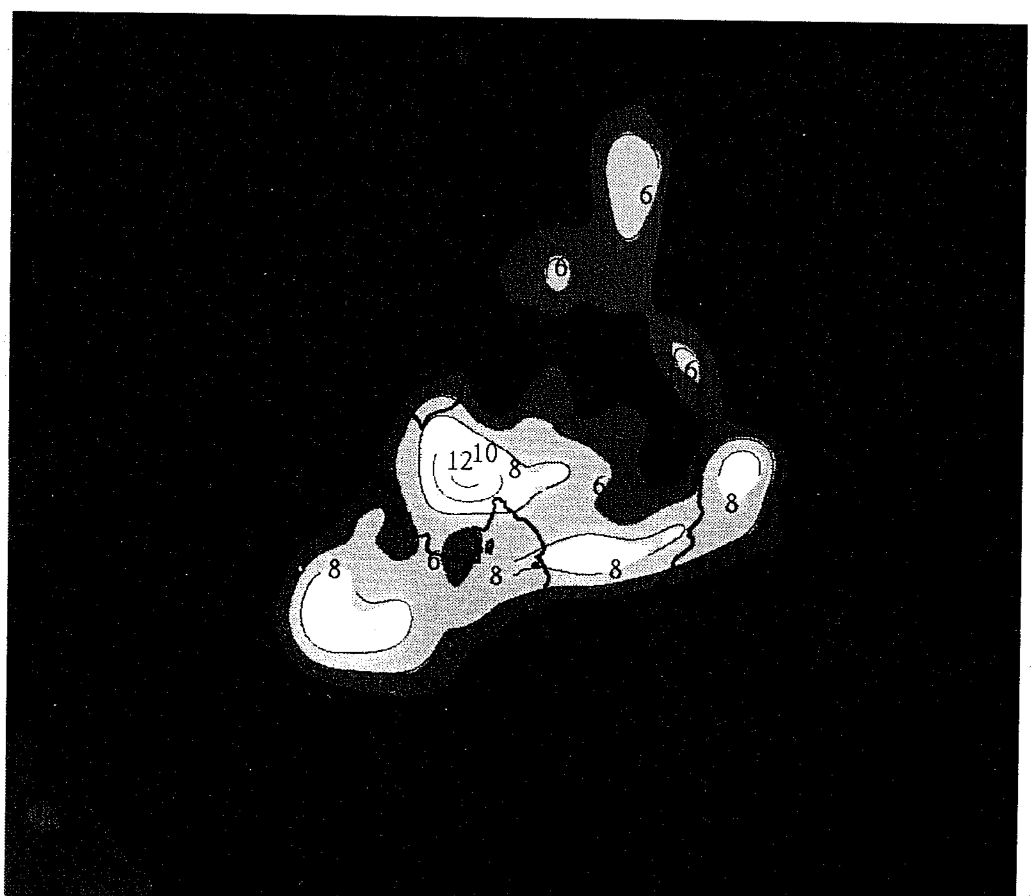


Fig. 13 (a) 70 hPa difference of 12(a) and 12(b), (b) 425°K potential vorticity calculated from the 1D-VAR analysis of 12(a).

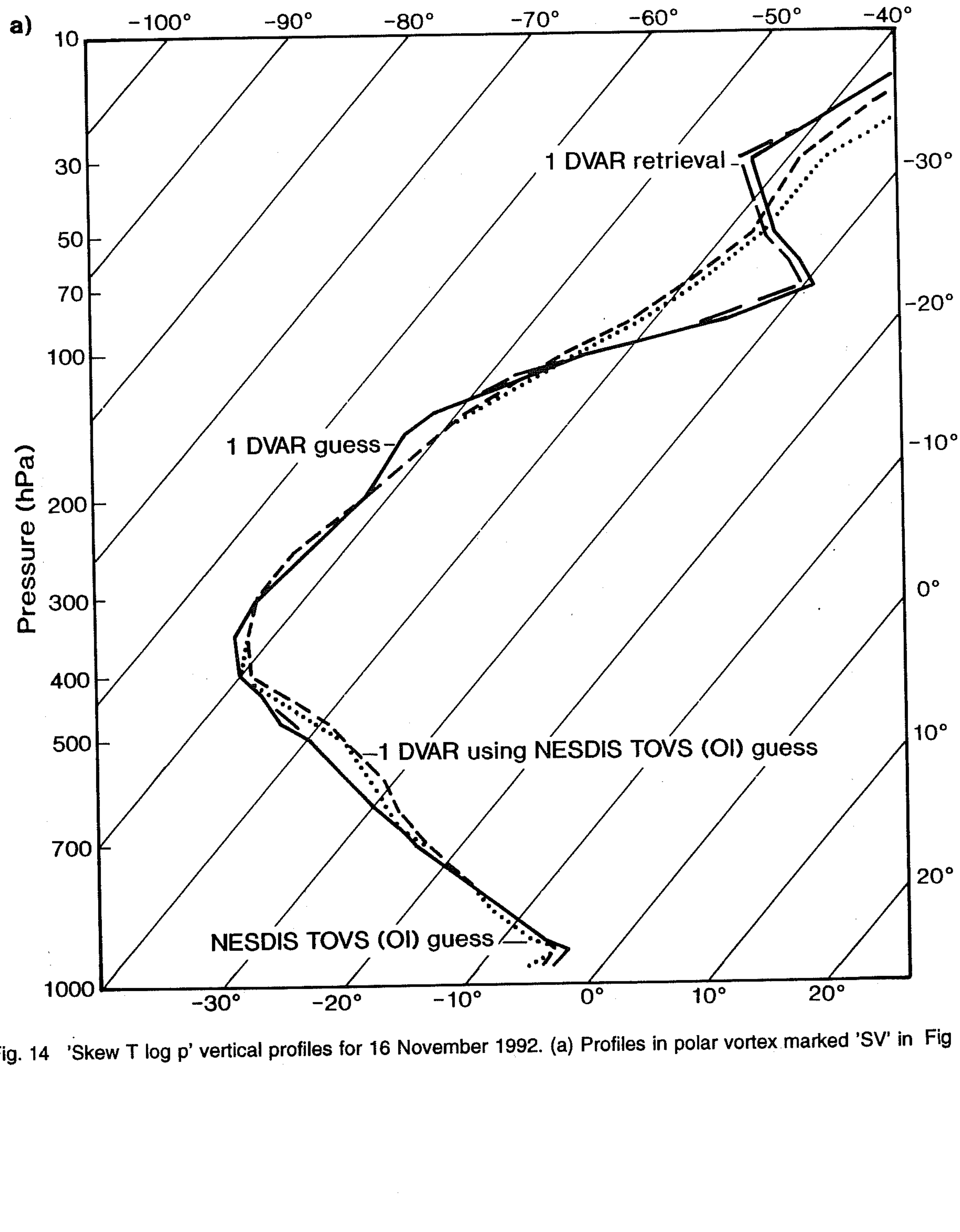


Fig. 14 'Skew T log p' vertical profiles for 16 November 1992. (a) Profiles in polar vortex marked 'SV' in Fig 13(a).

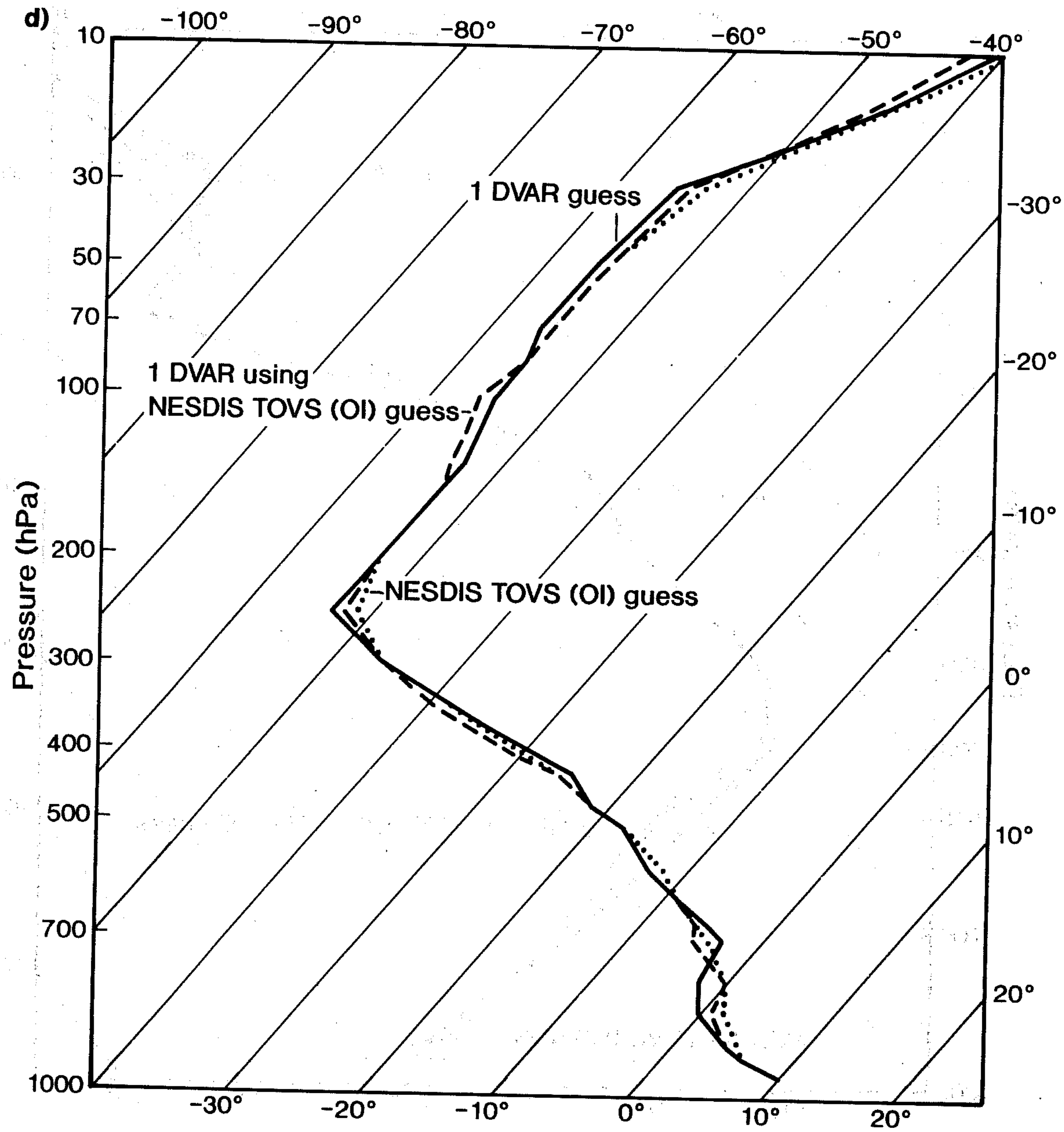


Fig. 14 cont (b) Profiles outside polar vortex marked 'OV' in Fig 13(a).

c)

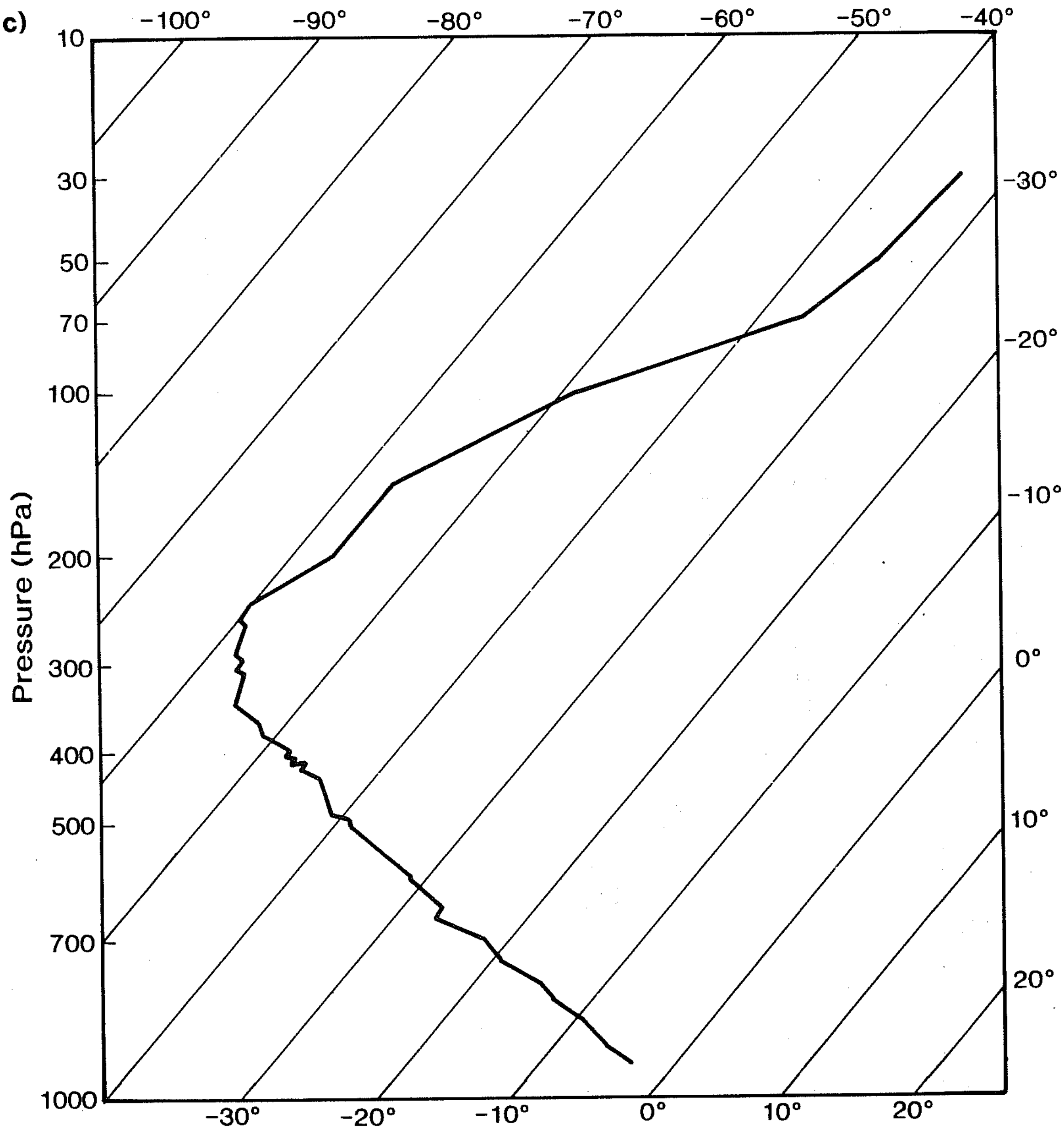


Fig. 14 cont. (c) Antarctic radiosonde profile station (Casey, 66°S-110°E) number 89611 shown in Fig 13(a).

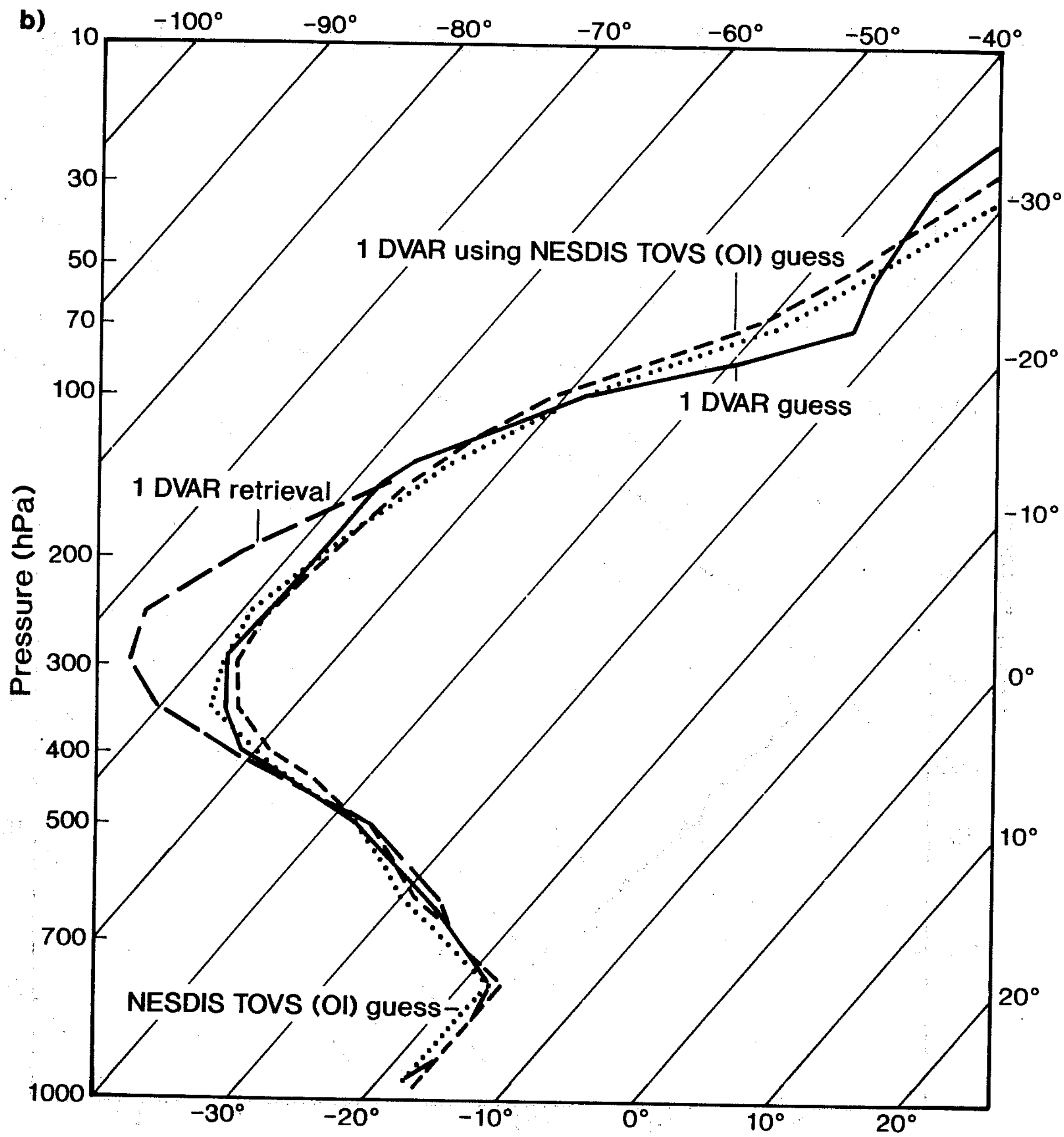


Fig. 14 cont (d) Profiles near radiosonde station 89611.

c)

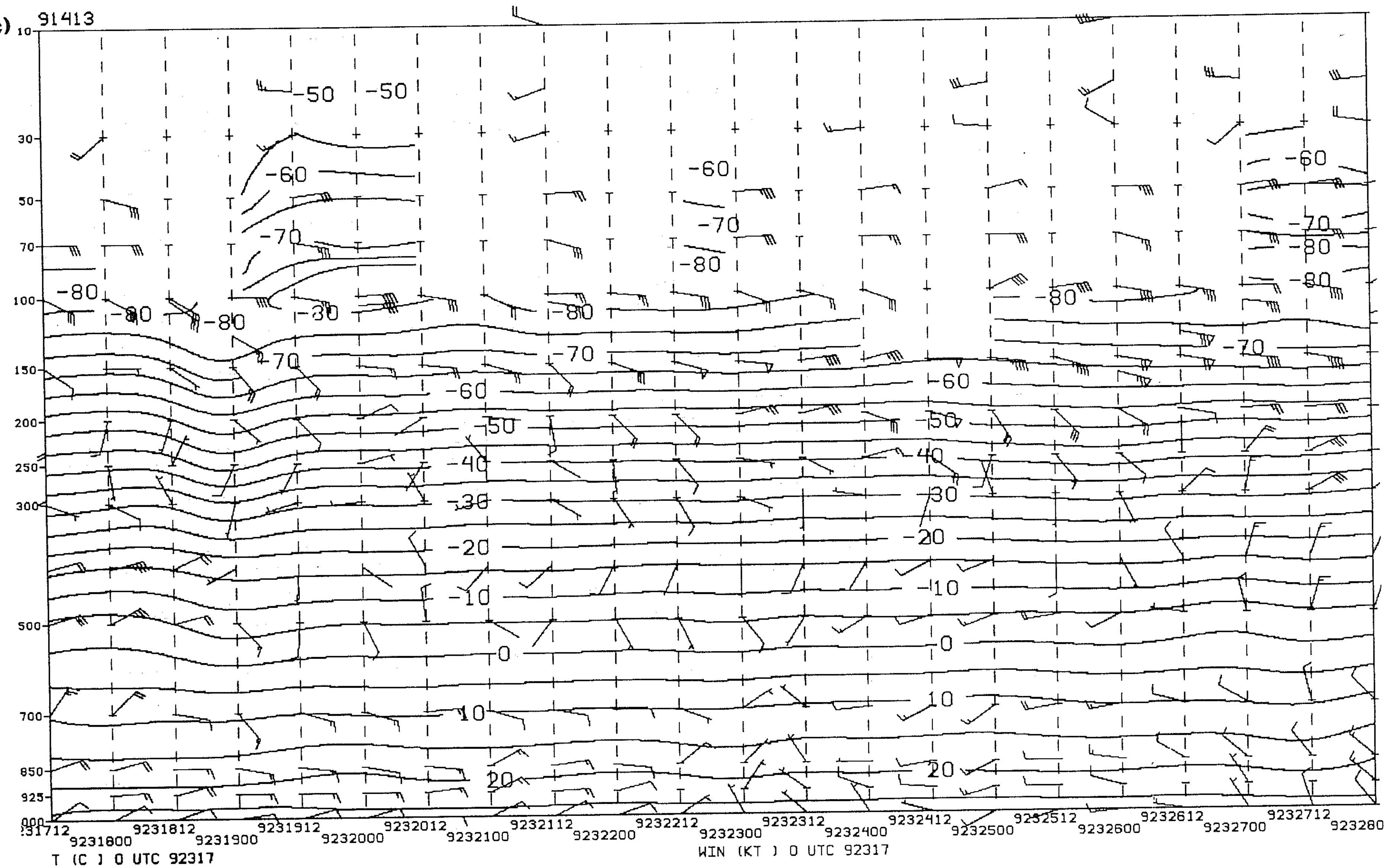


Fig. 15 Temperature and wind time sections from 921116 to 921122. (a) YAP Island 9°29'N 138°05'E.

b)

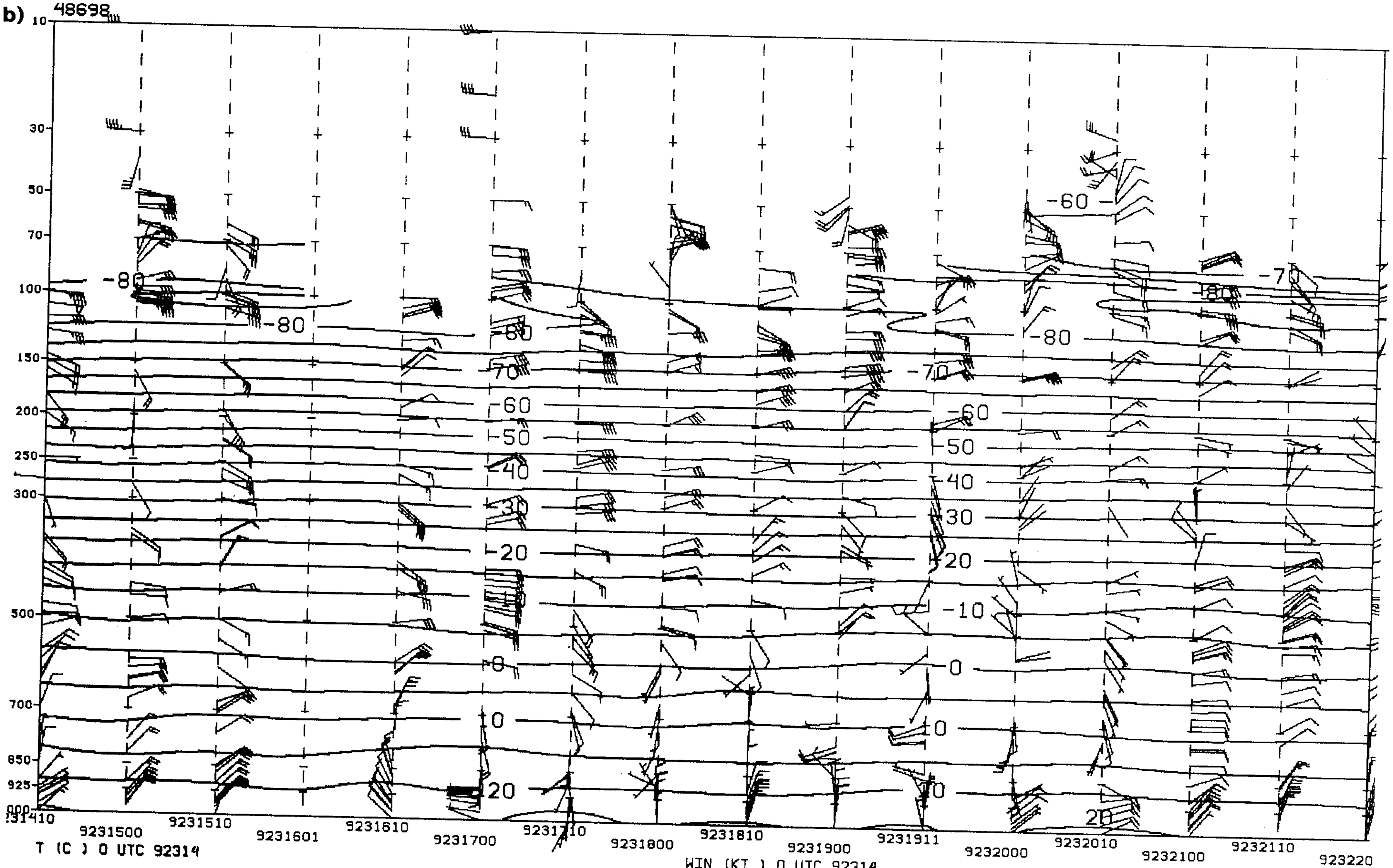


Fig. 15 cont. (b) Singapore 1°22'N 103°59'E.

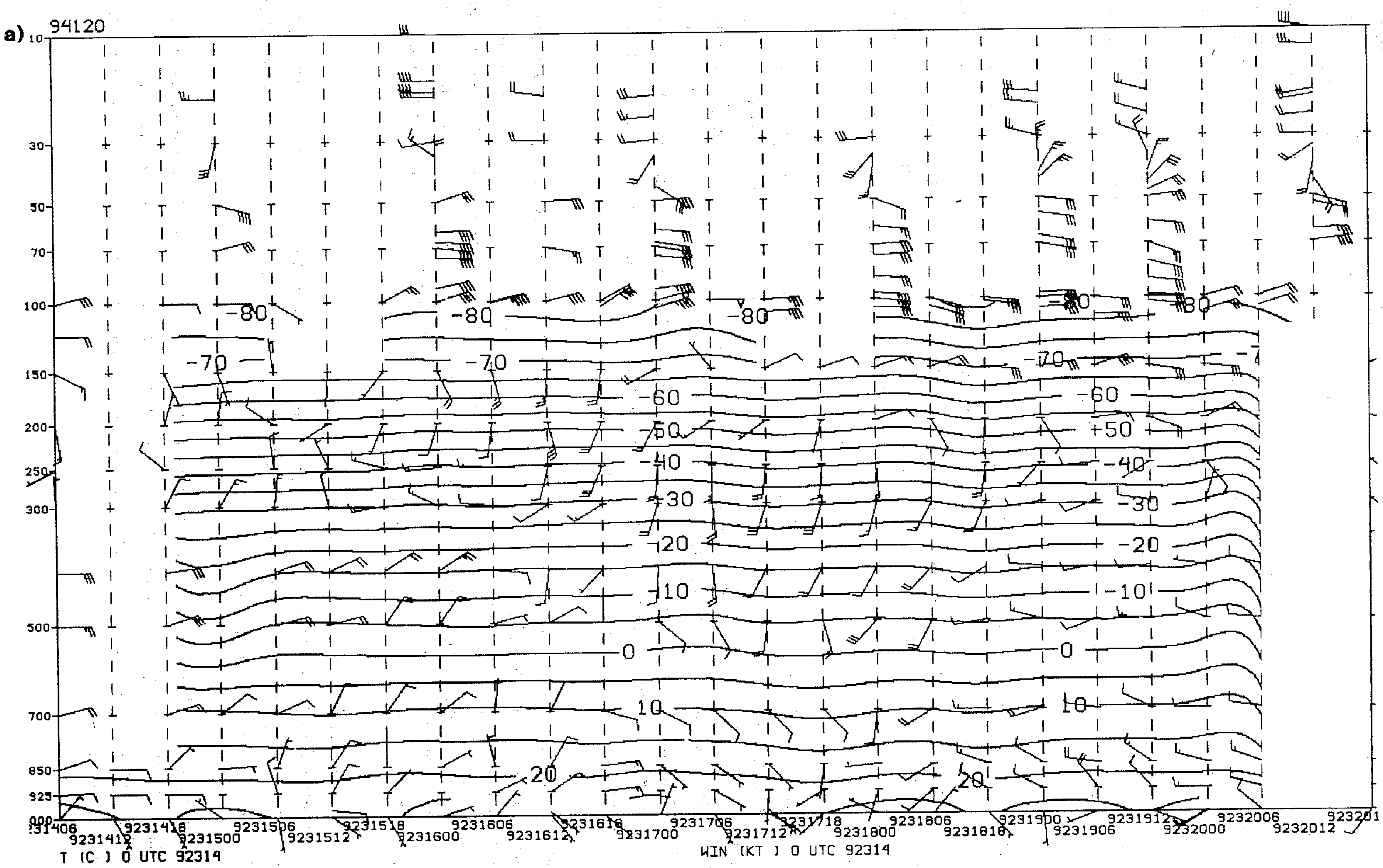


Fig. 15 cont. (c) Darwin 12°24'S 130°52'E .

Fig 16(a) show the results of the first 19 level experiment using 1D-Var fully in the tropics. There is a strong bias pattern at about 250 hPa (positive) and a negative bias about 70 hPa, the bias at 20 hPa is less important as it is not at a model level. This bias pattern is clearly larger that the current operational results, Fig 16(e). This experiment was repeated using 31 levels, which is more like operations, but the results in Fig 16(b) show only slight improvements. A further 19 level experiment was run combining NESDIS TOVS above 100 hPa with 1D-Var below, Fig 16(c). This experiment still contained a bias problem. Finally a 3D-Var experiment using TOVS radiances also shows the same characteristic problem with bias.

A study has been made of the growth of this bias problem. Fig 17(a) shows two profile time series taken at the equator at 130°E from the 1D-Var and the control experiment. The stratospheric temperature bias appears after six to twelve hours of assimilation and then remains almost constant throughout the rest of the experiment.

A single time series, taken at the same location as above, has been plotted in Fig 17(b) for the 3D-Var experiment. This time section now contain winds and temperatures. After about two days of assimilation a strong temperature and wind oscillation is observed in the stratosphere which is not supported by observations (Fig 15). This problem does not always occur in either 1D-Var or 3D-Var. Similar time sections have been taken from other experiments in September 1993 and did not exhibit the same bias or oscillation.

8. PROBLEMS WITH THE FORECAST MODEL IN THE TROPICAL STRATOSPHERE

Given the problems found in the data assimilation it was decided to look at the 10 day forecast in the same way as the analysis. The model version was cycle 47 using 31 levels at T106. A time section starting at 12 UTC on 16 November 1992 at the equator and 130°E is shown in Fig 18(a). The lack of vertical stratospheric resolution is clearly seen by looking at the winds at model levels at 30 hPa and 50 hPa. These winds constantly change direction and speed unlike what is observed. As the forecast proceeds in time the winds at 70 hPa also begin to lose their easterly component.

In an attempt to improve the stratospheric model structure, a 38-level T106 cycle 47 was run with seven additional stratospheric levels and the results for the time section are shown in Fig 18(b). The easterlies near 20 hPa are maintained thought the forecast period but there is a clear problem in the wind field starting near 50 hPa and dropping down to 70 hPa during the forecast period. Finally a 32-level version of the model was run keeping a stratospheric resolution similar to the 38 level version, and the tropical time section, Fig 18(c), has similar characteristics to the 38 level model.

9. CONCLUSIONS

The most pressing difficulty with stratospheric analysis is the lack of radiosondes observations. The TOVS radiances measure the general broad scale structure but fail to see strong vertical or horizontal temperature gradients that occur in the stratosphere.

The stratospheric analysis has improved since the introduction of 19 levels into the ECMWF model in 1986. Before this the assimilation system required the use of climatology in the stratosphere. However the current operational model has only four levels above 100 hPa and this must be considered when evaluating the ECMWF analysis system.

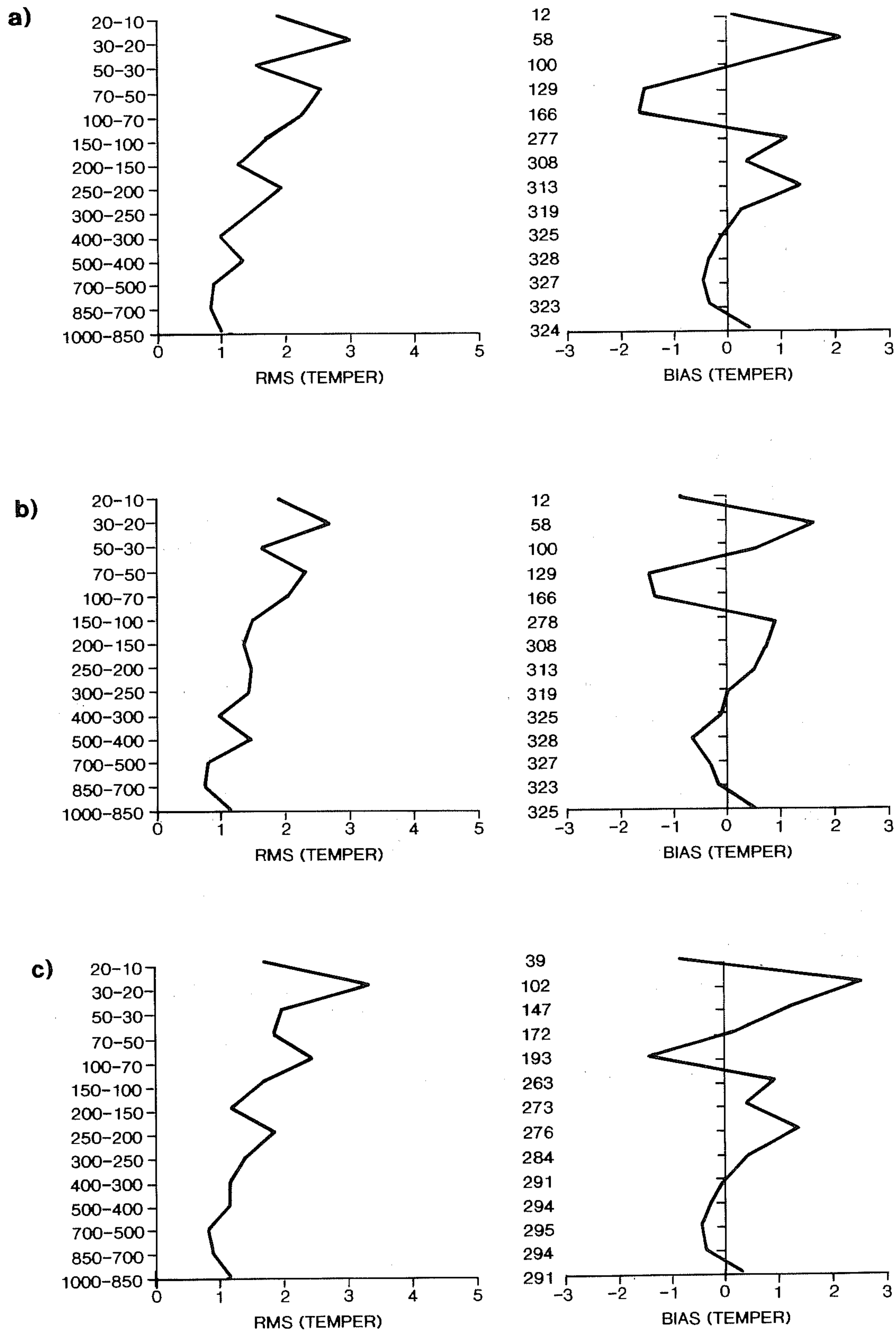
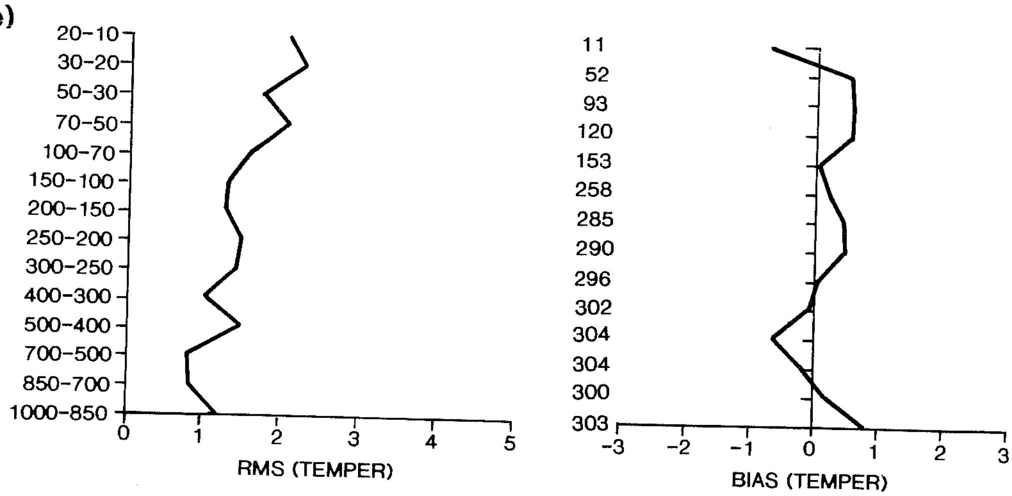


Fig. 16 RMS and BIAS plots for tropical region: Lat. 10°S to 10°N, Long. 80°E to 180°E. (a) 1D-VAR 19 levels, (b) 1D-VAR 31 levels, (c) 1D-VAR 19 levels NESDIS above 100hPa.

e)



d)

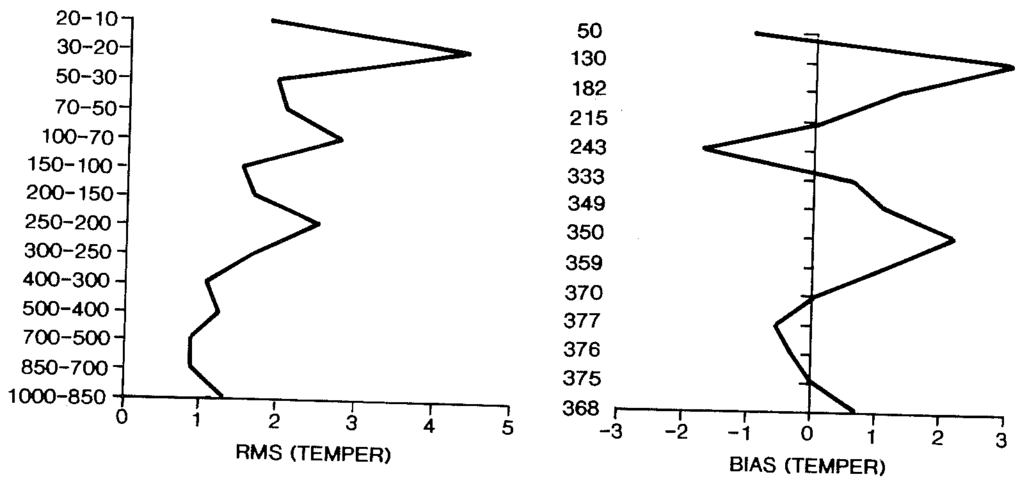


Fig. 16 cont. (d) 3D-VAR 19 levels, (e) current operation no TOVS in Tropics.

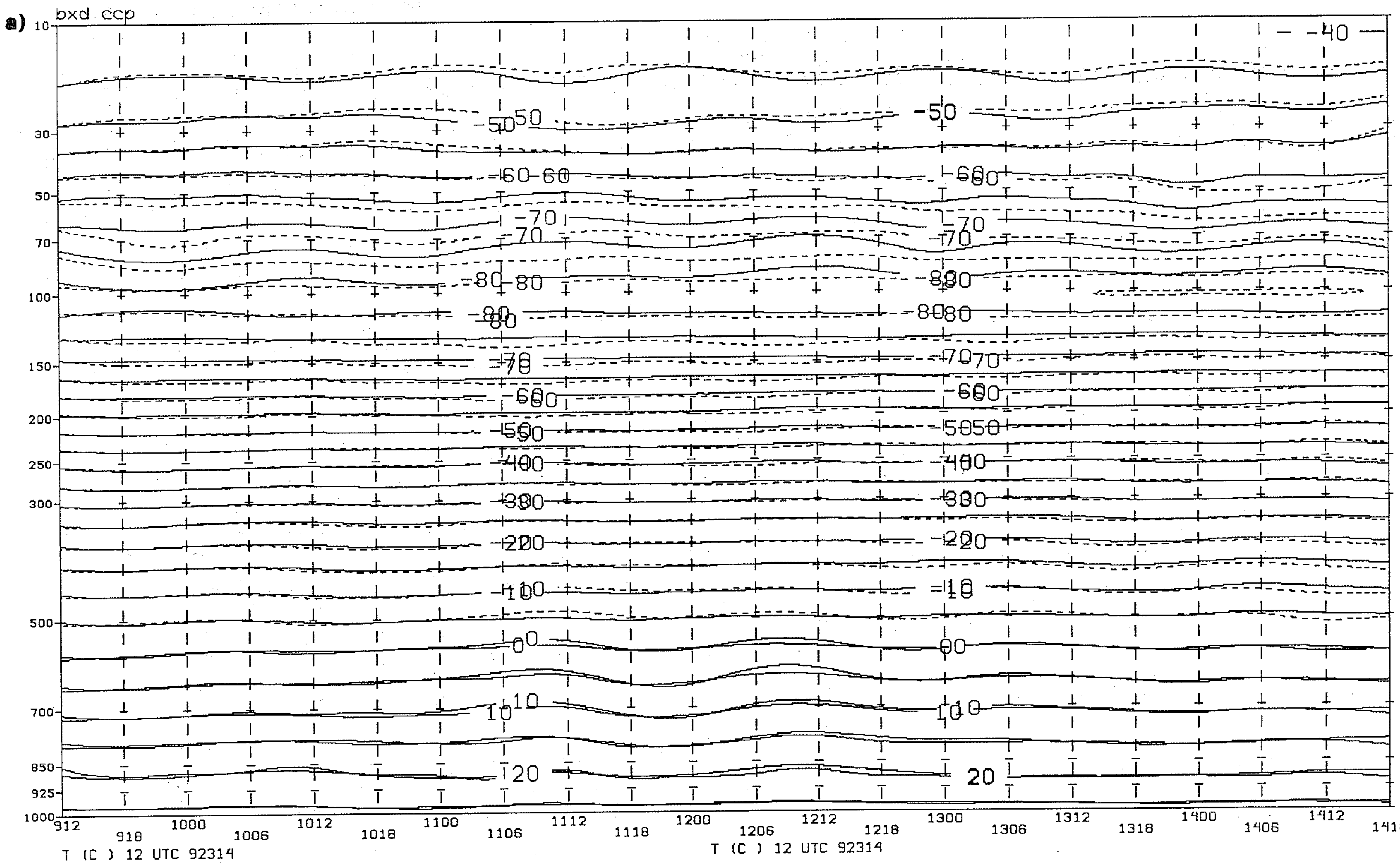


Fig. 17 Temperature time sections at Equator 130°E. (a) Two data assimilation experiments- 'bxd' current operations at 19 level T106 (solid) and 'ccp' 1D-VAR 19 level T106.

b)

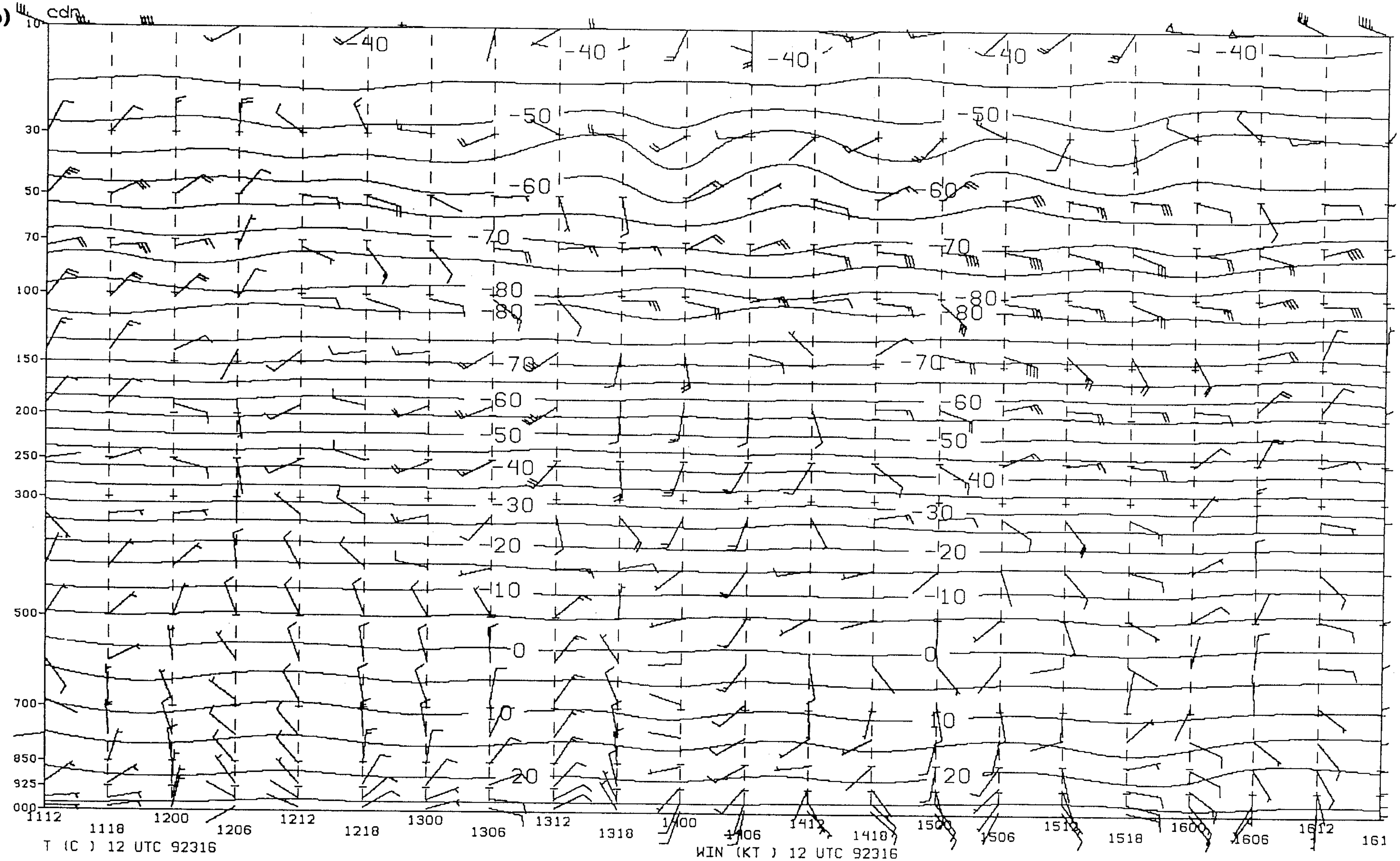


Fig. 17 cont. (b) 3d-VAR data assimilation 'cdn'.

b)

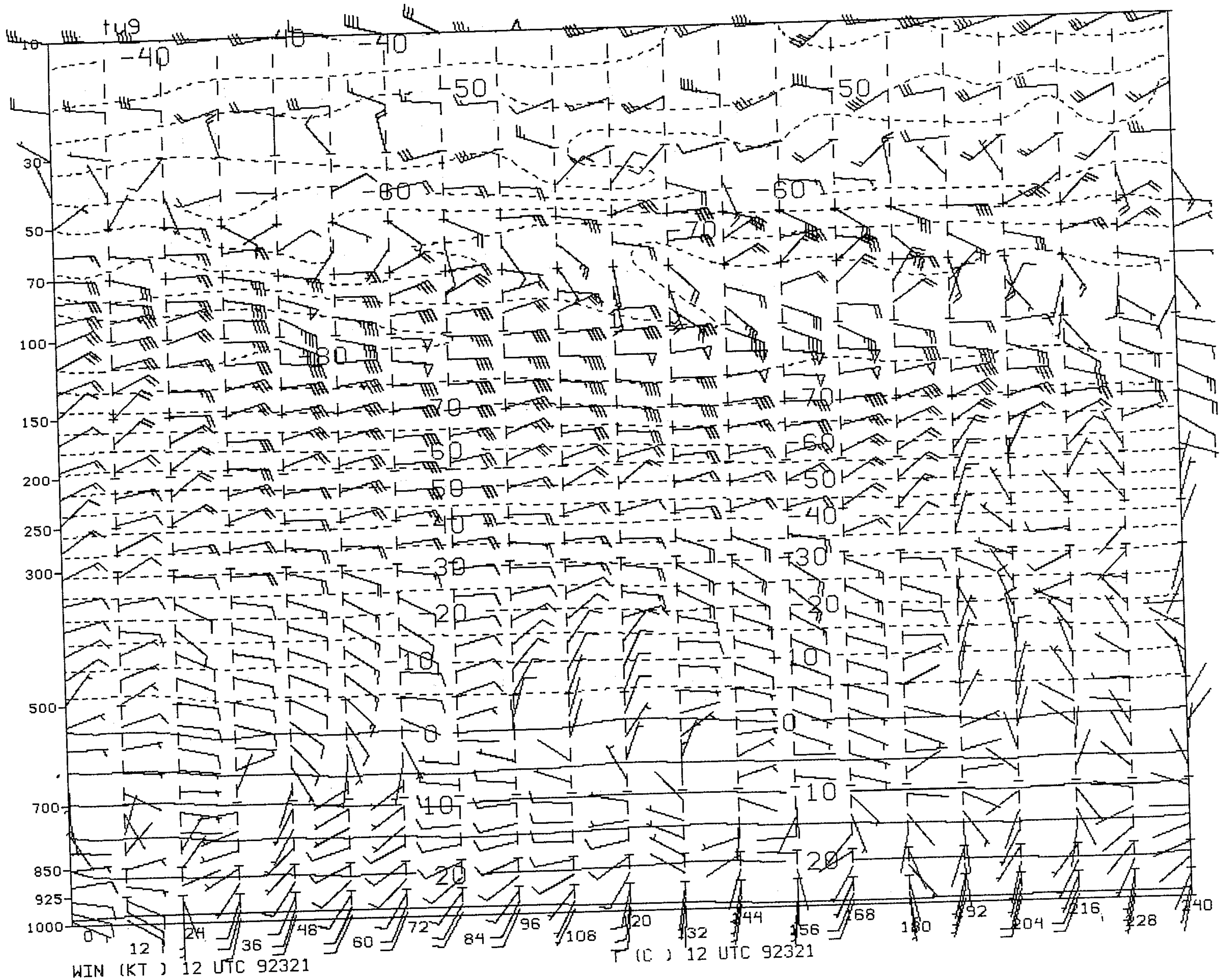


Fig. 18 cont. (b) 10 day forecast 38 level T106 'tu9'.

c)

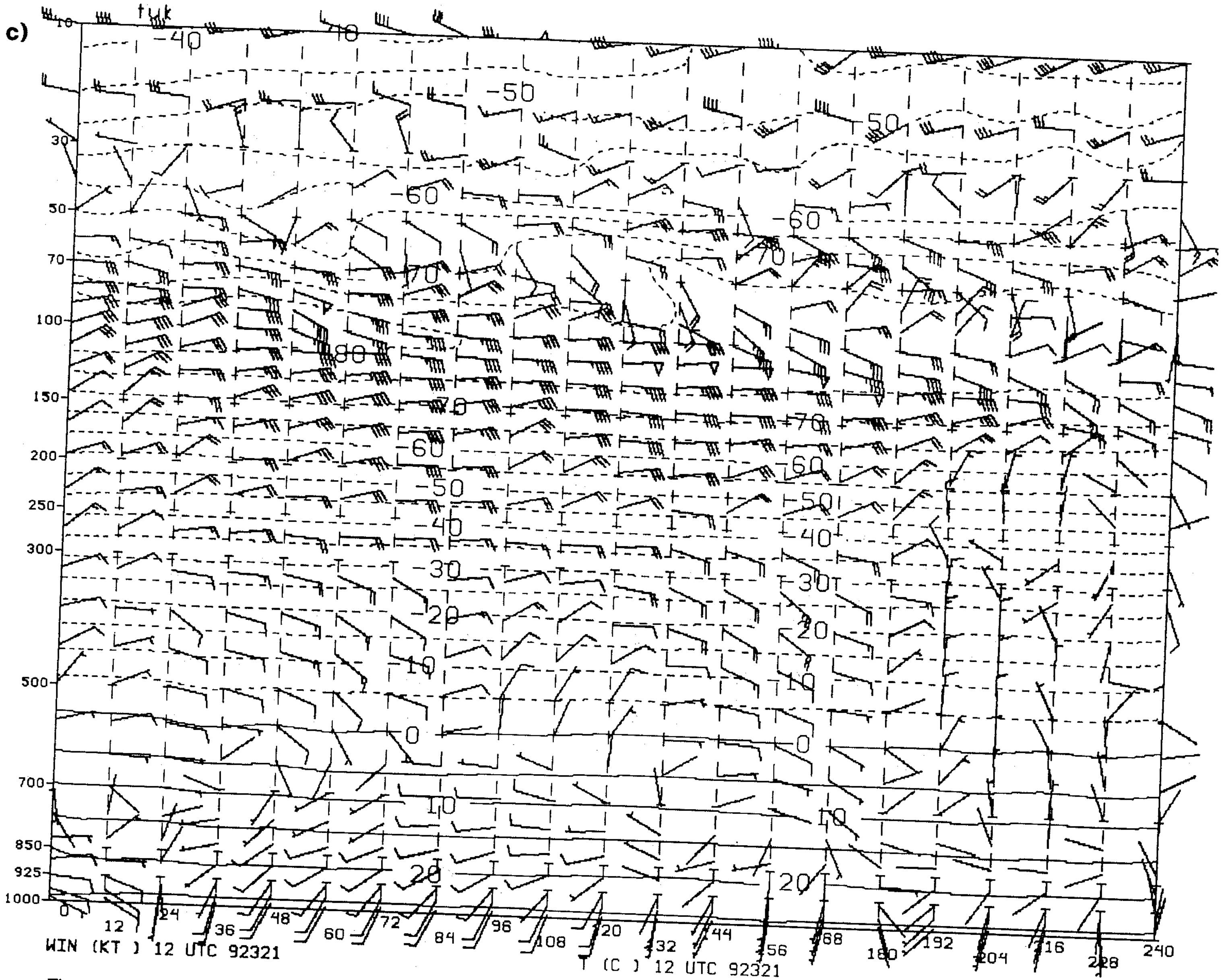


Fig. 18 cont (c) 10 day forecast 32 level T106 'tuk'.

a)

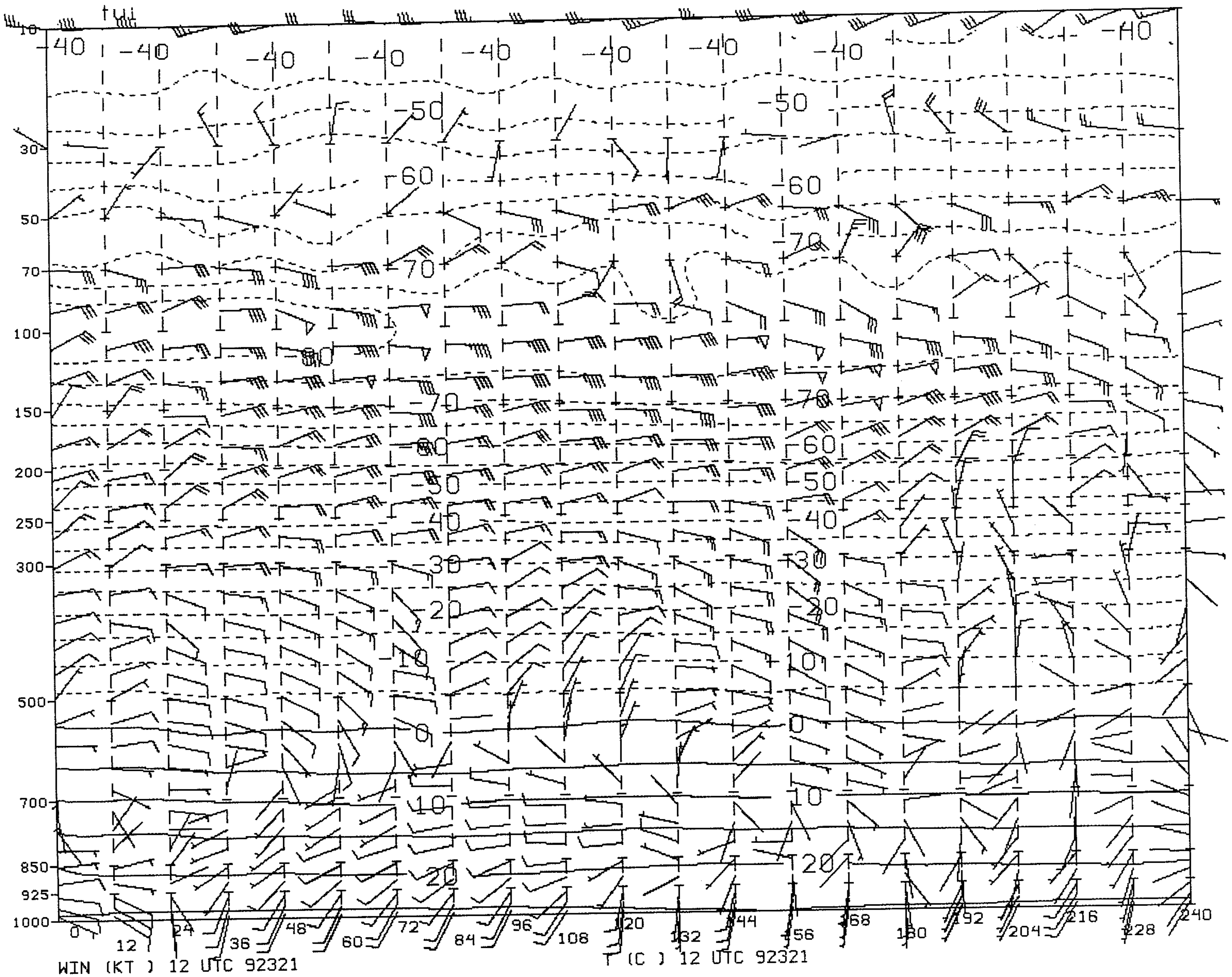


Fig. 18 Temperature time sections at Equator 130°E. (a) 10 day 31 level T106 forecast 'tui'.

The forecast error covariances used in the stratospheric should vary with the QBO phase. The new 3D-Var new formulation of 'non-separable structure functions' appears to be better than OI in non-tropical regions. The monthly mean comparison of tropical radiosonde observations and the assimilation are in reasonable agreement to about 50 hPa thought all phases of the QBO.

The Northern Hemispheric stratospheric PV, computed from the OI analysis, is somewhat noisy near radiosondes but smoother in the Southern Hemisphere. The new 3D-Var analysis system has improved stratospheric PV without smoothing the true PV gradients.

The use of TOVS radiances in the stratosphere leads to problems in both 1D-Var and 3D-Var. The current solution is to use NESDIS retrievals in the stratosphere in the polar regions. This problem need to be understood.

The forecast model has a problem with the forecast not maintaining the constant flow in the tropics during a ten day forecast. This problem does not appear to be just associated with vertical resolution. More investigation is required.

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