Short-range Forecasting Research

Short Range Forecasting Division

Technical Report No. 21

EVALUATION OF DIFFUSION AND GRAVITY WAVE CHANGES TO THE GLOBAL FORECAST MODEL

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1. Introduction

Following a period of test running alongside the CYBER model, Unified Model (UM) forecasts were introduced into the operational suite in June 1991, at version 2.0 of the new model. The main deficiencies of performance revealed by objective and subjective verification at that time were as follows:
A relatively large wind speed error at jet levels; an increase in jet strengths during the forecast period and consequent overdevelopment of synoptic features, particularly in the southern hemisphere; a systematic cooling(/heating) in the upper troposphere(/lower stratosphere); and surface drying through the assimilation cycle. Two sets of changes to the current operational global model were investigated as candidates for improving model performance:

i)∇4∇2 diffusion (D4D2). The UM dynamics code supports conservative even order horizontal diffusion on non-humidity variables (u, v, θ_L) and the humidity variable (q_T) separately. Operationally, the scheme was chosen to be 4th order for both sets of fields (∇4∇4 diffusion), in order to eliminate small scale noise due to grid splitting. Diffusion coefficients were the same for each model level, set at 0.4E8. Climate model experience has shown some advantage in using a lower order diffusion for the humidity fields, with the effect of reducing the scale dependence of diffusion, allowing larger smoothing of the inherently rougher humidity fields while keeping some small scale structure. A coefficient of 0.3E6 was selected for 2nd order humidity diffusion, other values being unchanged (∇4∇2 diffusion). No additional tuning was performed for this parameter.

ii) Linear profile gravity wave drag (GWLINP). The operational method was based on a vertical profile of gravity wave drag derived from a Richardson number criterion. This scheme gives a stress that is independent of height until a critical level is reached as diagnosed by a minimum Richardson number, and then the wave amplitude (and stress) is reduced to maintain waves at a marginal stability. An alternative scheme assumes a linear reduction of stress with pressure, being set to zero above the critical level. This scheme is closer to the old CYBER model formulation and was implemented for a period during the pre-operational CRAY trial when verification results were relatively good. Climate model experience during the pre-operational trial period preferred the Richardson profile scheme. Single forecast experiments revealed little difference in synoptic evolution between the two methods.

2. Method

Earlier experience with changes to the unified model indicated that the full extent of their impact was sometimes only revealed after 1-2 days of their introduction into the assimilation cycle. Hence a consecutive period for assimilation and forecast was chosen for comparative trials, limited to 7 days by storage requirements. Successive 6 day forecasts were performed starting from data time 00Z on each day in two 1-week periods : 9-15 February 1991 and 1-7 July 1991. Starting model analyses for each experiment were obtained by running a continuous assimilation cycle for each week using archived ac observation files (post-quality control, processed observations), beginning from the previous 18Z analysis. The complete assimilation cycle and forecasts were repeated for control and new experiments; output fields were archived and charts produced for subjective assessment.

Objective verification was obtained for each experiment from ac diagnostics by running 1 timestep assimilations from the forecast dumps at T+36, T+72 and T+144 using the update run ac observation files for the respective times. RMS and bias values of observation-model were averaged over the 7 forecasts for each observation type. Results are divided into 3 latitude bands: 90-22N, 22N-22S, 22-90S, and the respective number of observations per day were approximately 325, 50, 20 (SONDEs), 400, 175, 50 (AIREPs). Subjective assessment of the main synoptic features was performed by comparing control and trial runs. Additional comparisons against CYBER operational runs were available for the February week, concentrating on N. Atlantic development.

This approach has the deficiency that the amount of spin up varies from at least 6 hours for the first forecast to 6 days and 6 hours for the last forecast of the sequence, giving a possible underestimate of impact. Also, there will be a small bias towards the operational model at the time of archiving because of the quality control checking of observations against background fields.

Changes to the meteorological performance of the model between versions 2.0 and 2.2 were small, consisting of filtering modifications to make the model more stable and the correction of minor errors. In all results presented for comparison, control and trial were at the same version.

3. Experiments

a) 9-15 February 1991

This winter trial period was chosen initially because the unified model forecasts were generally too cyclonic in the north Atlantic and worse than the CYBER forecasts, during a predominantly zonal period with relatively strong winds in the northern hemisphere. The pre-operational model at that time was version 1.14 which performed badly during the period. Subsequent reruns with later versions gave an improved performance, mostly achieved through changes in the dynamics schemes. Because of possible difficulties with archived analyses, a starting analysis for all experiments was created, valid at 18z 8 February, by spinning up through the assimilation cycle using version 1.17 from 1 February, the start of routine archiving from the CRAY.

Experiments :	CONTROL	version 2.0 and 2.2
	D4D2	as CONTROL but $\nabla 4 \nabla 2$ diffusion
	GWLINP	as CONTROL but linear profile gravity wave drag

Subjective assessment for D4D2 and GWLINP at version 2.0.
Objective assessment for D4D2 and GWLINP at version 2.2.

b) 1-7 July 1991

The first week in July was chosen as a good week for the summer trial period as it was basically very warm and thundery over the U.K, with a mostly meridional flow regime. The operational model was then at version 2.0. There was no subjective assessment of GWLINP for this week.

Experiments :	CONTROL	version 2.1
	D4D2	as CONTROL but ∇4∇2 diffusion
	GWLINP	as CONTROL but linear profile gravity wave drag

Subjective assessment for D4D2 at version 2.1.
Objective assessment for D4D2 and GWLINP at version 2.1.

4. Objective results

a) 9-15 February

D4D2

Figure 1 shows the RMS vector error of sonde winds at T+72 for 90N-22N, indicating a significant improvement in accuracy for most heights but particularly near jet heights at model levels 11 and 12 (corresponding to 300 and 250 mb). This was maintained at T+144. Results for other regions, with a much smaller number of verifying observations, were more mixed: D4D2 gave a better performance at T+72 but this was reversed by T+144. Conversely, for 22S-90S the CONTROL run was closest to sonde observations at T+72 but not at T+144. The impact on wind errors at T+36 was small but mostly beneficial. These results are partially confirmed by AIREP observations. Figure 2 combines AIREP RMS vector errors at level 12 for all 9 categories (3 latitude bands and 3 forecast times), which shows a positive impact for all comparisons except 22-90S at T+36 and indicates a clear advantage to D4D2.

The cold bias against sonde potential temperature measurements at heights near and below jet levels was increased while the compensating over-warming in the stratosphere was unchanged: Figure 3 shows the temperature bias at T+72 for 90N-22N to be increased by 0.3K at level 10, typical of other verification results. A moist bias was introduced into relative humidity fields below level 8 (500mb) while the dry bias above was slightly reduced (Figure 4). Hence the atmosphere above 500mb was both cooled and moistened relative to the control forecast and relative to the observations.

GWLINP

Figure 5 shows a large improvement of RMS vector wind errors in the stratosphere at T+72 but little or no improvement at jet levels and below. AIREP results (Figure 6) are not coherent, indicating an equal number of improved and worsened statistics. The maximum cold bias was increased significantly, e.g. by 0.7K at levels near the tropopause at T+72 for 90N-22N (Figure 7). There was little or no change in humidity biases.

Table 1 gives a summary of temperature and wind errors for different areas and forecast times averaged over the February period.

b) 1-7 July

D4D2

The impact of D4D2 on all verification scores was much smaller for the July week compared to the February period. Sonde wind vector error changes at all forecast times were similar in character to the February period but with a reduced signal. Similarly, AIREP results shown in Figure 8 indicate only small differences between CONTROL and D4D2 errors. There appears to be a systematic reduction in surface pressure compared to the CONTROL case. Potential temperature and humidity errors were similar to the February period, with a moistening of all layers and an increased cooling in the upper troposphere.

GWLINP

The scheme had a small or negative impact on errors and, unlike the February period, there was no improvement of wind error in the stratosphere. Differences in AIREP errors were small and mixed (Figure 9). There was no difference between CONTROL and GWLINP temperature and humidity biases.

Table 2 gives a summary of temperature and wind errors for different areas and forecast times for the July period.

5. Subjective assessment

a) 9-15 February

The February trial period occurred during a week of poor unified model forecasts with depressions and troughs being too deep in the north Atlantic. Generally, forecasts from the two trial versions D4D2 and GWLINP were very similar to the CONTROL forecast up to T+72 but occasional slight differences in evolution developed in the later stages of forecasts.

i) Case studies

Figure 10(a) shows the analysis for the north Atlantic at 00 GMT 17/02/91. The problem with most forecasts verifying at this time is illustrated clearly by Figure 10(b). This T+120 forecast from the CONTROL version is too cyclonic with four fully developed depressions in the forecast area compared to only two in the analysis. The most noticeable error is the prediction of a deep spurious low at 989mb in the southwest approaches at 20W. Also the depression centred near Murmansk has overdeepened in the CONTROL forecast by 13mb whilst the predicted ridge over Denmark is incorrect. T+120 forecasts from the two trial versions (D4D2 in Figure 10(c), GWLINP in Figure 10(d)) do not show any improvement. The spurious depression in the southwest approaches is 5mb less deep in the D4D2 forecast which is a plus point but this is countered by an overdeepening of the Ukrainean low. Although GWLINP has the best solutions for the Canadian and Murmansk depressions, it also predicts a deep spurious low in the western Atlantic.

Figure 11(a) shows the analysis for the north Atlantic verifying at 00 GMT 20/02/91. The main features of interest are the depression between Iceland and Norway, and the trough in the Atlantic at 20W. The CONTROL forecast, Figure 11(b), is too cyclonic, overdeepening the depression by 18mb and almost generating a new low centre at 51N 20W. Consequently the forecast gradient over the British Isles is much too strong. The D4D2 forecast, Figure 11(c), has predicted the depression centre to be further northwest over Iceland with a lighter gradient over the UK, but the depression is still 18mb too deep. The GWLINP forecast, Figure 11(d), is the least cyclonic of the three and predicts a lighter gradient over the British Isles. However, this forecast fails to predict the deep depression east of Iceland and smoothes out detail in the Atlantic trough.

ii) Mean fields

Figures 12(a) and (b) compare the mean surface pressure analysis for the February period with the mean T+144 forecast field from the CONTROL version. As expected, the CONTROL forecast has a deeper trough in the north Atlantic than the analysis with the centre of low pressure displaced southeastwards. The mean pressure is 4mb too low over the British Isles and the Azores anticyclone is slightly weaker. In the southern hemisphere, the pressure field is rough over Antarctica and about 12mb too high, and the depression at 65S 10E is 8mb less deep than analysed. Subjective assessment of individual trial cases for this week indicated that although there were no marked changes in evolution between CONTROL and D4D2 forecasts, pressure values were slightly higher over the north Atlantic for the latter. This is borne out in a comparison of the mean T+144 surface pressure charts in Figures 12(b) and (c). For D4D2 the Atlantic trough is less deep and pressure values higher compared to the CONTROL, and 2-3mb higher over the British Isles, which is closer to the analysis. In the southern hemisphere CONTROL and D4D2 show the same features over Antarctica. The GWLINP forecast, Figure 12(d), like the CONTROL forecast, is too cyclonic over the north Atlantic and has a deeper trough west of Ireland. Surface pressure is about 15mb too high over Antarctica.

In Figures 13(a) and (b), we compare mean T+144 250mb wind isotachs from CONTROL and D4D2 forecasts. Differences are minor even at T+144, showing no major changes in evolution. The band of strong winds exceeding 30 m/s from the Pacific across America has weakened in the D4D2 forecast. Elsewhere however, the strong wind bands are as strong as in the CONTROL. The subtropical jet across north Africa is slightly further north in D4D2. Mean T+144 250mb wind isotachs for CONTROL and GWLINP forecasts are compared in Figures 14(a) and (b). The Florida to Newfoundland jet extends further across the Atlantic at 45N in the GWLINP forecast but the subtropical jet across Africa and Asia is narrower and slightly weaker.

iii) Cross-sections

Figures 15 and 16 show zonal mean 'u' and 'v' wind components at model levels from the T+144 CONTROL and D4D2 forecasts respectively. If zonal mean westerly components are compared, jet cores can be seen to be very similar although there is an indication that the southern hemisphere jet may be slightly weaker for D4D2. The main difference is the stronger easterly component in the lower troposphere north of 70N which may reflect overdeepening of depressions in this region. A comparison of zonal mean southerly components shows that the Hadley circulation is represented similarly in both forecasts.

The zonal mean westerly wind component from T+144 GWLINP forecasts, Figure 17(a) compares closely with the CONTROL version. The jet cores are the same in both hemispheres and the only difference is a slight increase between 300 and 400mb in the southern hemisphere. A comparison of zonal mean southerly components shown by Figure 17(b) indicates a slight weakening of the upper branch of the Hadley circulation for GWLINP forecasts.

iv) Other results for D4D2

A comparison of CONTROL and D4D2 depressions in the northern and southern hemispheres is shown in Table 3. For the first two days in the northern hemisphere, there is a clear signal of D4D2 depressions being less deep than in the February version but later results are more conflicting which confirms the impression gained from visual assessment. For the southern hemisphere summer, the results are more straightforward, indicating a very slight filling of depressions by the D4D2 version.

A similar comparison of model jets (wind maxima exceeding 90KT) is shown in Table 4 below. Similar conclusions can be drawn from these results. For the southern hemisphere summer, there is a slight overall decrease in jet strength when we compare the D4D2 trial version of the unified model with the February version. For the north Atlantic winter, the results are more complicated. Although the overall impact is a slight reduction in jet speed, there are variable results at T+96.

b) July 1-7

D4D2

There was a clear initial impact in days 1-2 of D4D2 on the north Atlantic forecasts consisting of a slight smoothing of pressure and humidity fields. The main results were a reduction in rainfall amounts, a retention of extra moisture in the atmosphere, depressions slightly less deep and jets slightly weaker.

The differences between forecast depressions in the two versions has been summarised in Table 5 below. As in the February trial, the net impact is a slight filling of depressions. However, as in the February trial, the differences between the two versions become more complex in days 3-6 with almost as many depressions being slightly deeper in the D4D2 version as less deep.

The differences between forecast 500mb lows in the two versions has been summarised in Table 6. The impact on upper lows during this period was very small.

6. Summary

Both objective and subjective assessment indicate more impact from changes to the model for February rather than July cases. The February trial occurred during a period of poor CRAY operational forecasts with over-cyclonic development in the North Atlantic. Tables 1 and 2 give a selection of objective verification statistics of model potential temperature and wind errors for February and July respectively.

i) D4D2 diffusion.

February period. There were no marked evolution changes and the overall picture was still too cyclonic. A slight but clear smoothing impact was seen in forecasts for days 1-2 with most depressions being less deep and jets weaker. This impact continued in the southern hemisphere through days 3-5. However for days 3-5 in the Northern Hemisphere the impact was more blurred with some depressions deepening and some jets strengthening. Overall D4D2 was less cyclonic. Nearly all wind verification figures were improved compared to sonde and AIREP observations. A moist bias was introduced at levels below 500 mb and the dry bias above 500 mb was slightly ameliorated. The cold bias near jet levels was increased.

July period. There were no marked evolution changes. A slight but clear smoothing impact was seen in the forecasts for days 1-2 resulting in a reduction of rainfall amounts, a retention of extra moisture in the atmosphere, a slight filling of depressions and weakening of jet strength. For days 3-5, the picture was more complicated with occasional depressions deepening and jets strengthening. No clear signal emerged from verification of winds, with as many statistics degraded as improved. Temperature and humidity results were similar to February, particularly in showing a larger moist bias at all levels.

In short, D4D2 tends towards a better handling of cyclonic conditions at the expense of a larger cold bias near 250 mb and a greater moist bias, brought about by smoothing the moisture fields, inhibiting the development of some small scale features, reducing the intensity of jets and spreading out the humidity fields.

ii) GWLINP.

February period. Some improvement in wind vector error scores was seen, particularly above 100mb, but less than for D4D2. Little change in relative humidity occurred. The cold bias near jet levels was increased significantly. Assessments indicated that the overall synoptic development was very similar to the CONTROL case apart from small scale differences near orography. Differences were essentially local and of mixed benefit.

July period. Little impact on objective scores.

The GWLINP scheme shows some advantages in wind verification figures for the February period but the improvement is partially reversed during July.

Following the presentation of these assessments, D4D2 was accepted for inclusion as an operational change and was introduced with version 2.3 of the unified model on 12 November 1991. The GWLINP scheme was considered to show insufficient advantage to be accepted. Subsequent to the completion of trials and calculation of results, an error was found affecting both CONTROL and GWLINP versions of the gravity wave drag scheme. The error modified the initiating lowest model level stress in a manner common to both schemes. Overall objective results were only marginally changed for the CONTROL case and it is very unlikely that the conclusions of trials described here would be affected.

FIGURES

Fig. 1 Root mean square vector wind error (m/s) of sonde observations versus model level for CONTROL and D4D2 experiments at T+72 for 90N-22N, averaged over 7 forecasts for the period 9-15 February 1991.

Fig. 2 Root mean square vector wind error (m/s) of AIREP observations at model level 12 (250mb) for 90N-22N (T+36,72,144), 22N-22S (T+36,72,144) and 22S-90S (T+36,72,144) for CONTROL and D4D2 experiments averaged over 7 forecasts 9-15 February 1991.

Fig. 3 Bias from sonde potential temperature observations for CONTROL and D4D2 experiments at T+72, 90N-22N, averaged 9-15 February, (°K).

Fig. 4 As Fig. 3 for sonde relative humidity observations (%).

Fig. 5 As Fig. 1 for GWLINP experiment.

Fig. 6 As Fig. 2 for GWLINP experiment.

Fig. 7 As Fig. 3 for GWLINP experiment.

Fig. 8 As Fig. 2 for D4D2 experiment over period 1-7 July 1991.

Fig. 9 As Fig. 2 for GWLINP experiment over period 1-7 July 1991.

Fig. 10 (a) Mean sea level pressure (MSLP) analysis valid 00 GMT 17/02/91.
(b) As (a) for T+120 CONTROL forecast valid 00 GMT 17/02/91.
(c) As (a) for T+120 D4D2 forecast valid 00 GMT 17/02/91.
(d) As (a) for T+120 GWLINP forecast valid 00 GMT 17/02/91.

Fig. 11 (a) MSLP analysis valid 00 GMT 20/02/91.
(b) As (a) for T+120 CONTROL forecast valid 00 GMT 20/02/91.
(c) As (a) for T+120 D4D2 forecast valid 00 GMT 20/02/91.
(d) As (a) for T+120 GWLINP forecast valid 00 GMT 20/02/91.

Fig. 12 (a) Average MSLP of 00 GMT analyses 15/02/91 to 21/02/91.
(b) As (a) for T+144 CONTROL forecasts valid 15/02/91 to 21/02/91.
(c) As (a) for T+144 D4D2 forecasts valid 15/02/91 to 21/02/91.
(d) As (a) for T+144 GWLINP forecasts valid 15/02/91 to 21/02/91.

Fig. 13 (a) Average wind speed of T+144 CONTROL 00 GMT forecasts valid 15/02/91 to 21/02/91.
(b) As (a) for T+144 D4D2 forecasts.

Fig. 14 (a) As Fig. 13(a)
(b) As (a) for T+144 GWLINP forecasts.

Fig. 15 (a) Zonal mean westerly wind component ('u') average of T+144 CONTROL forecasts at 00 GMT valid 15/02/91 to 21/02/91.
(b) Zonal mean southerly wind component ('v') average of T+144 CONTROL forecasts at 00 GMT valid 15/02/91 to 21/02/91.

Fig. 16 (a) As Fig. 15(a) for D4D2.
(b) As Fig. 15(b) for D4D2.

Fig. 17 (a) As Fig. 15(a) for GWLINP.
(b) As Fig. 15(b) for GWLINP.

TABLE 1. Verification of forecasts against radiosonde data. Statistics are for period 8-15 February 91.

a) Potential temperature (°K). Mean error (model-observed)/ RMS error.

	level 8 (500 mb)			level 12 (250 mb)		
	90N-22N	22N-22S	22S-90S	90N-22N	22N-22S	22S-90S
T+36						
CONTROL	-0.3/2.6	-0.1/1.5	-0.4/2.3	0.1/3.7	-1.1/2.6	-0.8/4.2
D4D2	-0.5/2.4	-0.4/1.5	-0.6/2.4	0.0/3.8	-1.5/2.8	-1.1/4.3
GWLINP	-0.3/2.4	-0.1/1.5	-0.3/2.4	-0.2/3.3	-1.1/2.6	-0.7/4.2
T+72						
CONTROL	-0.5/4.0	0.0/1.9	-0.3/3.1	-0.6/5.4	-1.5/3.2	-2.9/5.5
D4D2	-0.7/3.8	-0.2/1.9	-0.4/3.1	-1.0/5.4	-2.1/3.4	-3.4/5.8
GWLINP	-0.5/4.0	0.1/1.9	-0.3/3.2	-1.1/4.9	-1.5/3.2	-3.0/5.5
T+144						
CONTROL	-1.0/6.0	0.0/2.4	-0.4/5.8	-2.0/7.3	-2.5/3.8	-3.7/8.5
D4D2	-1.3/5.9	-0.4/2.4	-1.3/5.3	-2.7/7.6	-3.2/4.3	-4.5/8.1
GWLINP	-1.1/6.1	0.0/2.5	-0.2/5.8	-3.0/7.1	-2.4/3.8	-4.1/8.5

b) Wind (m/s). Mean error u component (model-observed)/ RMS vector error

	level 8 (500 mb)			level 12 (250 mb)		
	90N-22N	22N-22S	22S-90S	90N-22N	22N-22S	22S-90S
T+36						
CONTROL	-0.1/7.6	-1.0/5.8	-0.8/8.4	-0.7/10.3	2.1/9.1	-0.5/11.0
D4D2	-0.1/7.4	-0.9/5.6	-0.9/8.5	-0.8/10.0	1.8/9.1	-0.5/11.1
GWLINP	-0.1/7.7	-0.8/5.8	-0.4/8.5	-0.6/10.1	2.2/9.2	-0.1/11.0
T+72						
CONTROL	0.1/11.4	-1.1/6.8	0.7/10.3	-0.1/15.1	5.1/11.5	0.8/13.1
D4D2	0.1/11.0	-1.0/6.6	0.4/10.7	-0.3/14.3	4.6/10.8	0.7/13.8
GWLINP	0.0/11.6	-0.7/7.6	1.0/10.4	0.0/14.8	5.2/11.6	1.5/13.5
T+144						
CONTROL	0.5/16.6	-1.2/8.2	3.2/15.5	0.7/21.4	4.7/12.5	1.2/22.9
D4D2	0.3/16.2	-1.5/8.2	3.4/15.1	0.4/20.1	6.0/13.3	2.8/21.2
GWLINP	0.6/16.5	-0.7/8.1	3.1/15.4	1.4/21.5	5.1/13.4	1.5/21.8

TABLE 2. Verification of forecasts against radiosonde data. Statistics are for period 1-7 July 91.

a) Potential temperature (°K). Mean error (model-observed)/ RMS error.

	level 8 (500 mb)			level 12 (250 mb)		
	90N-22N	22N-22S	22S-90S	90N-22N	22N-22S	22S-90S
T+36						
CONTROL	-0.3/1.8	-0.3/1.6	-0.3/3.7	-0.9/3.1	-1.3/2.2	-0.6/3.8
D4D2	-0.4/1.8	-0.4/1.5	-0.7/3.7	-1.2/3.3	-1.6/2.4	-0.8/3.7
GWLINP	-0.2/1.8	-0.3/1.5	-0.3/3.8	-0.9/3.1	-1.3/2.1	-0.7/3.8
T+72						
CONTROL	-0.4/2.7	-0.6/1.8	-0.7/4.3	-1.4/4.3	-2.5/3.3	-1.5/4.7
D4D2	-0.6/2.7	-0.8/2.0	-1.3/4.5	-1.8/4.4	-2.8/3.5	-1.8/4.6
GWLINP	-0.4/2.7	-0.5/1.7	-0.8/4.6	-1.5/4.2	-2.5/3.3	-1.3/4.5
T+144						
CONTROL	-0.7/3.8	-0.3/1.7	-1.6/7.1	-2.7/6.2	-3.4/4.2	-1.9/4.9
D4D2	-0.8/3.8	-0.4/1.6	-2.4/7.9	-3.1/6.2	-3.7/4.4	-2.0/4.8
GWLINP	-0.7/3.8	-0.4/1.6	-1.8/7.1	-2.7/6.2	-3.4/4.2	-1.7/4.7

b) Wind (m/s). Mean error u component (model-observed)/ RMS vector error

	level 8 (500 mb)			level 12 (250 mb)		
	90N-22N	22N-22S	22S-90S	90N-22N	22N-22S	22S-90S
T+36						
CONTROL	0.1/5.6	0.6/5.9	1.9/10.1	0.1/8.5	-1.5/9.0	1.9/13.6
D4D2	0.1/5.5	0.6/5.8	1.8/ 9.8	0.0/8.4	-1.3/8.9	1.3/13.6
GWLINP	0.1/5.7	0.7/5.9	2.7/10.8	0.0/8.5	-1.6/9.0	2.5/14.0
T+72						
CONTROL	-0.2/8.2	0.6/6.7	2.1/15.5	-0.4/12.8	-1.7/10.3	-1.0/21.1
D4D2	-0.2/8.0	0.7/6.6	2.3/15.8	-0.4/12.8	-1.8/10.2	-1.0/21.1
GWLINP	-0.2/8.3	0.6/6.5	2.3/16.1	-0.5/13.0	-1.7/10.1	-0.8/22.0
T+144						
CONTROL	0.2/12.5	1.5/7.7	0.4/18.9	-0.1/18.5	-1.8/10.9	-3.1/26.2
D4D2	0.2/11.9	0.8/7.8	1.0/19.2	0.2/18.0	-0.2/10.5	-2.6/26.3
GWLINP	0.2/12.6	1.6/7.9	1.8/19.6	-0.3/18.5	-1.5/11.0	-1.2/26.1

TABLE 3. A comparison of depressions from D4D2 and CONTROL experiments for February 9-15 1991.

		D4D2 v CONTROL			
		bias(mb) D4D2-CONTROL	% of lows filled/deepened		bias(mb) D4D2-CONTROL	% of lows filled/deepened
T+24	N.HEM	0.8	50 : 12	S.HEM	0.6	38 : 33
T+48		0.9	50 : 24		0.1	49 : 39
T+72		-0.1	34 : 37		1.1	44 : 37
T+96		-0.0	50 : 36		2.3	63 : 29
T+120		-1.3	45 : 47		2.1	68 : 26

TABLE 4. A comparison of jets from D4D2 and CONTROL experiments for February 9-15 1991.

		D4D2 v CONTROL				
		bias(KT) D4D2-CONTROL	ratio of jets weaker:stronger		bias(KT) D4D2-CONTROL	ratio of jets weaker:stronger
T+48	NORTH	-3.6	69 : 25	SOUTHERN	-5.7	61 : 30
T+72	ATLANTIC	-2.7	62 : 36	HEMISPHERE	-4.9	67 : 27
T+96		0.2	41 : 51		-5.7	63 : 31
T+120		-1.6	59 : 36		-3.7	52 : 43

TABLE 5. A comparison of depressions from D4D2 and CONTROL experiments for July 1-7 1991.

		D4D2 v CONTROL			D4D2 v CONTROL	
		bias(mb) D4D2-CONTROL	% of lows filled:deepened		bias(mb) D4D2-CONTROL	% of lows filled:deepened
T+24	N.HEM	0.7	47 : 15	S.HEM	0.3	34 : 22
T+48		0.4	48 : 25		0.1	33 : 27
T+72		0.5	40 : 35		0.5	55 : 29
T+96		0.0	38 : 35		0.7	49 : 22
T+120		0.8	47 : 32		0.6	55 : 37

TABLE 6. A comparison of low centres for 500mb heights from D4D2 and CONTROL experiments for July 1-7 1991.

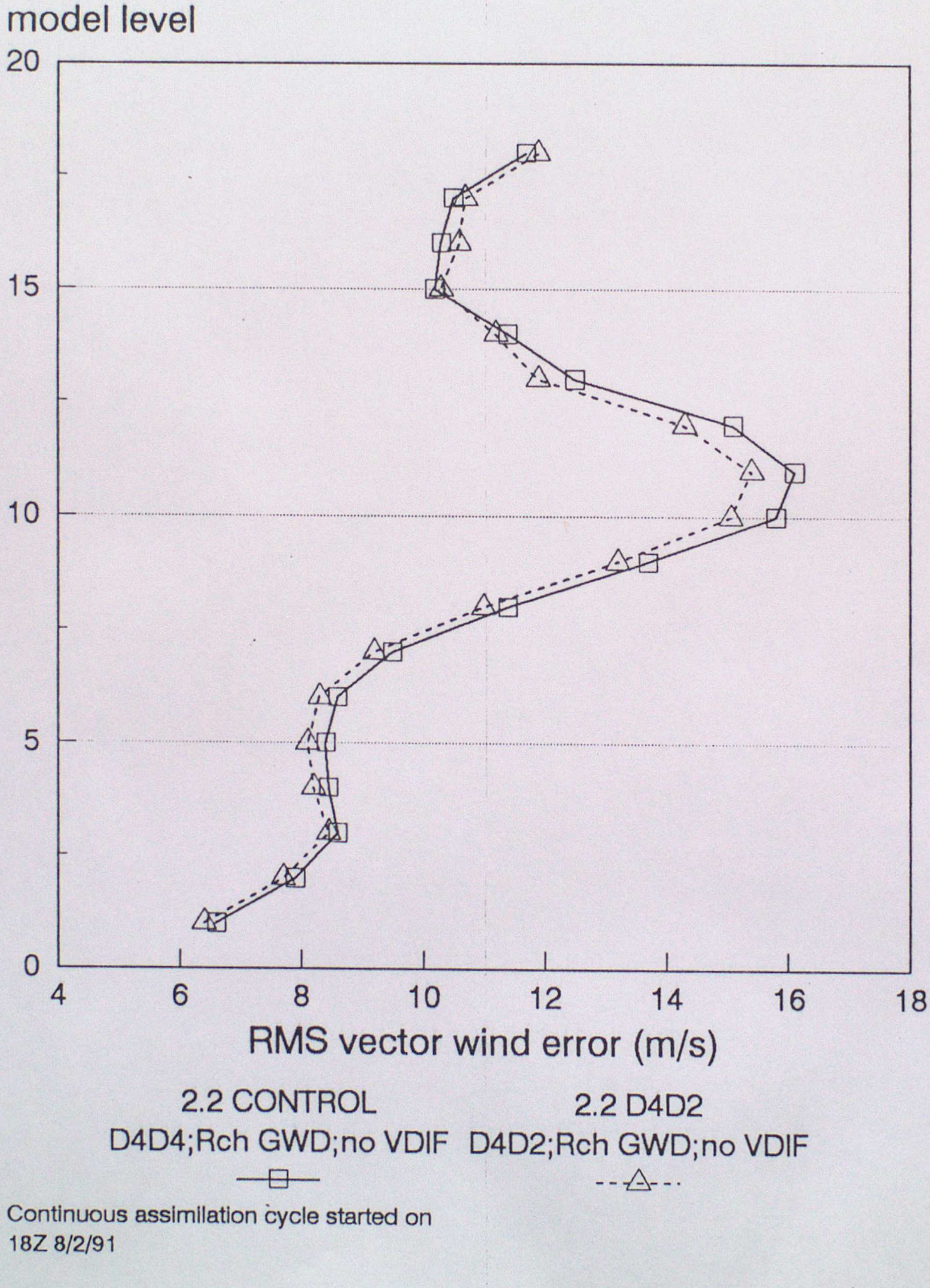
		D4D2 v CONTROL			D4D2 v CONTROL	
		bias(dm) D4D2-CONTROL	% of lows filled:deepened		bias(dm) D4D2-CONTROL	% of lows filled:deepened
T+24	N.HEM	-0.1	9 : 20	S.HEM	-0.0	17 : 39
T+48		0.0	25 : 25		0.1	37 : 19
T+72		-0.0	36 : 36		0.3	35 : 27
T+96		-0.1	29 : 42		-0.0	37 : 30
T+120		-0.3	39 : 32		0.6	68 : 23

FIGURE 1

Verification against AC observations

DT 00Z 9-15 Feb 1991 90N-22N

T+ 72 301(sonde winds)



Continuous assimilation cycle started on
18Z 8/2/91

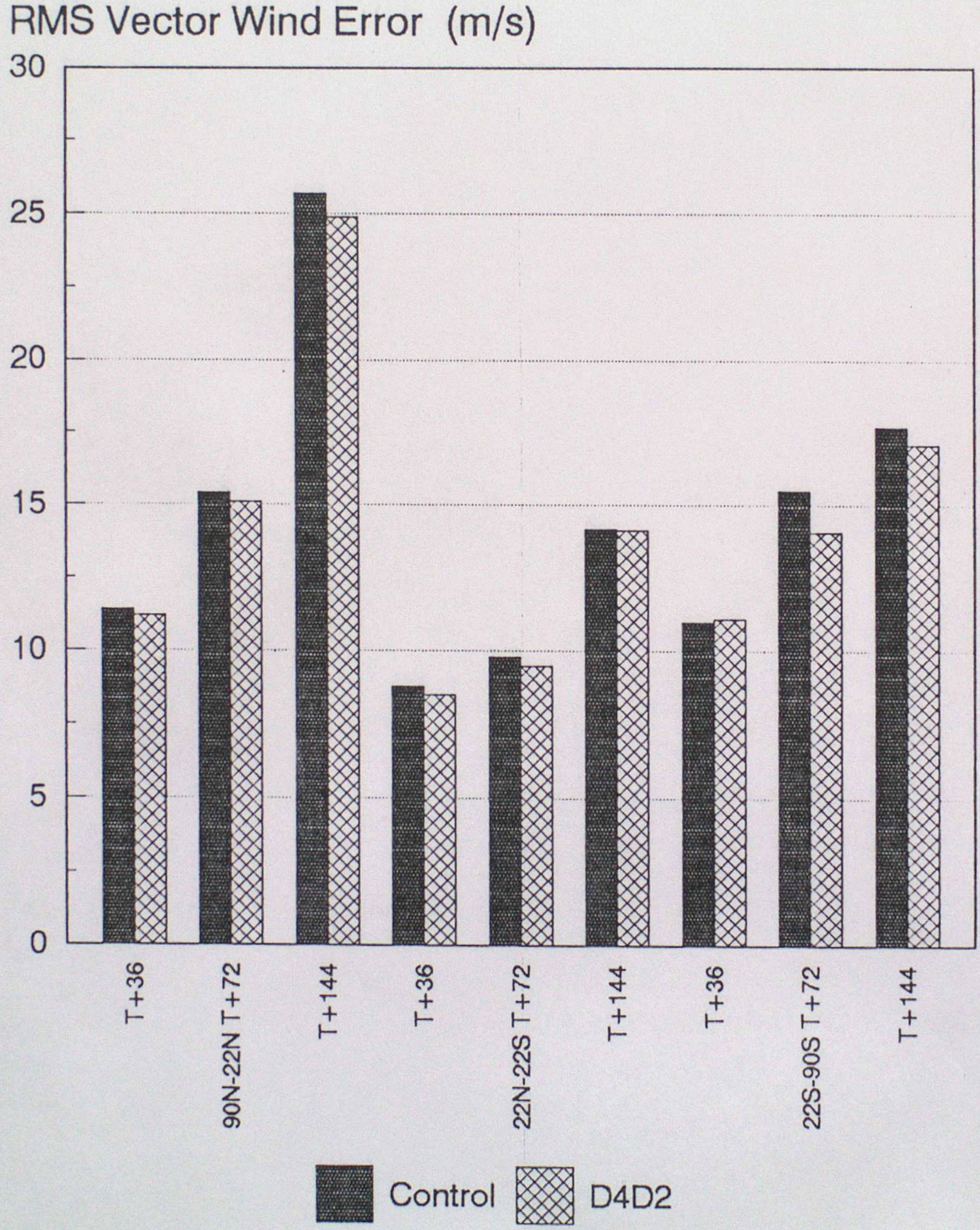
GFM_¦_p@

FIGURE 2

Verification against AC OBS

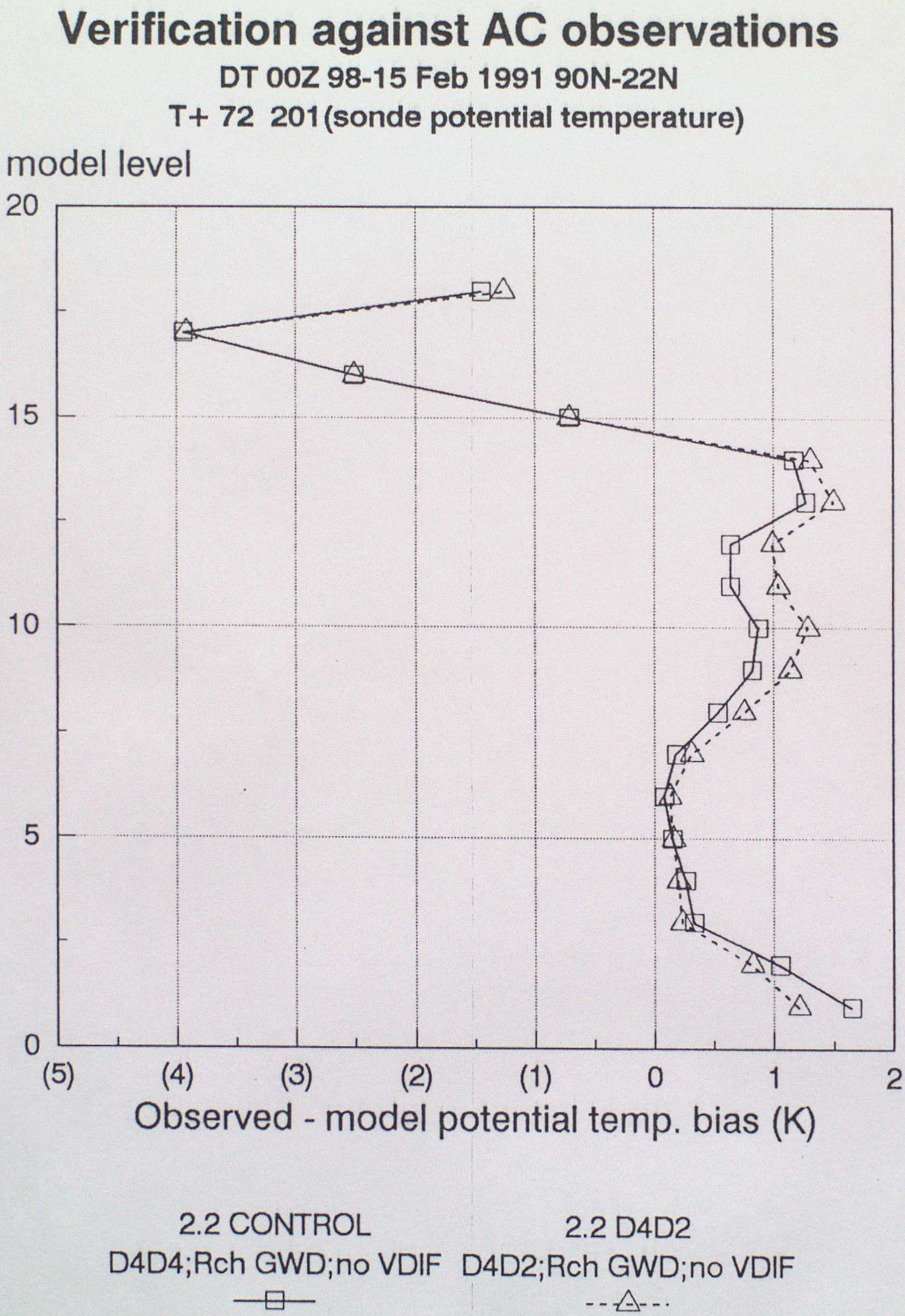
9-15 FEB 91 303(AIREPs) 250 mb

Vn2.2



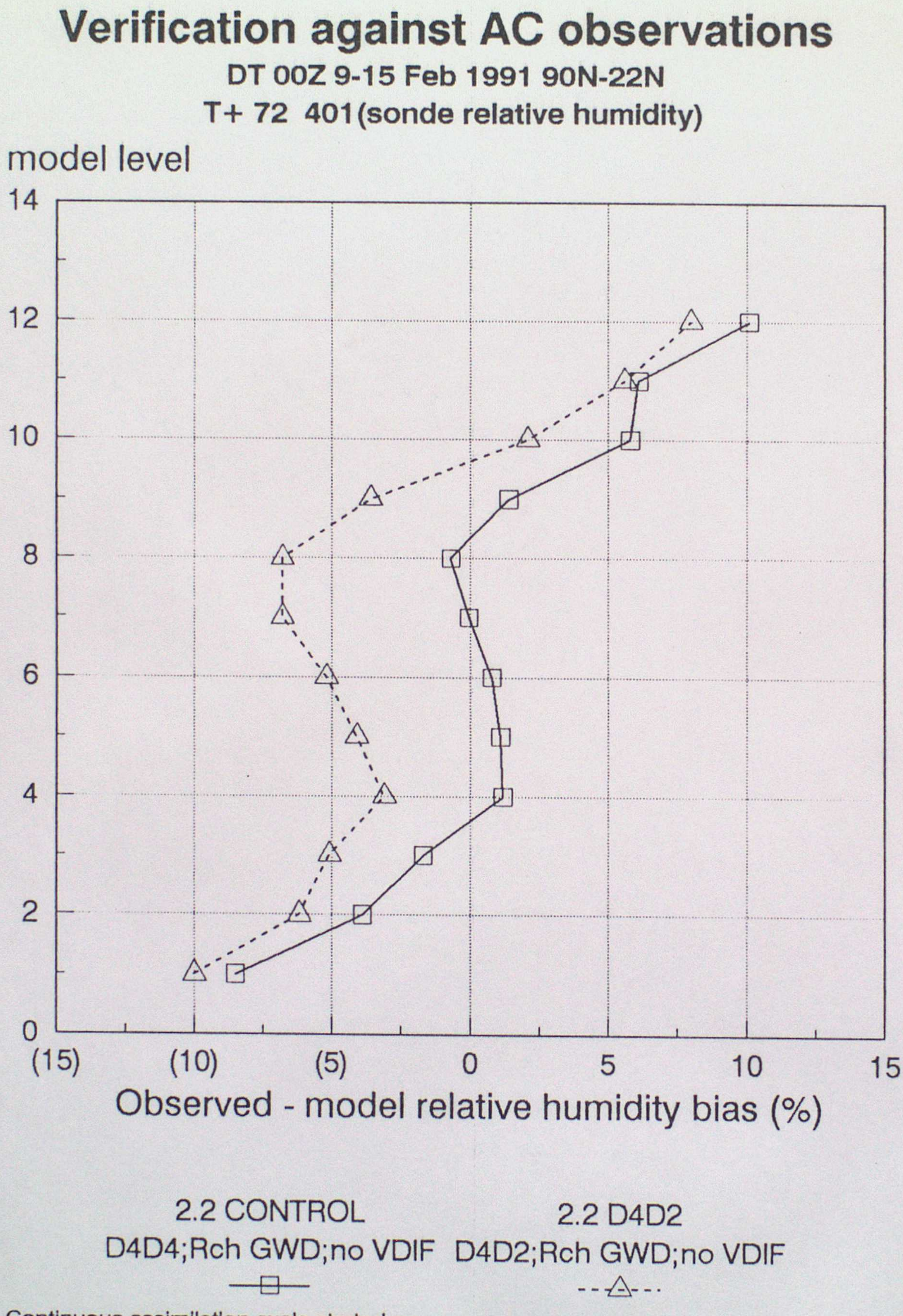
Continuous assimilation .
cycle started 18z 8/2/91

FIGURE 3



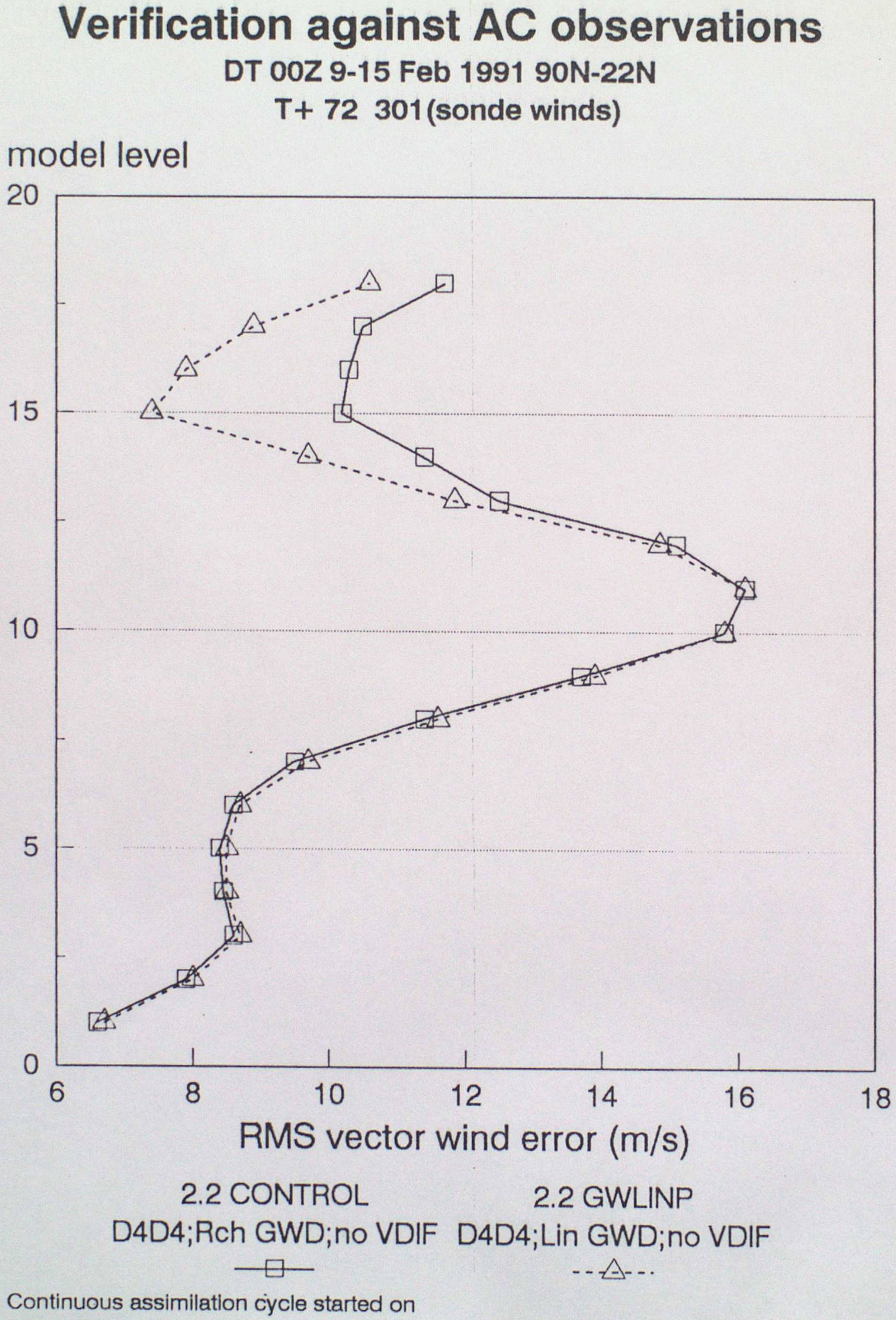
Continuous assimilation.cycle started on
18Z 08/02/91

FIGURE 4



Continuous assimilation cycle started on 18Z 8/2/91

FIGURE 5



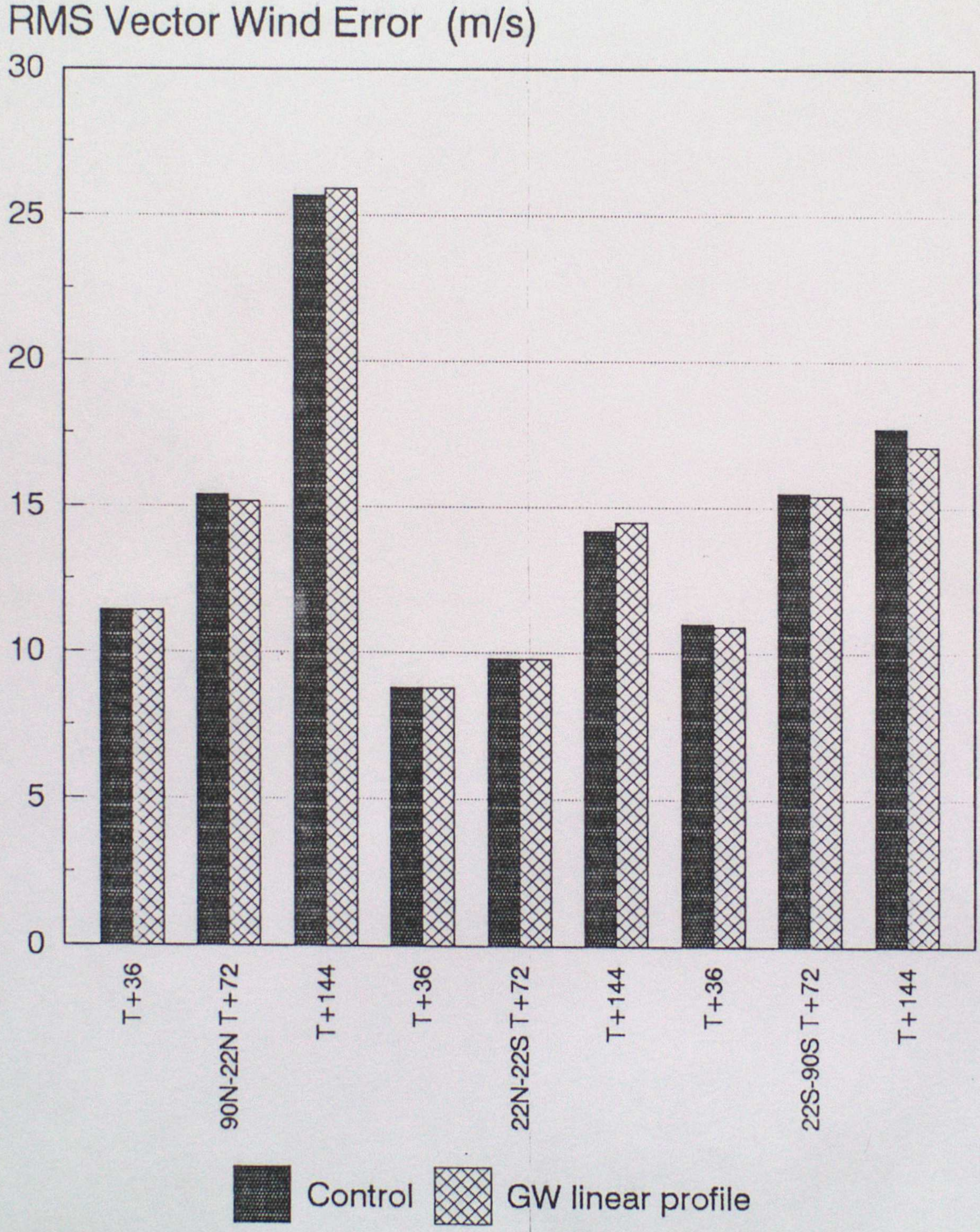
Continuous assimilation cycle started on
18Z 8/2/91

FIGURE 6

Verification against AC OBS

9-15 FEB 91 303(AIREPs) 250 mb

Vn2.2



Continuous assimilation cycle started 18z 8/2/91

FIGURE 7

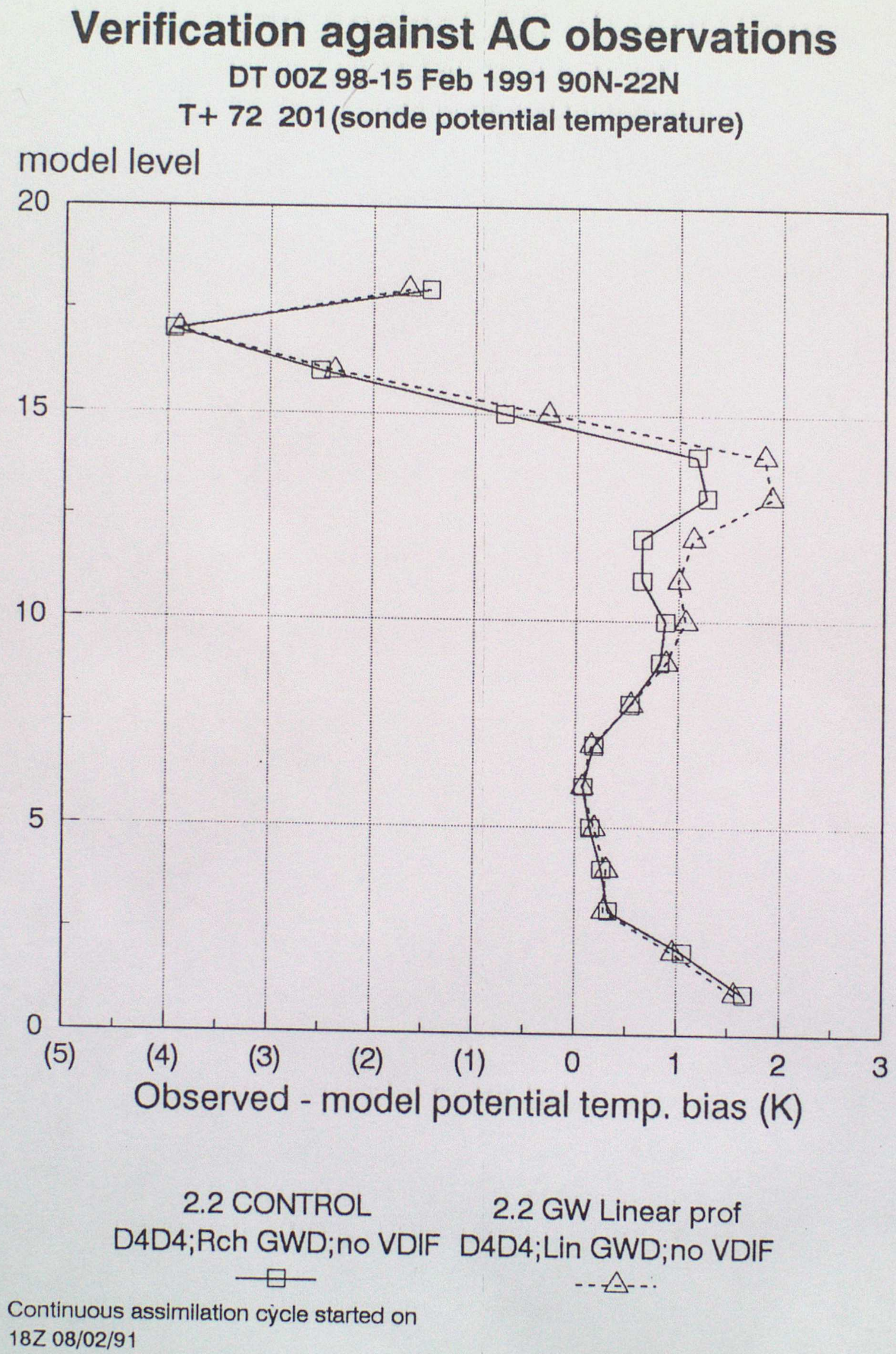
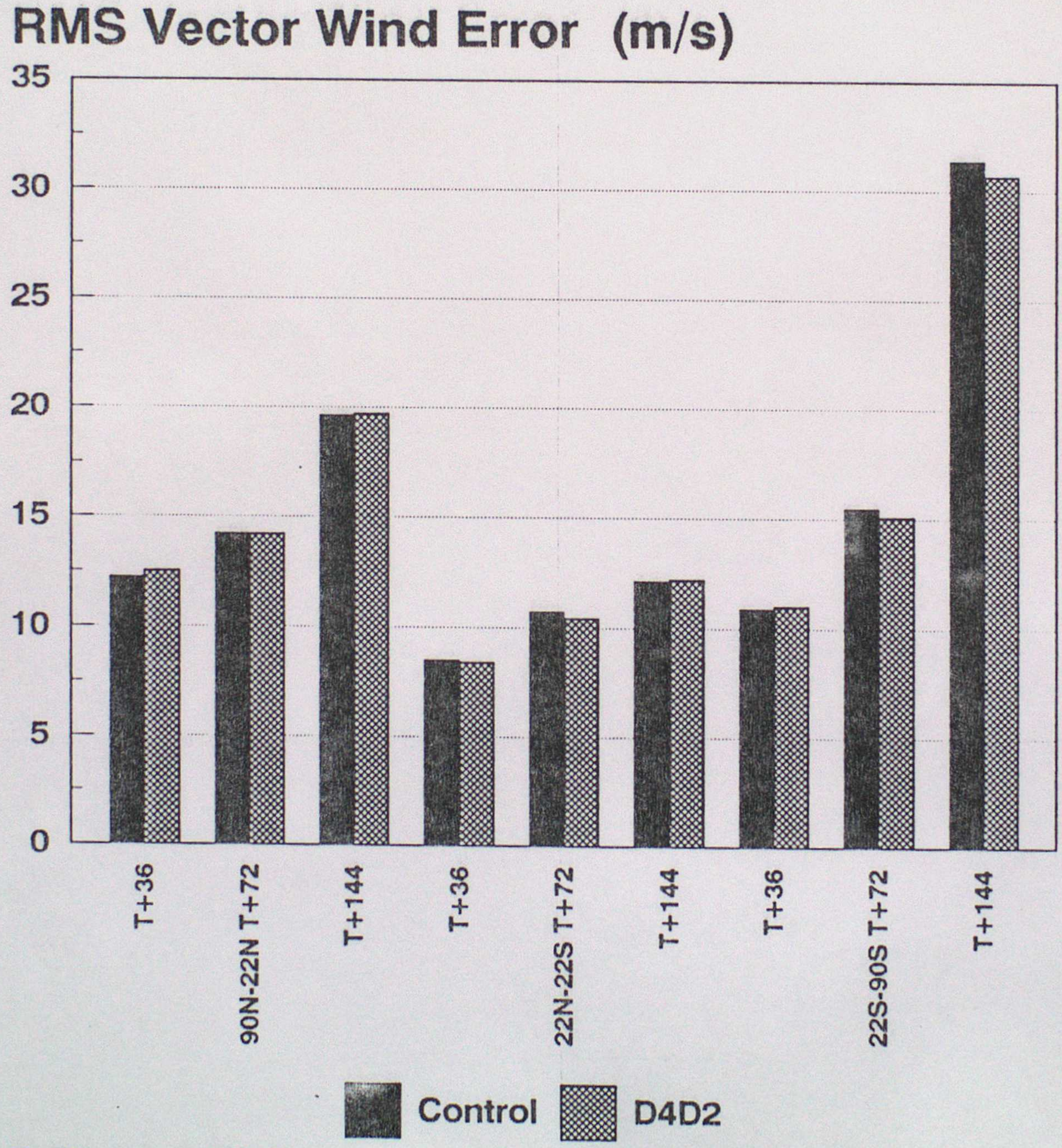

Verification against AC observations
DT 00Z 98-15 Feb 1991 90N-22N
T+ 72 201(sonde potential temperature)
model level
20
15
10
5
0
(5)
(4)
(3)
(2)
(1)
0
1
2
3
Observed - model potential temp. bias (K)
2.2 CONTROL
D4D4;Rch GWD;no VDIF
2.2 GW Linear prof
D4D4;Lin GWD;no VDIF
Continuous assimilation cycle started on
18Z 08/02/91

FIGURE 8

Verification against AC OBS

1-7 JULY 91 303(AIREPs) 250 mb

Vn2.1



Continuous assimilation cycle started 18z 30/6/91

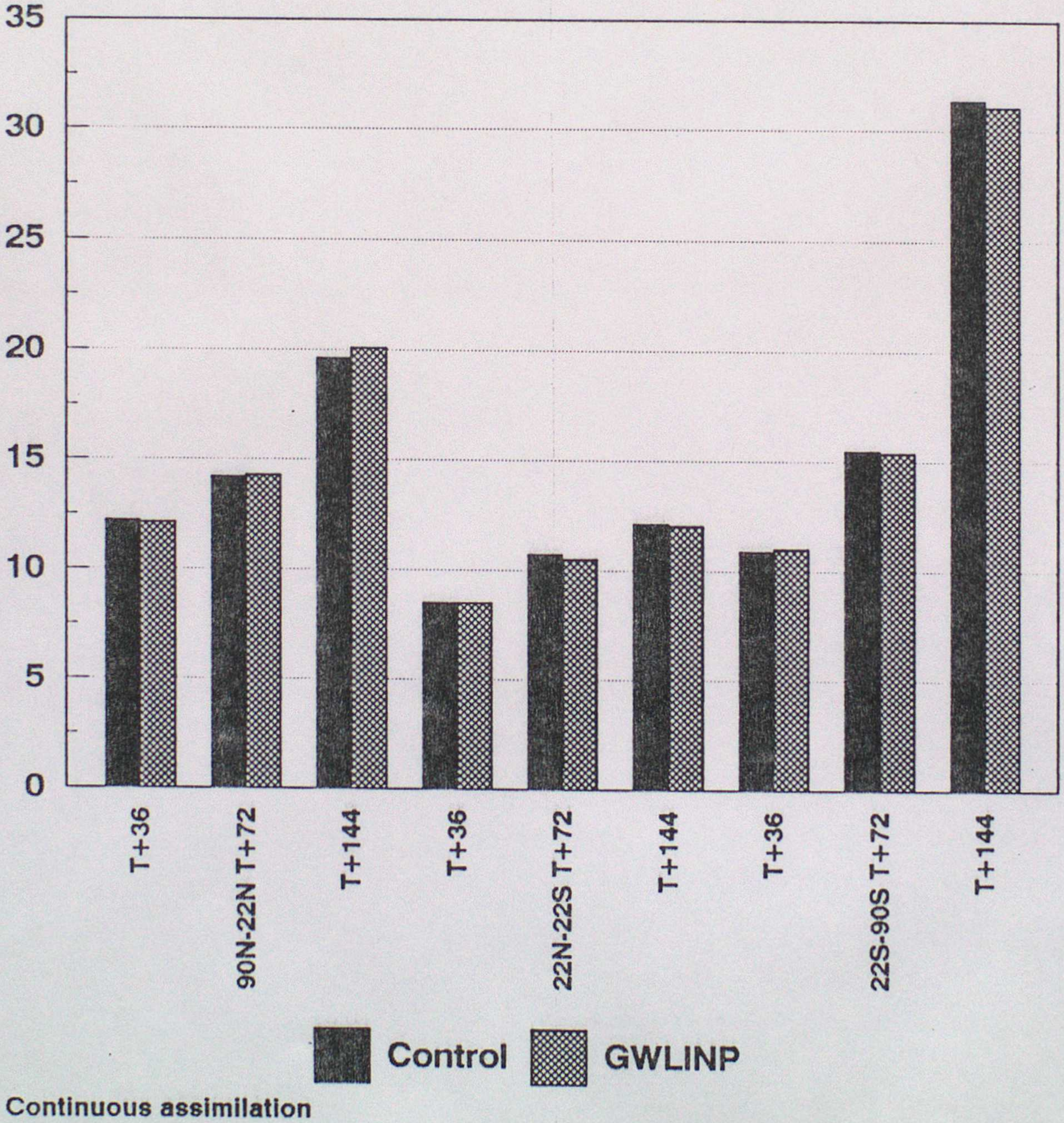
FIGURE 9

Verification against AC OBS

1-7 JULY 91 303(AIREPs) 250 mb

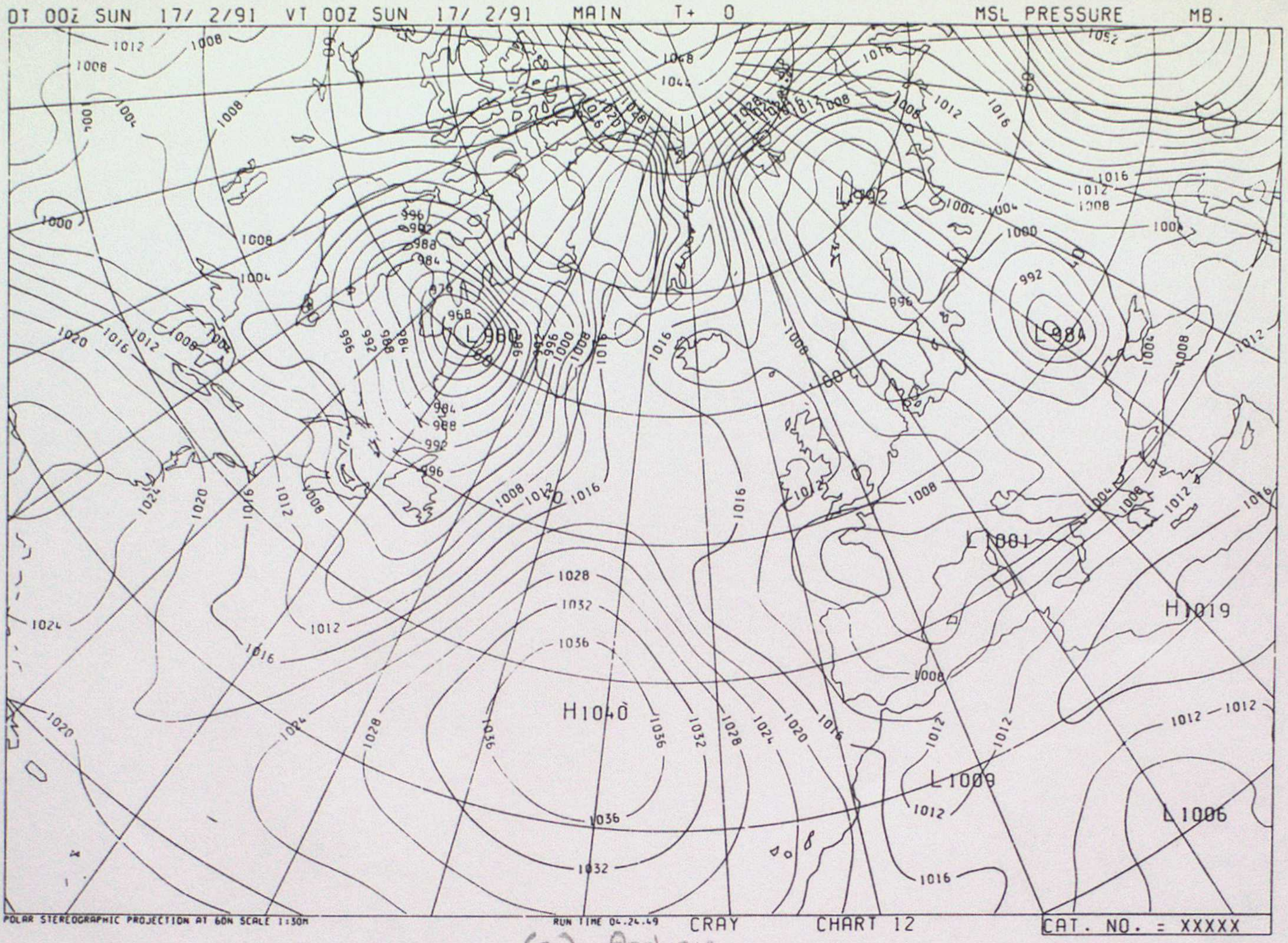
Vn2.1

RMS Vector Wind Error (m/s)

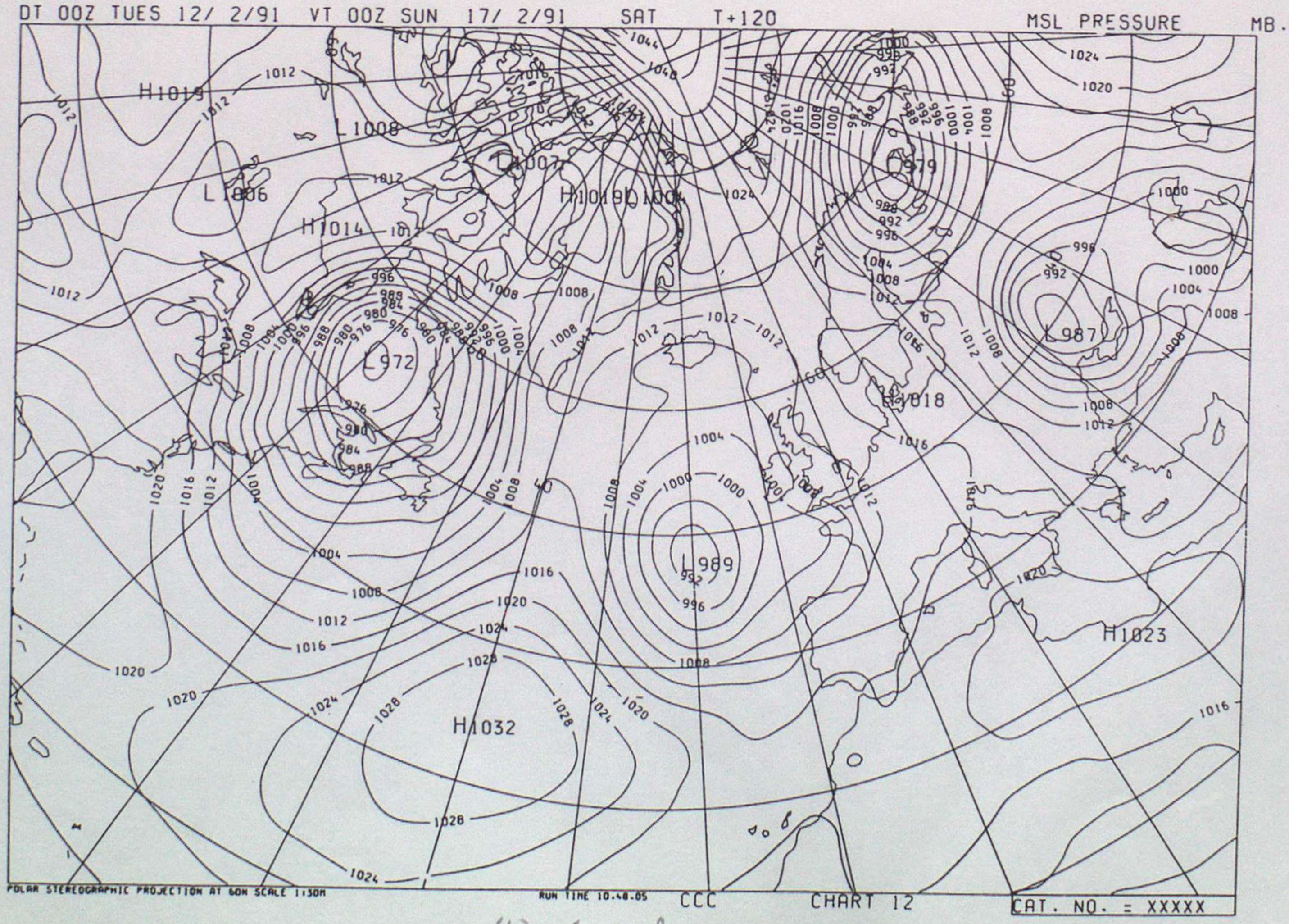


Continuous assimilation cycle started 18z 30/6/91

FIGURE 10 (a) and (b)



(a) Analysis

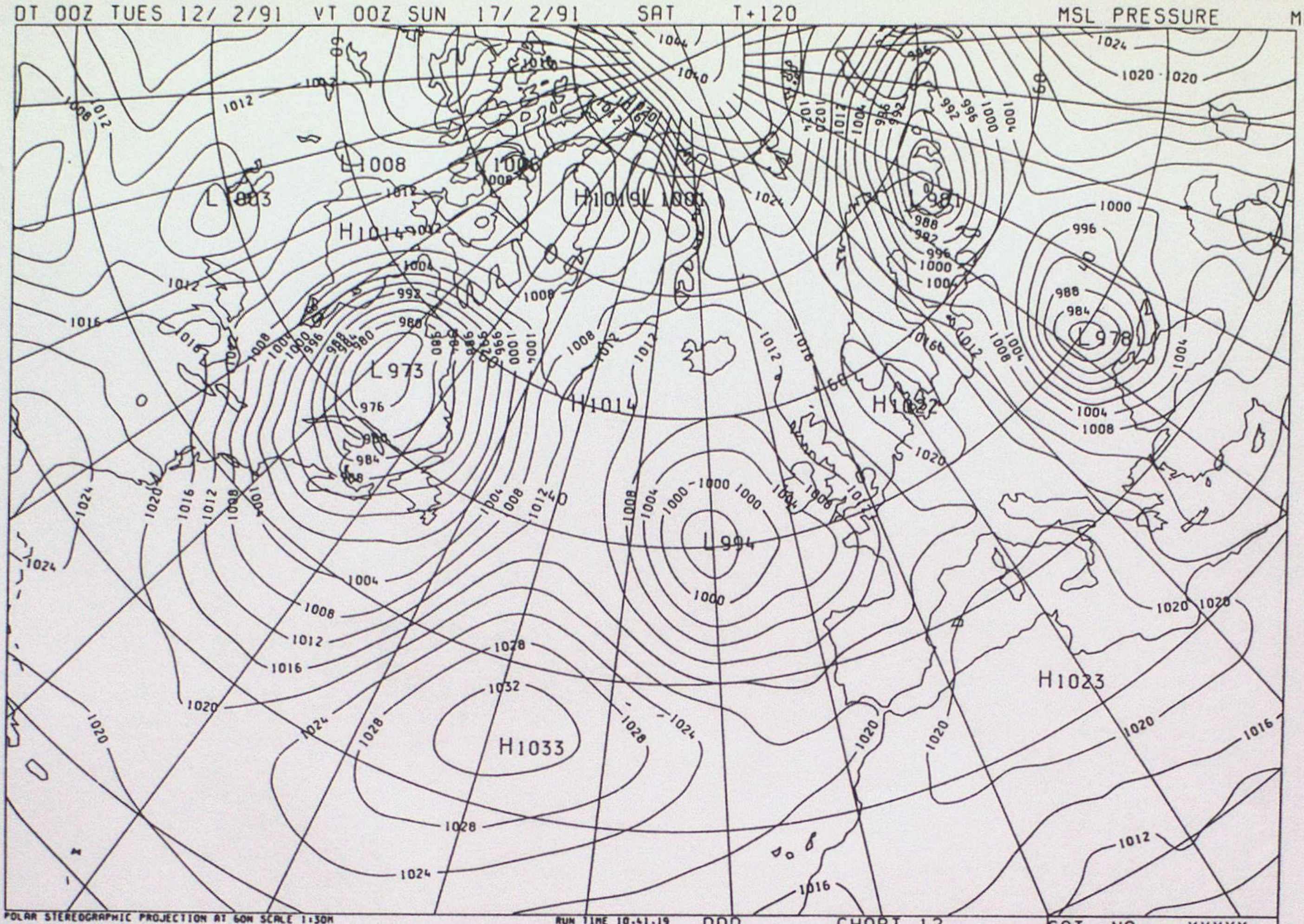


(b) Control

Figure 10

FIGURE 10 (c) and (d)

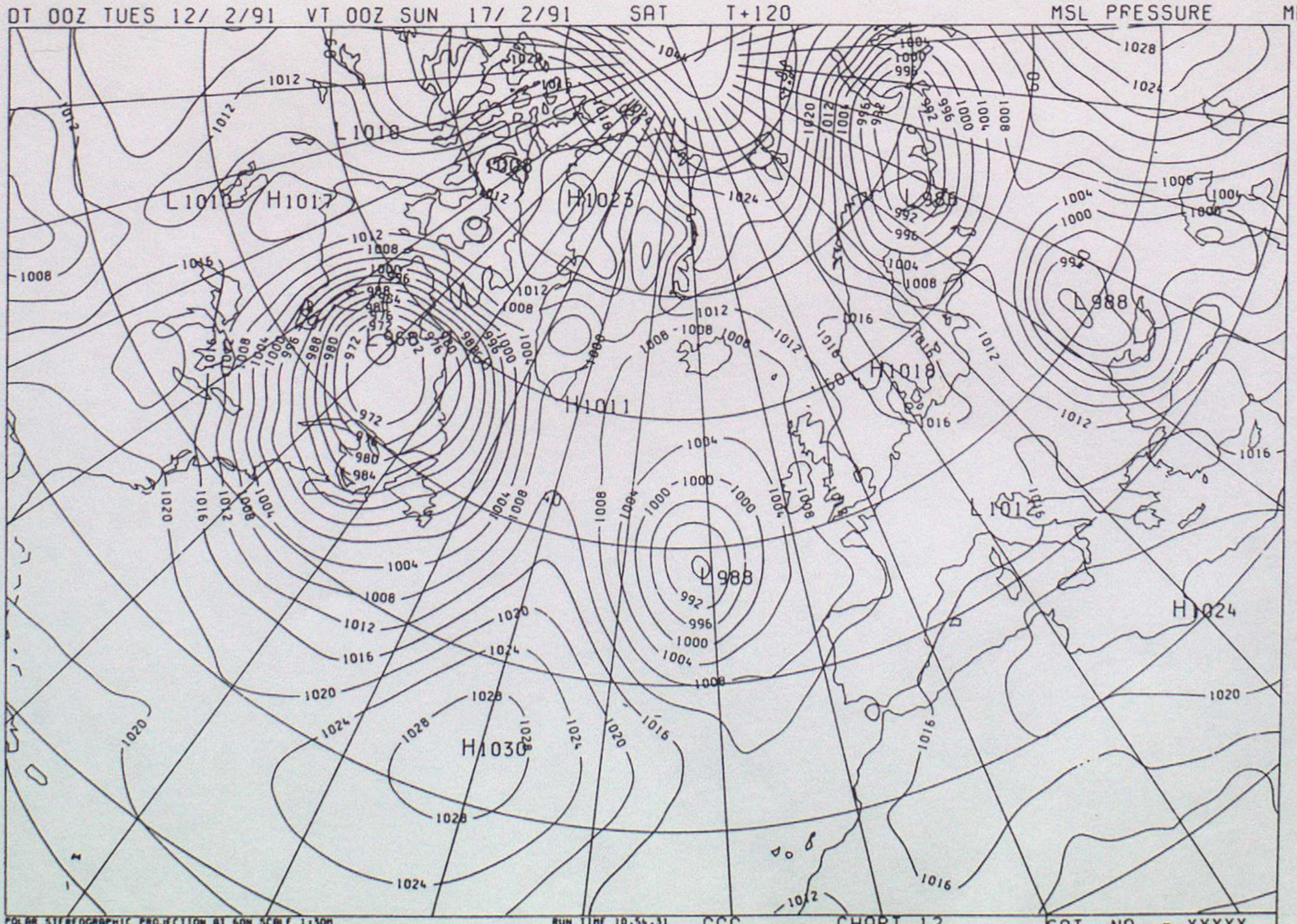
DT 00Z TUES 12/ 2/91 VT 00Z SUN 17/ 2/91 SAT T+120 MSL PRESSURE MB.



POLAR STEREOGRAPHIC PROJECTION AT 60N SCALE 1:30M RUN TIME 10.41.19 DDD CHART 12 CAT. NO. = XXXXX

(c) D4D2

DT 00Z TUES 12/ 2/91 VT 00Z SUN 17/ 2/91 SAT T+120 MSL PRESSURE MB.

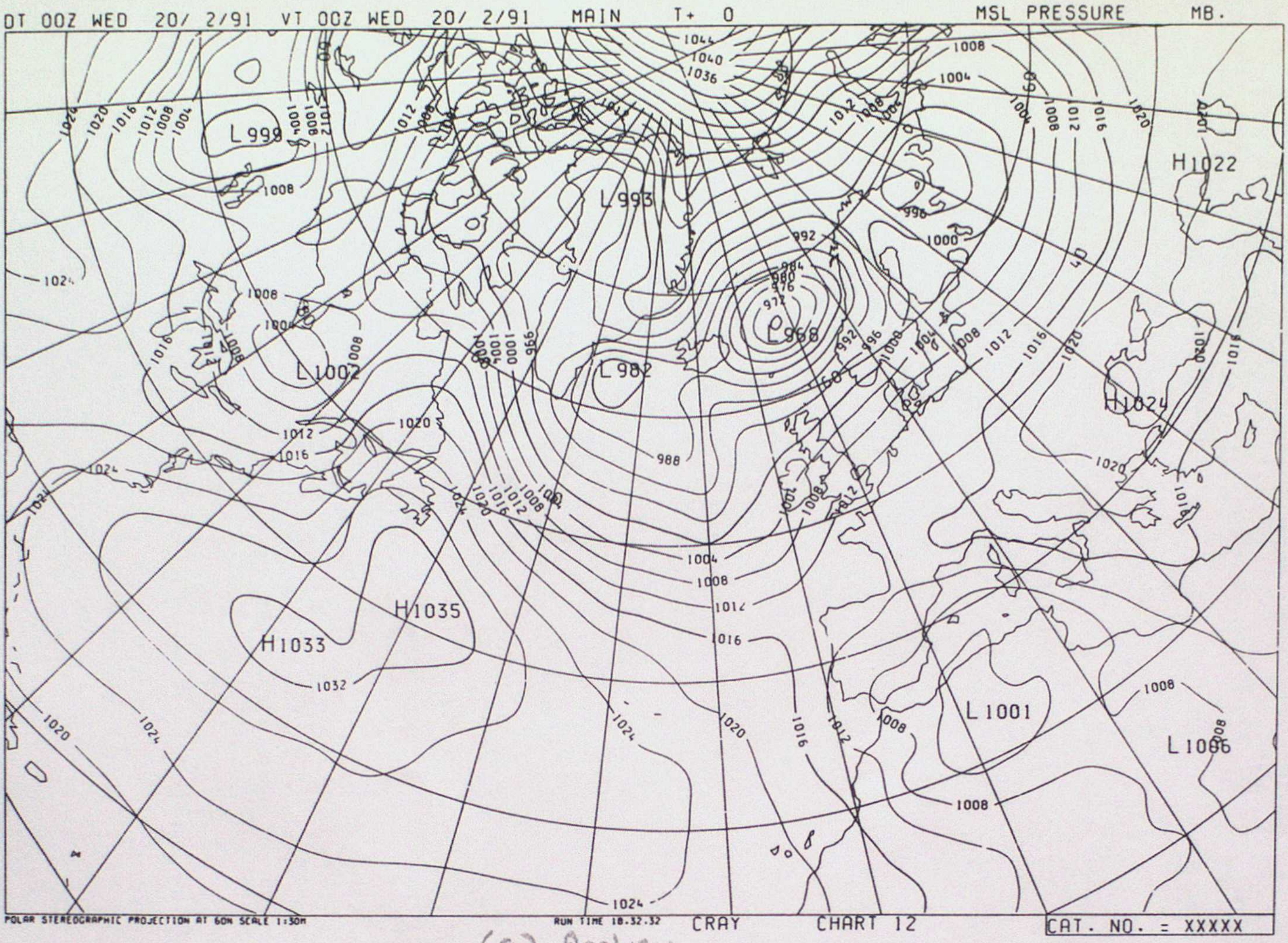


POLAR STEREOGRAPHIC PROJECTION AT 60N SCALE 1:30M RUN TIME 10.54.31 GGG CHART 12 CAT. NO. = XXXXX

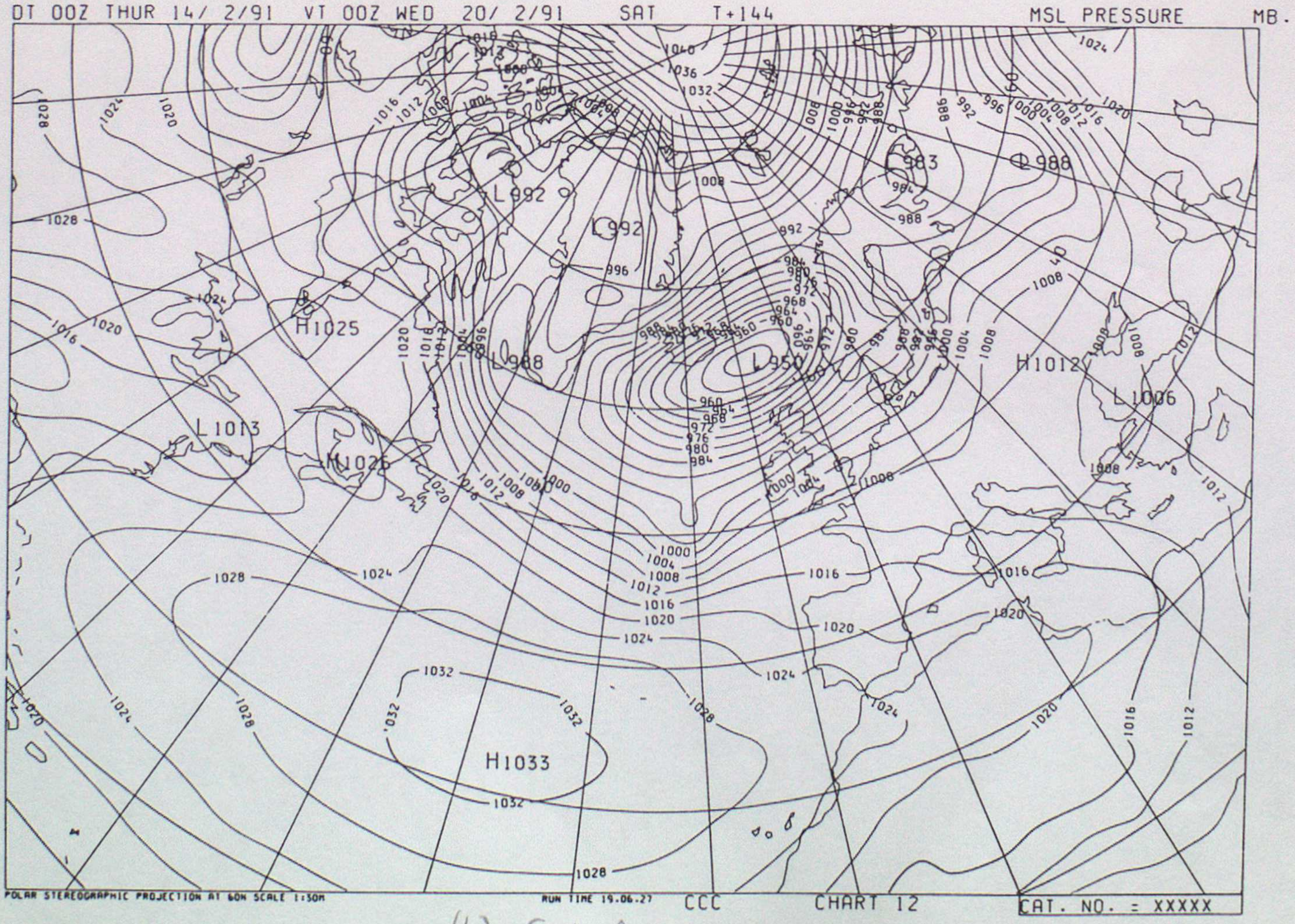
(d) GWLINP

Figure 10

FIGURE 11 (a) and (b)



(a) Analysis

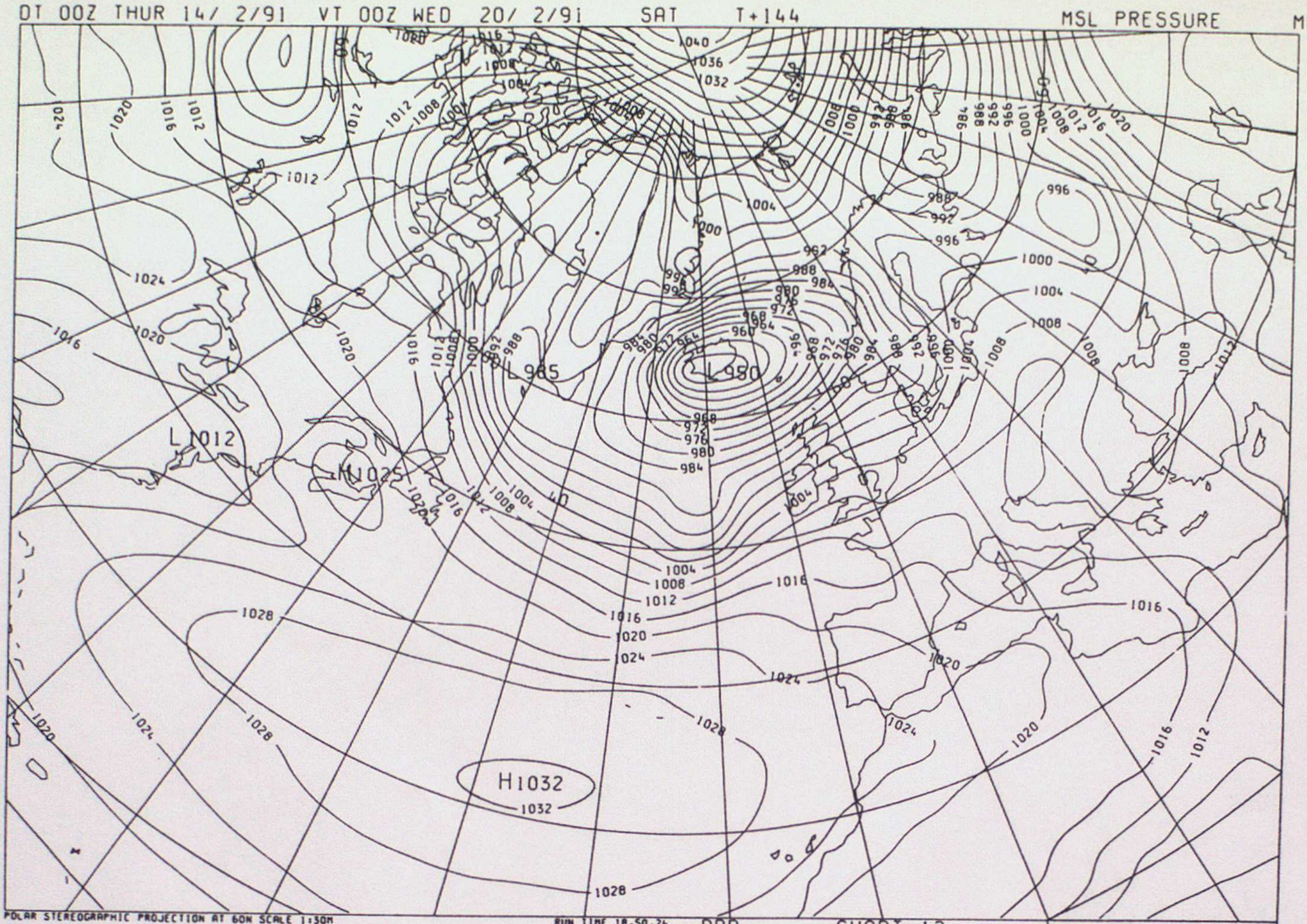


(b) Control.

Figure 11

FIGURE 11 (c) and (d)

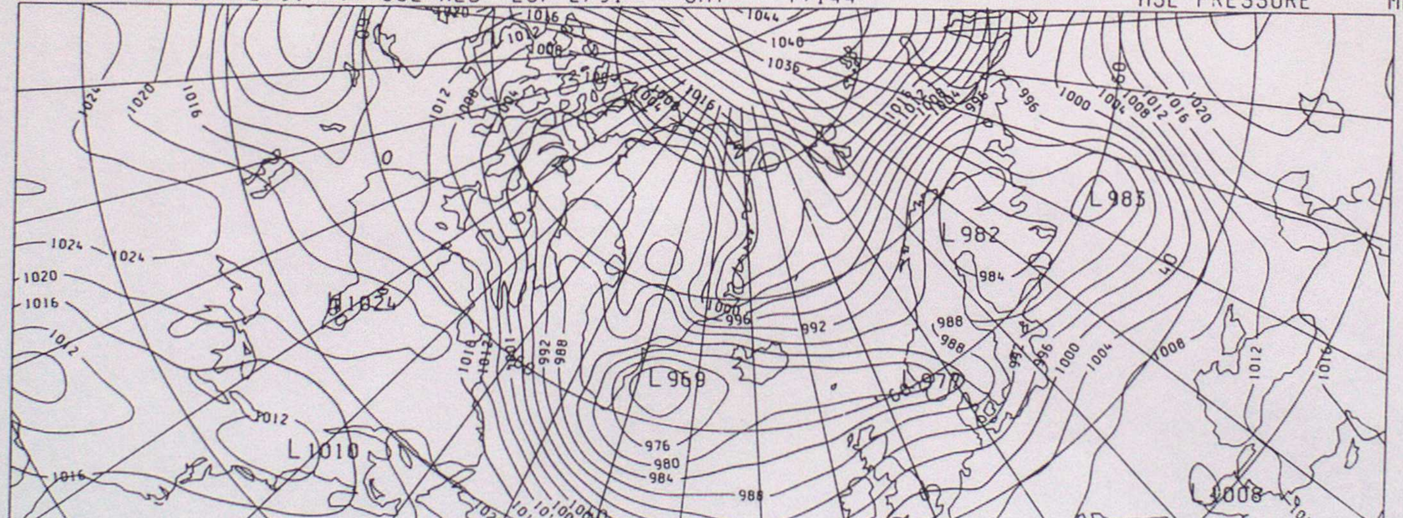
DT 00Z THUR 14/ 2/91 VT 00Z WED 20/ 2/91 SAT T+144 MSL PRESSURE MB.



POLAR STEREOGRAPHIC PROJECTION AT 60N SCALE 1:30M RUN TIME 18.50.24 DDD CHART 12 CAT. NO. = XXXXX

(c) D4D2

DT 00Z THUR 14/ 2/91 VT 00Z WED 20/ 2/91 SAT T+144 MSL PRESSURE MB.



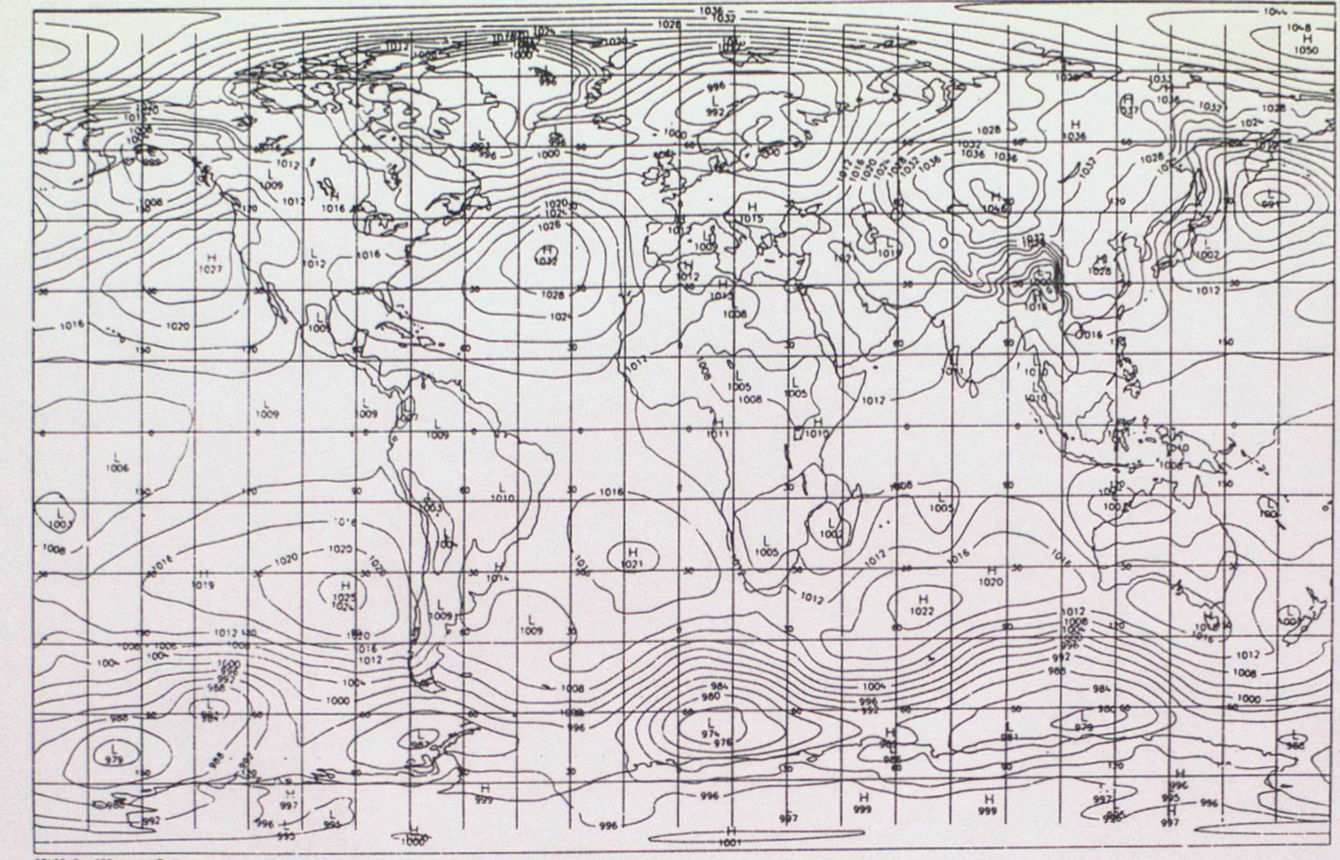
POLAR STEREOGRAPHIC PROJECTION AT 60N SCALE 1:30M RUN TIME 19.14.17 GGG CHART 12 CAT. NO. = XXXXX

(d) GWLINP

Figure 11

FIGURE 12 (a) and (b)

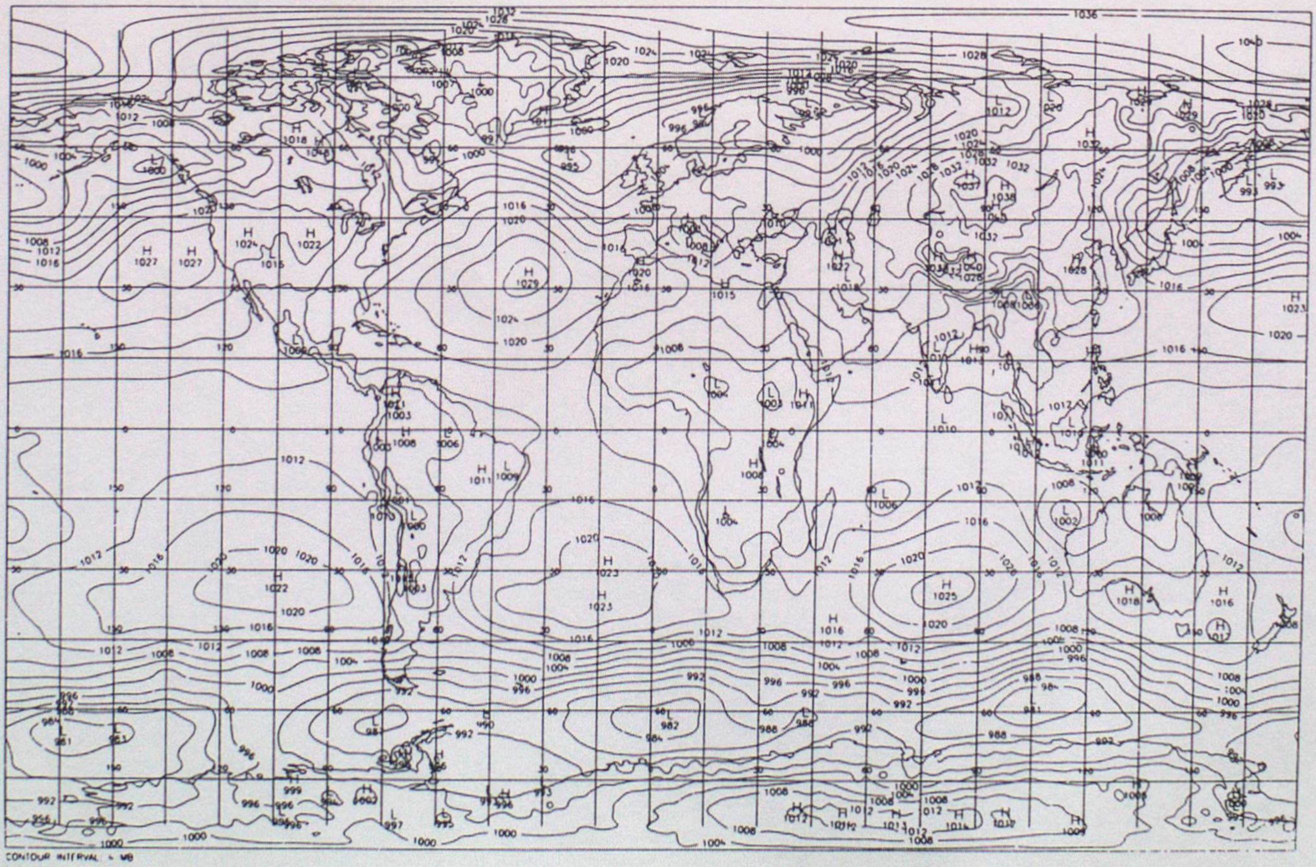
MSLP FROM THE UNIFIED MODEL
IN .UUANAL.FEB1521M
AVERAGE FROM 0Z ON 15/2/1991 TO 0Z ON 21/2/1991
SEA LEVEL EXPERIMENT NO.: 1



CONTOUR INTERVAL 4 MB

(a) Analysis

MSLP FROM THE UNIFIED MODEL
IN .UCONSEQ.MSLP144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
SEA LEVEL T+144



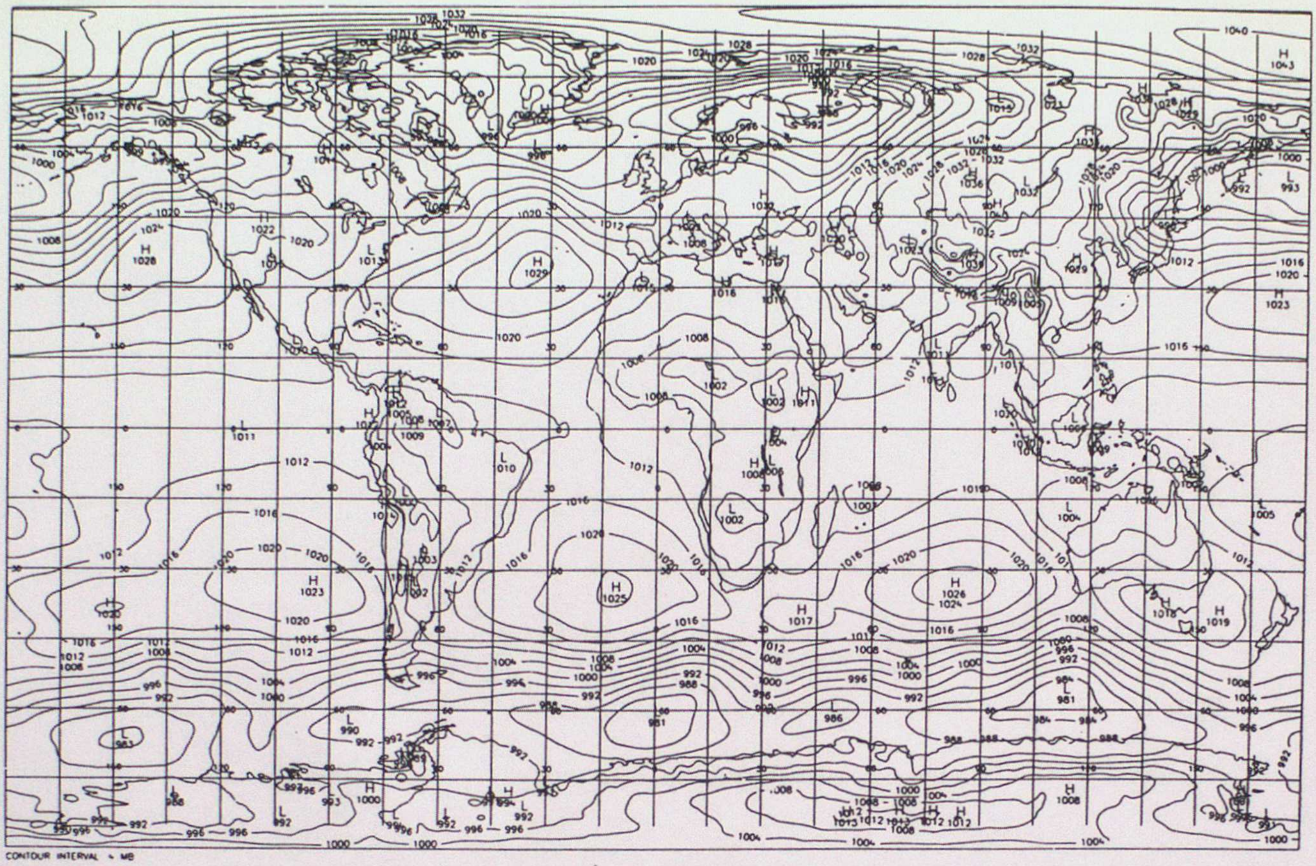
CONTOUR INTERVAL 4 MB

(b) Control

Figure 12

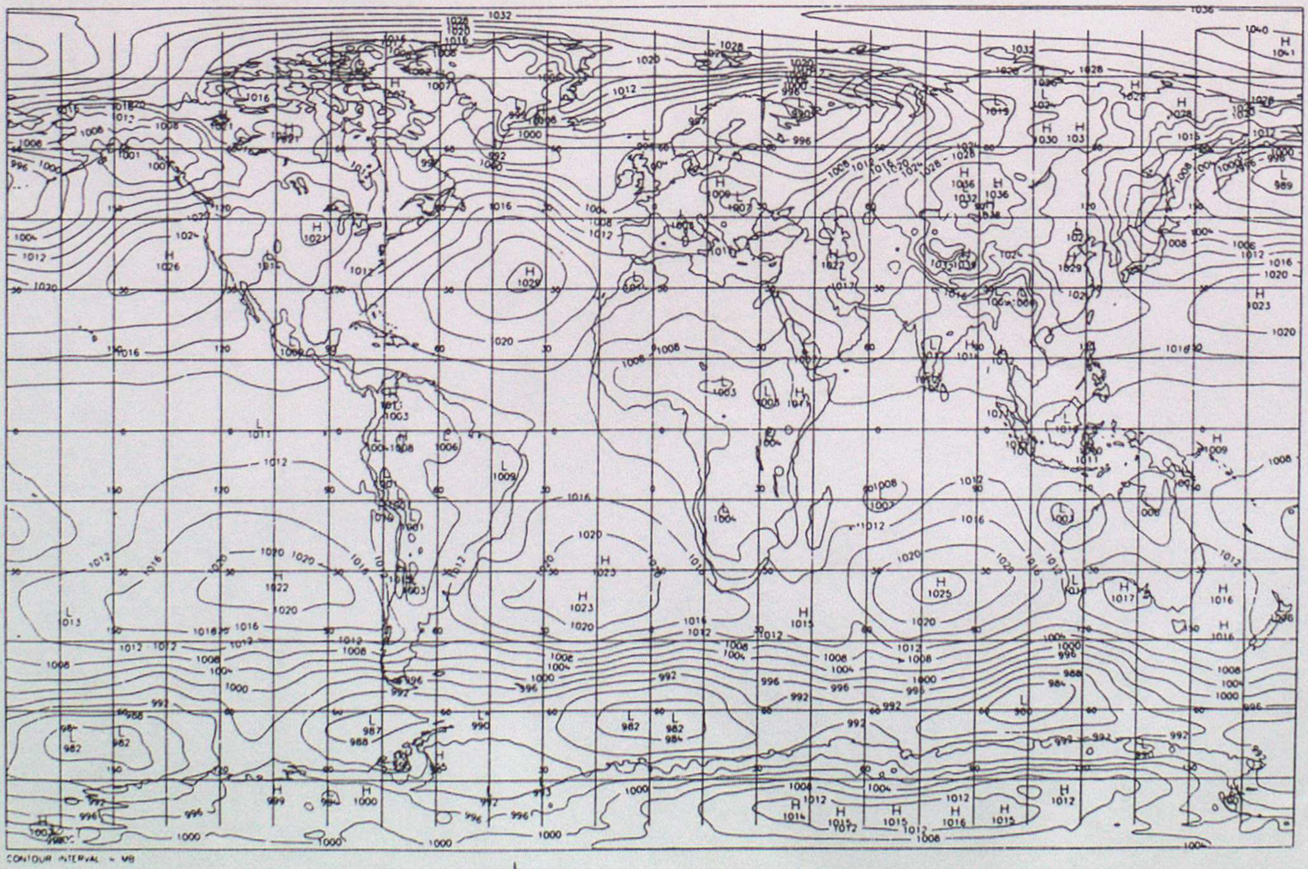
FIGURE 12 (c) and (d)

MSLP FROM THE UNIFIED MODEL
IN .UD42SEQ.MSLP144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
SEA LEVEL T+144



(c) D4D2

MSLP FROM THE UNIFIED MODEL
IN .UGWLSEQ.MSLP144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
SEA LEVEL T+144

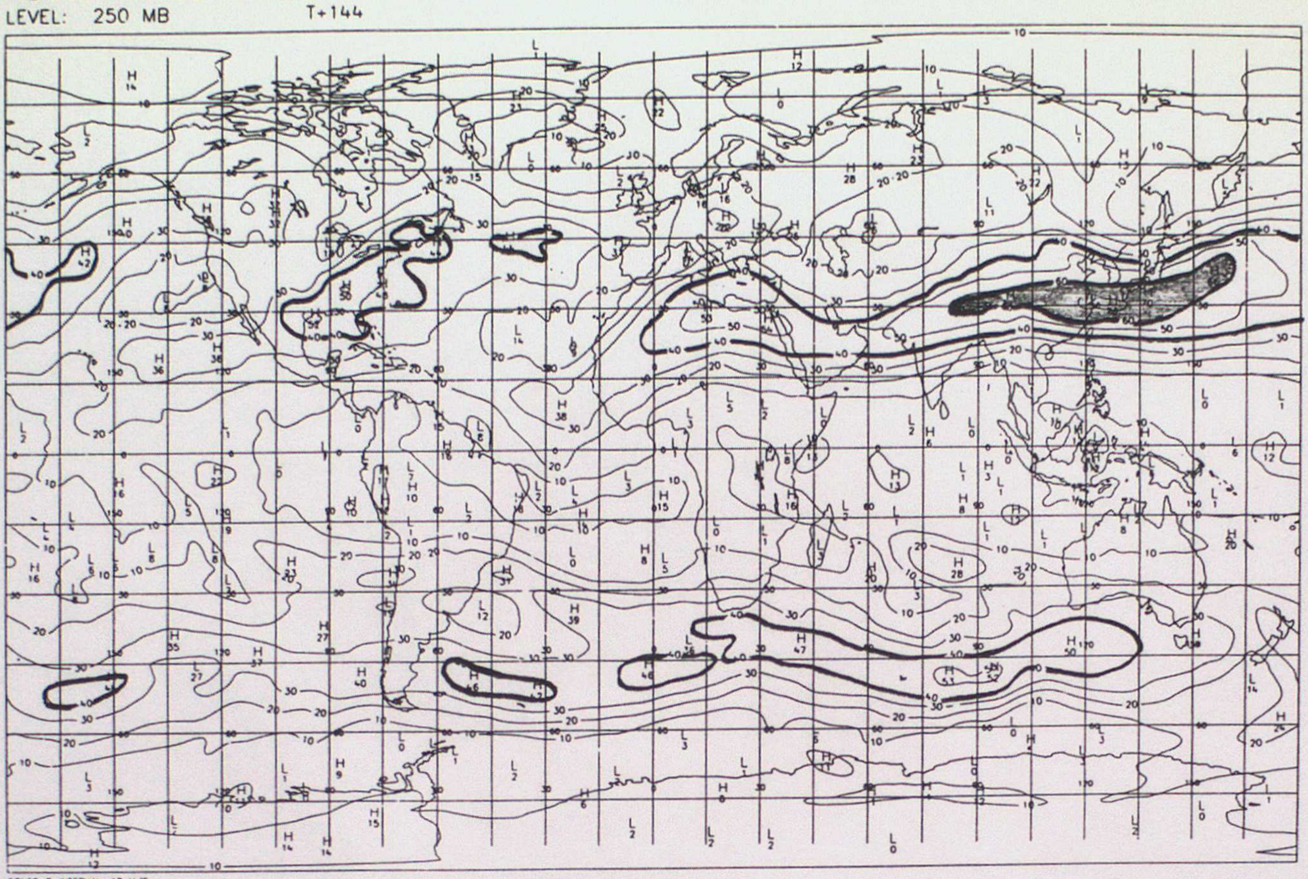


(d) GWLINP

Figure 12

FIGURE 13 (a) and (b)

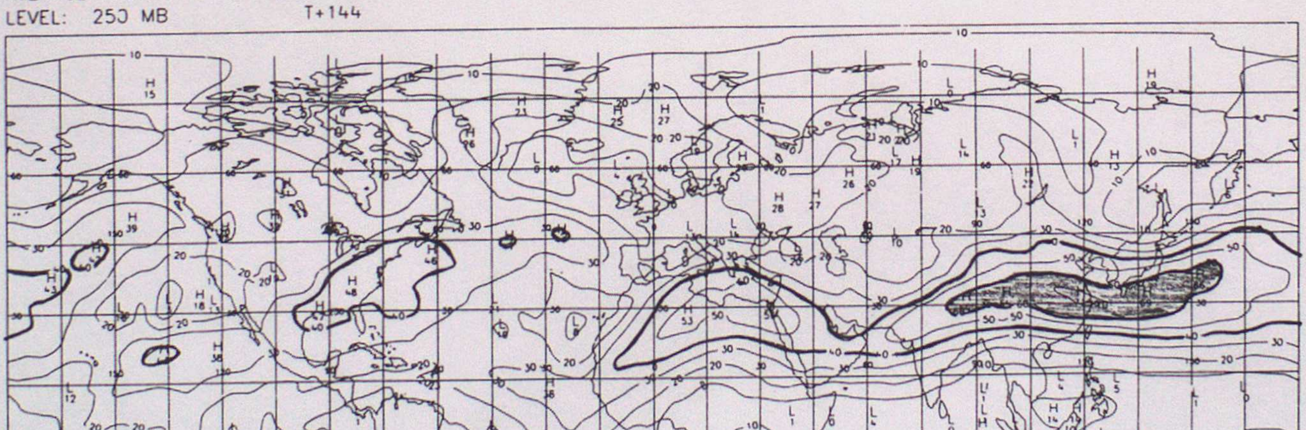
WIND FIELD FROM THE UNIFIED MODEL
IN .UCONSEQ
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
LEVEL: 250 MB T+144



CONTOUR INTERVAL: 10 M/S

(a) Control

WIND FIELD FROM THE UNIFIED MODEL
IN .UD42SEQ
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
LEVEL: 250 MB T+144



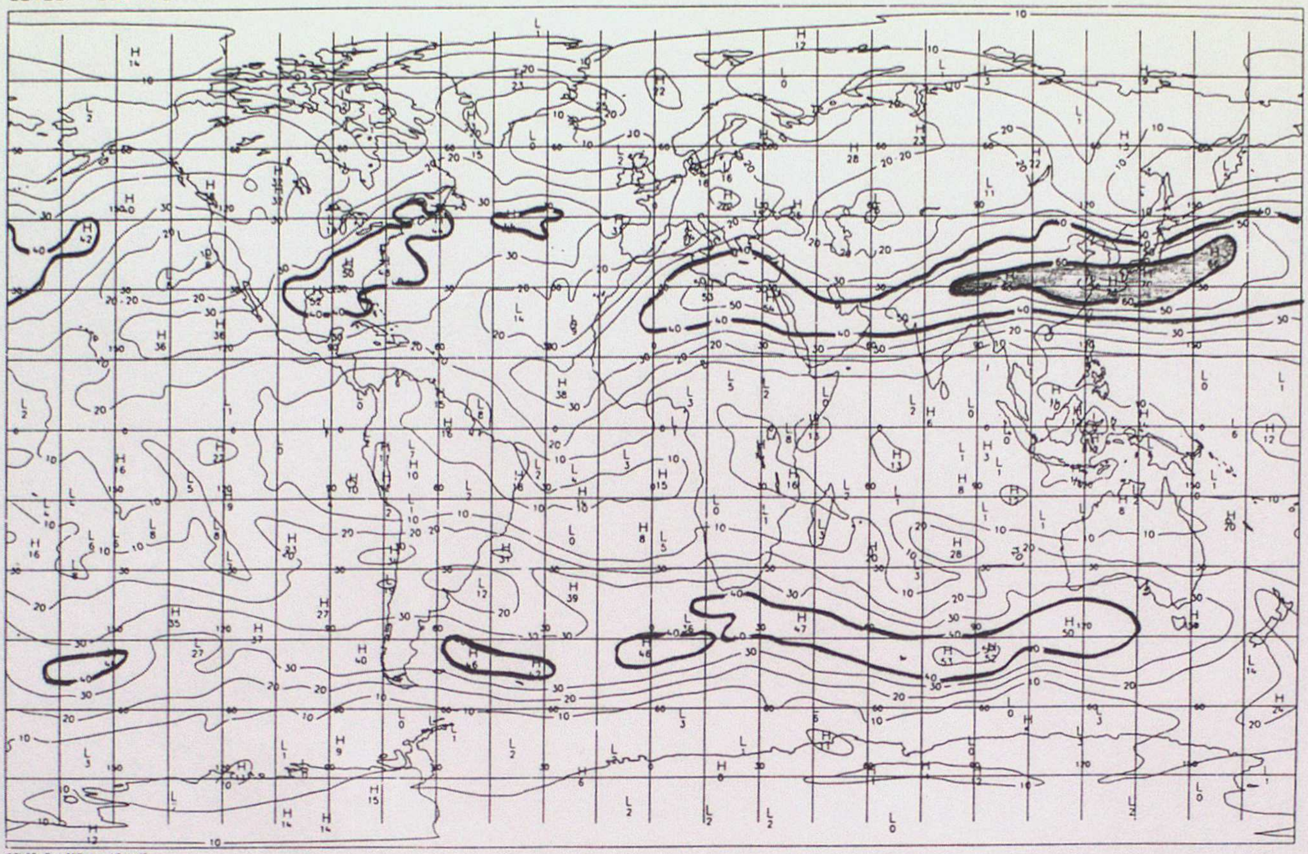
CONTOUR INTERVAL: 10 M/S

(b) D4D2

Figure 13

FIGURE 14 (a) and (b)

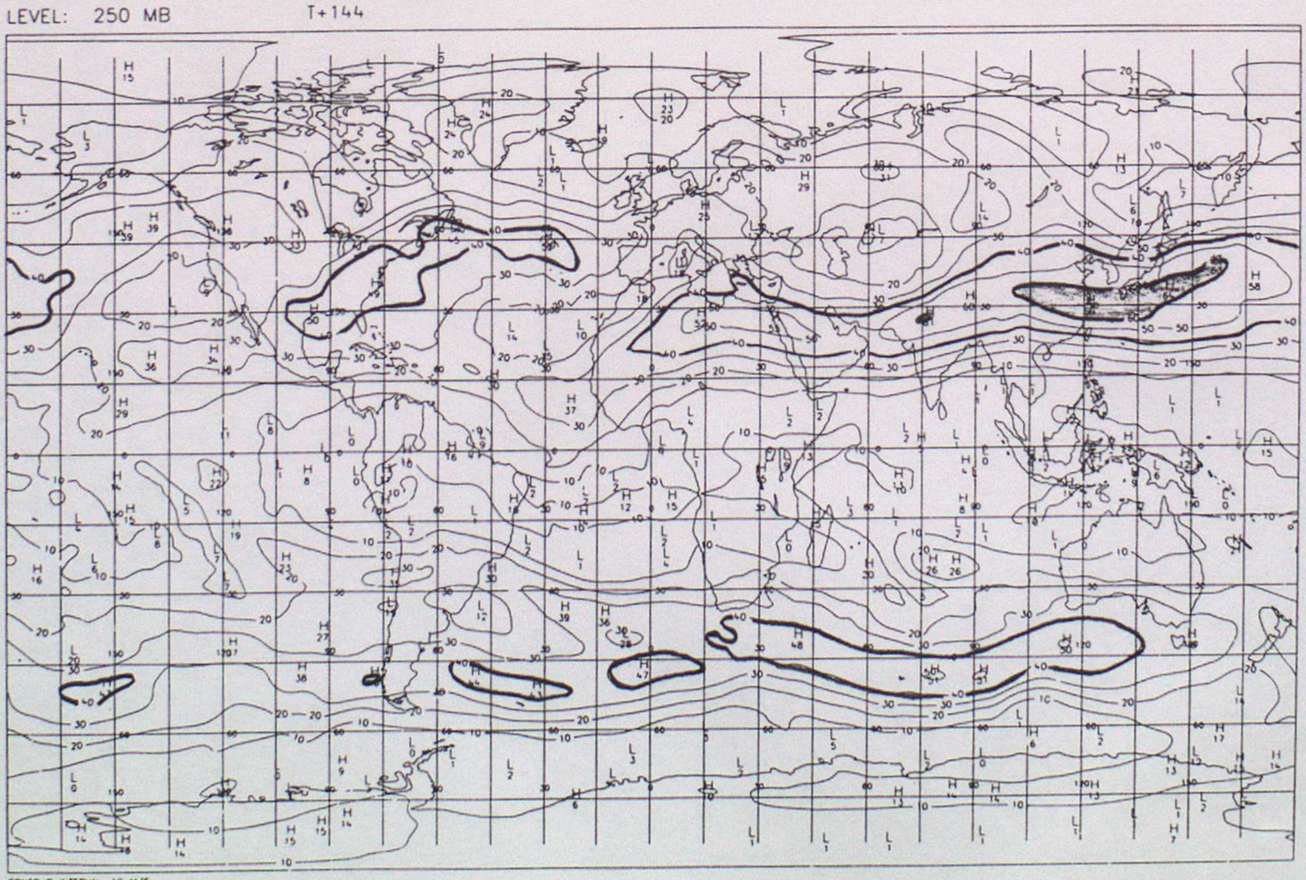
WIND FIELD FROM THE UNIFIED MODEL
IN .UCONSEQ
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
LEVEL: 250 MB T+144



CONTOUR INTERVAL: 10 M/S

(a) Control

WIND FIELD FROM THE UNIFIED MODEL
IN .UGWLSEO
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
LEVEL: 250 MB T+144



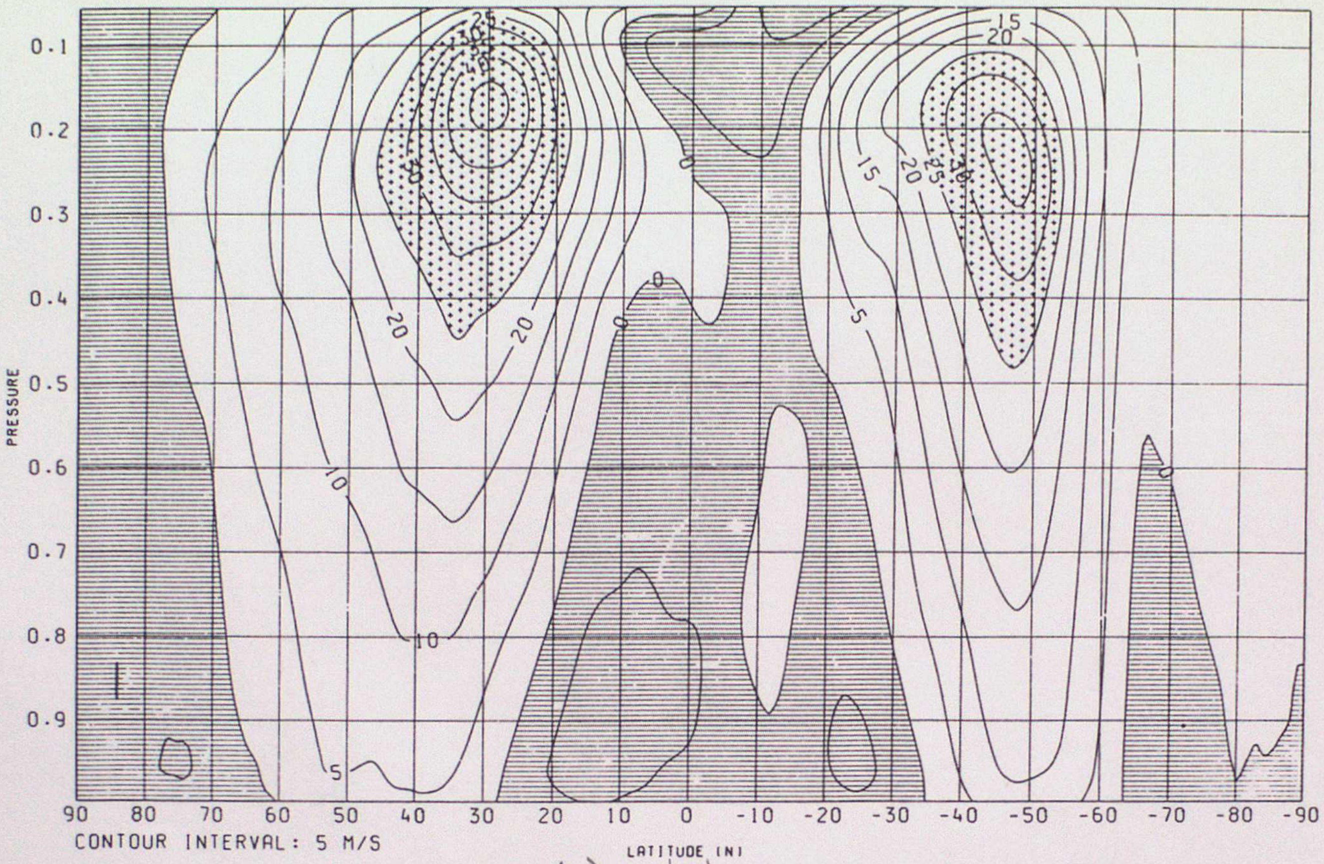
CONTOUR INTERVAL 10 M/S

(b) GWLINP.

Figure 14

FIGURE 15 (a) and (b)

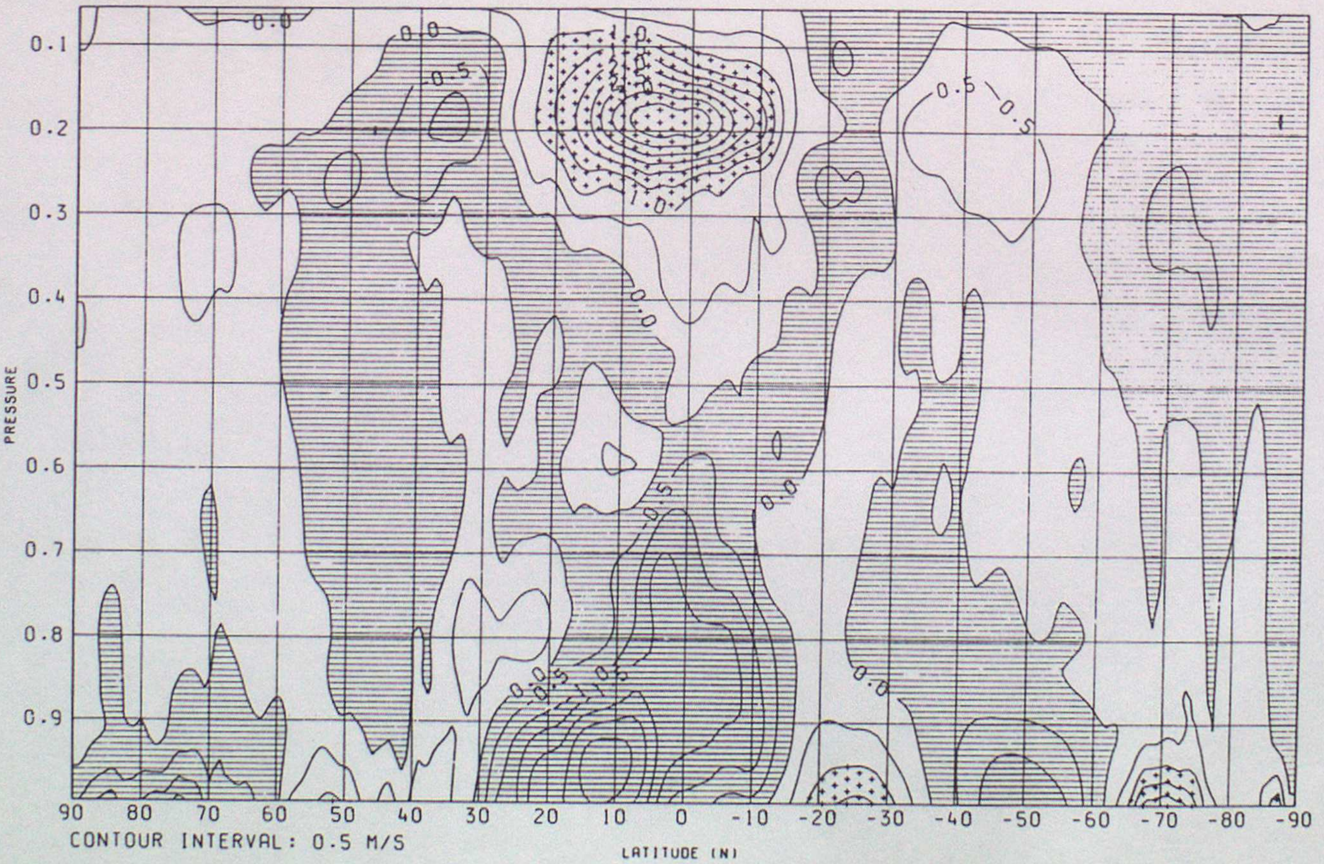
ZONAL MEAN U-WIND
IN .UCONSEQ.DC144M
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED



CONTOUR INTERVAL: 5 M/S

(a) 'u'

ZONAL MEAN V-WIND
IN .UCONSEQ.DC144M
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED



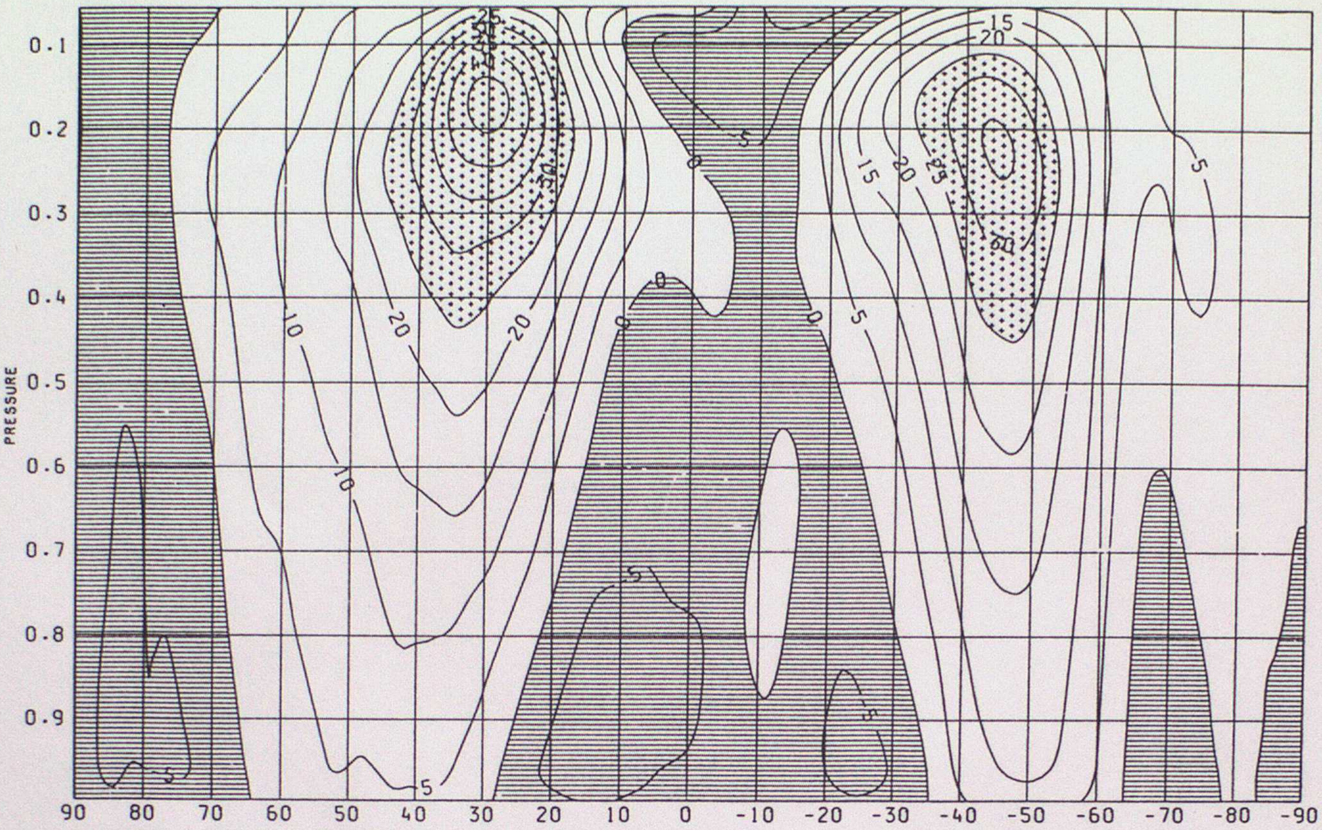
CONTOUR INTERVAL: 0.5 M/S

(b) 'v'

Figure 15

FIGURE 16 (a) and (b)

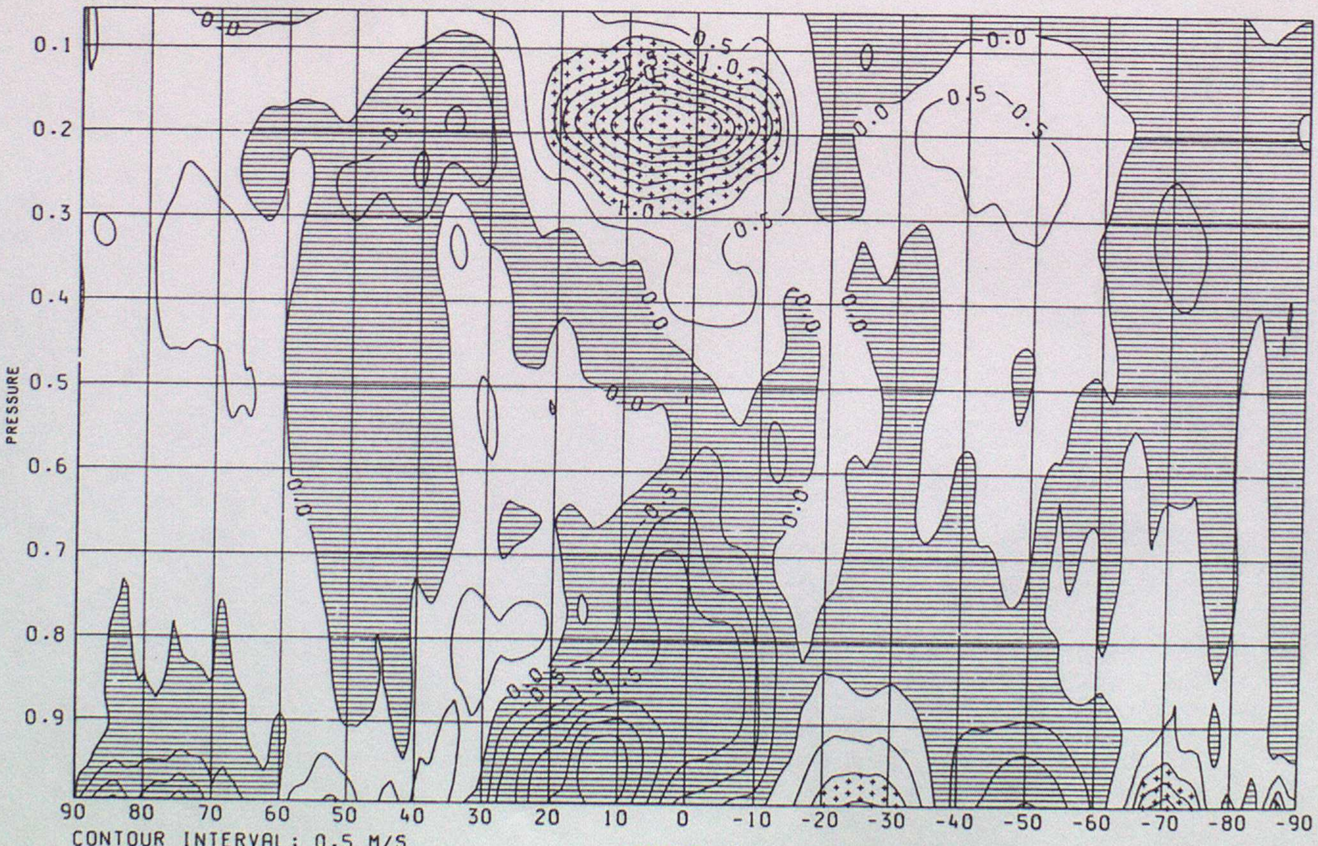
ZONAL MEAN U-WIND
IN .UD42SEQ.WIND144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED



CONTOUR INTERVAL: 5 M/S

(a) 'u'

ZONAL MEAN V-WIND
IN .UD42SEQ.WIND144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED

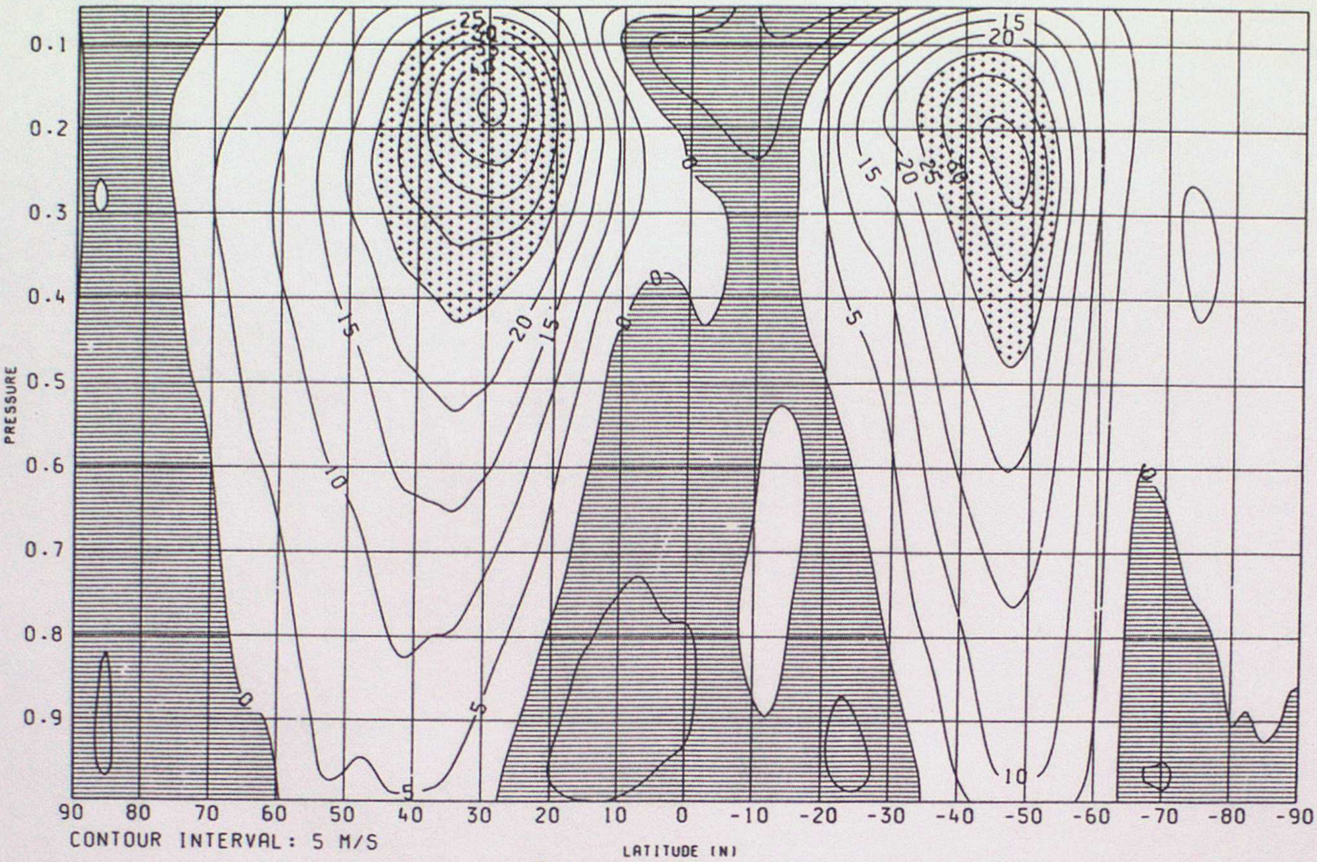


CONTOUR INTERVAL: 0.5 M/S

Figure 16 (b) 'v'

FIGURE 17 (a) and (b)

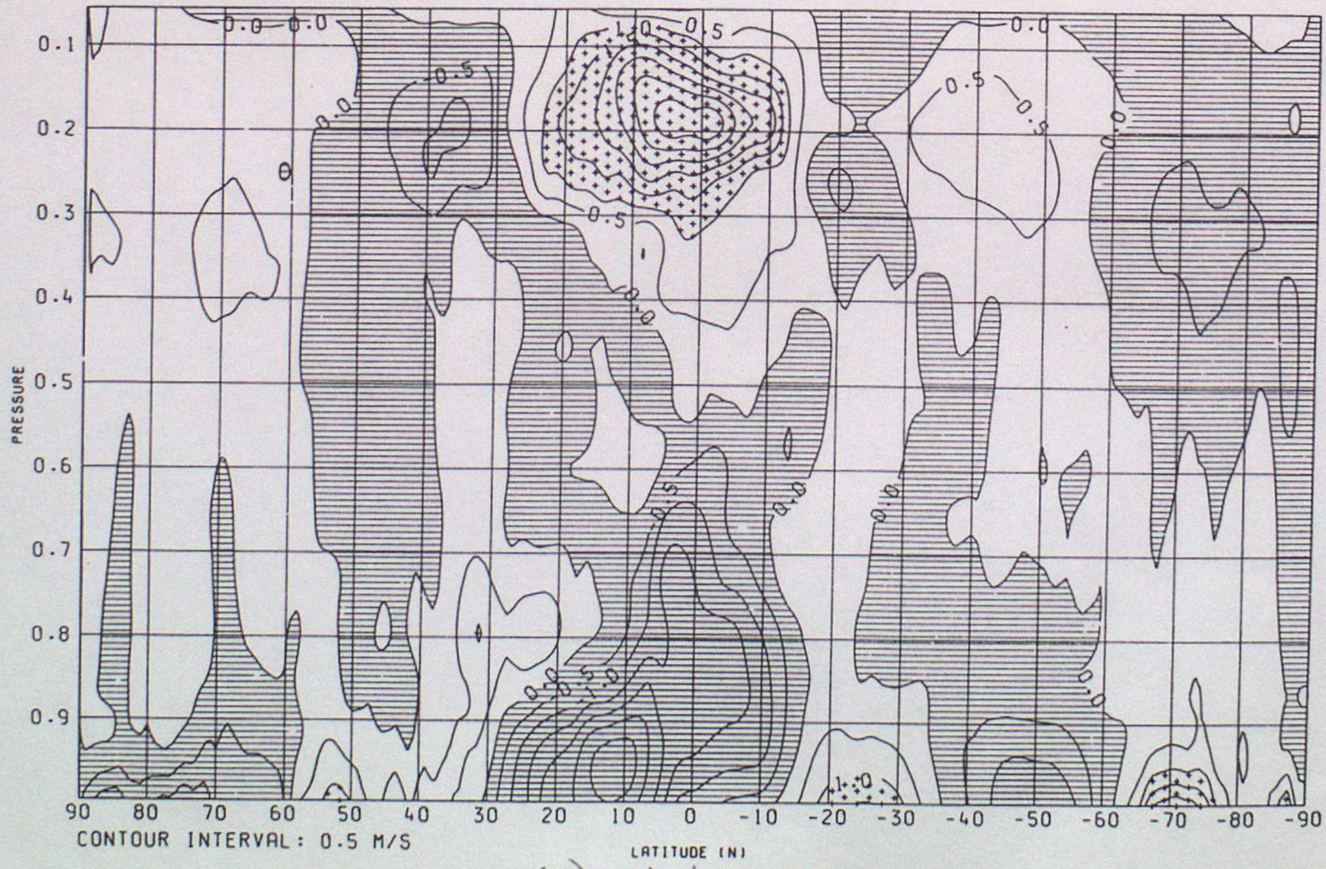
ZONAL MEAN U-WIND
IN .UGWLSEQ.WIND144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED



CONTOUR INTERVAL: 5 M/S

(a) 'u'

ZONAL MEAN V-WIND
IN .UGWLSEQ.WIND144
AVERAGE FROM 0Z ON 15/2/1991 DAY 46 TO 0Z ON 21/2/1991 DAY 52
NEGATIVE VALUES SHADED



CONTOUR INTERVAL: 0.5 M/S

(b) 'v'

Figure 17