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Boundary layer structures and surface variables in operational forecasts

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1. Introduction

The two operational forecast models, the global model and the limited area fine-mesh model, both use the same scheme to describe the transfer of heat, moisture and momentum through the earth's boundary layer. This scheme is due to Richards (1980) and is fully described by Dickinson (1985). The companion paper at this meeting (Carson (1986)) has described the general methods for modelling land surface interactions and the boundary layer. I shall make only a few brief points regarding certain aspects of the operational scheme before reviewing the forecast results in the following sections. The boundary layer in the operational models has a maximum of four levels contained within it, at heights above model topography of approximately 25m, 200m, 550m and 1200m. The boundary layer top is diagnosed as the model half level at which the vertical heat flux falls to zero. The boundary layer depth can, therefore, take a value of 50m, 350m, 750m or 1600 metres approximately, these values being the top of the layers whose mid-points are defined by the model levels. The thin bottom layer has caused some problems with this scheme, because the vertical diffusion equations are solved explicitly and it is necessary to limit the size of the fluxes to the maximum allowable for computational stability. In atmospherically unstable conditions this leads to truncation of the surface fluxes and to overcome this the bottom two layers are coupled together and the excess surface flux beyond the maximum which is permitted for computational stability is passed through the bottom level and attributed to the next level. A convective adjustment is performed to remove any instability within the bottom layers.

The other diagnosed quantity is surface temperature. An important part of the prediction equation for surface temperature, in addition to the radiative, sensible and latent heat flux terms, is a term to model the heat flux between the surface and deeper soil layers. This additional term was only incorporated into the scheme for fine-mesh operational forecasts during December 1985 and has not yet been implemented in the operational global model. In relation to surface temperature forecasting, it is worth bearing in mind that the specification of surface type is comparatively crude. Land grid points are assigned one of four surface types: "snow- covered", "ice-covered", "temperate" or "arid". These values are based on monthly climate data and a fixed value of soil moisture content is assigned depending and the surface type. There is scope for the soil moisture content to be manually adjusted for specific temperate regions in very dry summer conditions and also the retention of surface moisture by vegetation is catered for by including a surface resistance to evaporation during summer months.

This assessment of the scheme is divided into two parts. Section two will consider how well model profiles of temperature and moisture match verifying radiosonde profiles. Section three gives some results of the forecasts of surface variables. It is by no means obvious that the problems which are highlighted by the following subjective and objective verifications can be attributed to the boundary layer and surface parametrization. It is possible that the model dynamics may be incorrectly treating the thin bottom layers. Also the physical parametrizations are inter-related and it is difficult to partition the combined impact of the boundary layer scheme, the penetrative convection scheme and the interactive radiation scheme. Nevertheless, in the absence of suitable observations of the relevant fluxes it is worthwhile seeing what can be inferred from this indirect assessment.

2. Boundary Layer Structures

The forecast profiles being considered in this section have been selected after a close comparison of many forecast profiles with appropriate verifying radiosonde profiles. The chosen profiles from December 1985 demonstrate how the model performs in different situations and are intended to be representative of those different situations. All the profiles in Figures 1, 2 and 3 follow the same format. The thin computer drawn lines represent verifying observations from radiosondes and the thicker hand drawn lines represent 24 hour fine-mesh forecasts at the nearest gridpoint to the observation position. Solid lines give the temperature profile and pecked lines the dewpoint profile. Bearing in mind the relatively coarse vertical resolution the model forecast profiles show broad agreement with the observations, though some characteristic problems are evident.

Figure (1a) gives comparison profiles for Camborne on the 2nd December 1985. A strong cyclonic southwesterly situation existed and the observed ascent was moist to tropopause levels but not saturated. The model forecast at that time was much nearer saturation, although the shape of the two profiles is fairly similar. It has often been the case that too much rain is forecast by the model in these southwesterly warm sector situations. In contrast, figure (1b) shows the forecast and observed profiles at Camborne on the 13th December 1985. An anticyclonic southwesterly flow had persisted for several days and, as can be seen from the observations, the low levels were very moist. The forecast temperature profile was quite good at the lowest levels and the diagnosed boundary layer depth of 350 metres was probably not far wrong but, except at the bottom level of the model, the forecast moisture profile was much too dry, especially at higher levels. As a contrast in frontal regions the forecast profiles of both moisture and temperature are generally good as the comparison at Stornoway (Fig 1c) on the 17th December 1985 shows.

Fig (1d) is an example of a fog situation at Hemsby on the 10th December 1985. Given that the forecast model has only five levels below 750 mb, the forecast temperature profile matches the observed structure well. The forecast surface temperature is rather too cold, but this forecast was made before the introduction of the scheme which models the heat flux from deeper soil layers and the present version of the model would be significantly warmer at the surface. The shallow boundary layer is well represented and the forecast boundary layer depth has taken its lowest possible value of 50 metres. The main problem is the excessive dryness above the boundary layer which we have also seen in Fig (1b).

Fig (2a) shows the Shanwell profiles for the 13th December 1985. The flow was westerly with a front lying east-west across Northern England. This forecast profile is one of the few instances during December when the forecast boundary layer depth took its maximum value of 1600 metres. However, this was incorrect because the actual strong inversion at 880 mb has been missed. Experience suggests that the occurrence of deep forecast boundary layers is frequently confined to isolated gridpoints (except in very unstable situations). Figure 4 shows the forecast boundary layer depth for this case. The "bulls-eyes", representing single gridpoints with deep boundary layers, close to Shanwell and Aughton stand out clearly. The discrete nature of the boundary layer parametrization scheme where each gridpoint is treated in isolation to its neighbours does not contribute to the control of such features. It is noticeable that they nearly always occur at coastal grid points. Discontinuities such as land-sea boundaries or cloud boundaries have been recognised as a problem and the operational model now incorporates a filter to smooth the boundary layer increments of temperature and humidity before they are added to the model fields.

Figures (2b), (2c) and (2d) show profiles at Crawley on three consecutive days, 15th-17th December 1985. There was a weak front over the area on the 15th which moved away and the ridge extending from a stationary high pressure area over France became dominant. The profiles for the 15th (Fig 2b) are included because they illustrate the degree to which the forecast temperature profile (given its coarse vertical resolution) can represent a very complicated ascent. However the moisture profile from the model is completely wrong. It appears that when the model has a less stable layer between adjacent layers the upper of the two bounding surfaces is too moist whilst when the model has a stable layer, its upper boundary is too dry. On the 16th, there was a very strong inversion of 14°C across a very thin layer. This is clearly too fine scale a feature to be forecast by the model; the model has a completely incorrect profile below 900 mb. Similar profiles were noted at Aughton and Hemsby. The model has diagnosed a boundary layer depth which is about one model level too low and as a result is strongly stable from the surface upward rather than being nearly neutral to 900 mb. The surface humidity is quite well predicted but the dry layer, which in reality was above 900 mb, actually extends down to 975 mb in the forecast. The strongest inversion that the model generates in this case is about 1° or 2° between adjacent levels. The following day, (Fig 2d) the inversion has weakened and risen and the forecast profile is more realistic, though still incorrect. The diagnosed boundary layer depth in the forecast is 750 metres which is too low and the model is much too dry and warm between 900 and 850 mb. However the model resolution is such that the next highest model boundary layer depth is 1600m which would be greater than that observed.

The profiles in Figures (3a) and (3b) are for Camborne on the 19th and Crawley on the 20th December 1985. The flow was still predominantly West/Southwesterly. Weak showery troughs had recently crossed the country and the flow was rapidly stabilising ahead of an approaching warm front. Both figures show similar features. The relative coarseness of the vertical resolution gives a boundary layer which is apparently too shallow. The forecasts tend to be slightly warm at higher levels and most characteristically are much too dry at those same levels.

The final two pairs of profiles verifying on the 22nd December 1985 illustrate how unstable situations are handled. The ascents for Long Kesh (Fig 3c) and Camborne (Fig 3d) were both unstable for moist ascent to about 18000 feet with Camborne being marginally more unstable. The forecast profile for Camborne on the 22nd was the only one of the twelve discussed here where the surface fluxes were larger than the maximum allowable for computational stability and where the measure of transmitting part of the fluxes directly to the second level came into operation. Both figures exhibit the characteristic dry slot above the top of the boundary layer. An interesting difference between the two forecast ascents is at the surface where Long Kesh is saturated and Camborne is much drier. It is worth noting, however, that the Long Kesh gridpoint is considered by the model to be a land point whilst the Camborne gridpoint is a sea point. There do not seem to be any adverse effects at the Camborne gridpoint, due to the method of dealing with large surface fluxes. Kitchen (1986), who has recently developed an implicit scheme for vertical turbulent transfers within the boundary layer which is capable of accommodating large vertical fluxes directly without becoming numerically unstable, has suggested there is little difference above the bottom two levels between the implicit and explicit methods of calculation.

3. Verification of Surface Variables

Routine verifications of short period surface forecasts are available which compare forecasts with reports from all the UK synoptic stations. Only forecasts up to 12 hours are verified in this manner because the package has been designed for comparisons with short period forecasts from the mesoscale model. Objective verification of the fine-mesh forecasts against radiosondes are also undertaken operationally. Table 1 gives results of 24 hour fine-mesh forecast verification at 850 mb against radiosondes for January 1986. All radiosondes within the fine-mesh domain have been used.

	mean error (f/c-ob)		rms error
	land	sea	land and sea
850mb temp (°C)	-0.4	0.0	2.1
850 mb wind speed (knots)	1.4	-0.4	8.8
850 mb Relative Humidity (%)	-0.6	-7.7	20.5

Table 1 Forecast verification against radiosonde (850 mb)

The biases at 850 mb for temperature and wind are in the same sense as those at the surface. The model boundary layer is slightly cold over land and model wind speeds over land are too strong where as the converse is true over the sea.

The model's tendency to be too dry above the boundary layer, which was commented upon in the previous section, only shows up clearly over the sea in these statistics.

When verifying surface forecasts from the fine-mesh model, the model variables are adjusted onto a near surface layer more compatible with real terrain variations (in fact the orography for the mesoscale model) before comparing them with the synoptic reports. The fine-mesh forecast values are interpolated onto a level 10 metres above mesoscale model orography. Where an extrapolation below the fine-mesh bottom level at 25 metres above fine-mesh model orogrpahy is involved the following procedure is adopted. Fine-mesh bottom level values of relative humidity are used directly, a standard lapse rate is used to adjust the temperature and the fine-mesh bottom level winds are scaled by a factor of 0.85. The model screen temperature is assumed to be a mean of the 10 metre value and the interpolated model surface temperature. The gridpoint forecast values are then interpolated horizontally to the observation position.

The rest of the results in this section are based on 12 hour forecasts from 6z and 18z data times during January 1986. Table 2, gives the percentage of all temperature forecasts with a particular error. There were in excess of 5000 forecasts verifying at 6z and a similar number verifying at 18z.

Range of Error (°C) (F/C - OBS)	<-4	-4>-3	-3>-2	-2>-1	-1>0	0>1	1>2	2>3	3>4	>4
Data Time 6z Verif. Time 18z	1	2	6	13	19	21	17	12	5	4
Data Time 18z Verif. Time 6z	2	3	8	13	16	19	17	11	6	5

Table 2 T+12 Temperature Errors

From Table 2 we can see that the model forecasts temperature at 18z correct to within 2°C on 70% of occasions and gross errors in excess of 4°C occur on only 5% of occasions. The comparable figures for 6z forecasts are 65% and 7% respectively. The table also implies that there is a slight bias, with a rather greater proportion of forecasts being warm (58%) than cold. This is slightly misleading as there is a preponderance of stations close to the coast and the interpolation of forecast to observation position may involve a model sea point which at the surface is likely to be warmer than the land during January. A more realistic picture of forecast quality can be obtained by examining maps of forecast error. Figure 5, 6 and 7 show the mean temperature error, rms temperature error and number of forecasts in error by 3°C or more at 18z during January for each observing station. The wide disparity between results for inland and for coastal stations is clearly evident in these three figures. There is clearly a slight cold bias of between 0.5° and 1.0°C at most central England stations but r.m.s. errors for these stations are typically 1.5°C which is remarkably low considering the coarseness of the grid and the relative crudeness of the surface specification. In general errors greater than 3°C are confined to coastal stations and hardly ever occur elsewhere. The nighttime forecasts verifying at 6z have very similar errors in terms of geographical distribution. For example the mean and rms temperature errors at Birmingham for 6z forecasts are -0.4°C and 1.7°C respectively compared with -0.7°C and 1.5°C for 18z forecasts.

These figures represent a considerable improvement on previous months, following the introduction of the scheme to model the flux of heat between the surface and deeper soil layers. The most significant impact of this scheme is to provide a heat source to minimise the surface cooling to space at night. A measure of its success is the major reduction in nighttime forecast errors. For example, the November 1985 6z forecast mean and rms temperature errors at Birmingham were -4.3°C and 4.6°C.

Table 3 has an identical format to Table 2 but for surface relative humidity forecasts.

Range of Error (%) (F/C - OBS)	<-20	-20<-15	-15<-10	-10<-5	-5<0	0<5	5<10	10<15	15<20	>20
Data Time 6z Verif. Time 18z	1	2	3	7	15	20	18	14	9	9
Data Time 18z Verif. Time 6z	2	2	5	9	17	22	18	13	7	7

Table 3 T+12 Relative Humidity Errors

The table shows that about 60% of forecasts give values of relative humidity which are within 10% of that observed. However there is a worrying number of forecast which are much too moist, 10% of forecast relative humidities have values which are 20% greater than the observed values. Figure 8 shows the geographically distribution of the mean error in 18z forecast relative humidities. The positive, moist, biases are worst for inland stations where mean errors in excess of 10% are typical. Smaller errors occur for coastal stations and there is some evidence that forecast surface relative humidities are too dry over the sea.

The wind forecasts are summarised in Table 4 which also has an identical format to Table 2. Both forecast and observed winds have been converted to Beaufort force before the comparison.

Range of Error (F/C - OBS) Beaufort Force	<-3	-3	-2	-1	0	1	2	3	>3
Data Time 6z Verif Time 18z	0	1	5	16	29	26	14	6	2
Data Time 18z Verif Time 6z	0	2	7	19	29	25	12	4	1

Table 4 T+12 Wind Speed Errors

These forecast show considerable skill with an excess of 70% of forecasts having an error of one Beaufort Force or less. Less than 10% of forecasts have errors of greater than two Beaufort Force categories. The slight tendency to forecast winds too strong is almost entirely because the model does not forecast Force 1 with the same frequency that it is observed; it might be argued, however, that observations of very light winds may not be representative of the 75 km grid mean. Table 5 shows the model climatology compared with observations. It gives the frequency of occurrence of both forecast and observed windspeeds at each Beaufort Force as a percentage of about 11000 cases during January.

Beaufort Force	1	2	3	4	5	6	7	8	9
Forecast frequency (%)	3	11	19	29	17	12	6	2	1
Observed frequency (%)	12	12	17	26	16	10	4	2	1

Table 5 Forecast and Observed windspeed climatology

Figures 9, 10, 11 give the geographical distribution of forecast wind speed errors at 18z. They show mean errors, r.m.s. errors and frequency of occurrence of wind speeds errors in excess of one Beaufort force category. Many coastal and hill stations are clearly unrepresentative of the grid mean values from the model, being either overexposed on headlands or underexposed in sheltered valleys. Inland stations have rms forecast errors below 4 knots and are very rarely in error by more than one Beaufort Force.

Although not yet an operational model it is also relevant to consider briefly the results of recent mesoscale model forecasts. It is clear from the preceding discussion that in order to forecast surface variables with precision, particularly near coasts and hills, it requires a model with substantially higher resolution than the present operational fine-mesh model. The mesoscale model (Golding, 1984) has the advantage of a 15 kilometre gridmesh with correspondingly detailed orography. The physical parametrizations have been designed to take account of the scales represented by the model. Also a sophisticated scheme for the analysis of surface synoptic reports has been developed for preparing the fine-scale initial data of the surface, boundary layer and cloud field. The model is already giving results which are marginally better than those obtained from the fine-mesh model. Table 6 give r.m.s. 12 hour forecast errors for both models during January 1986.

Verif Time	Model	Temperature (°C)	Wind Speed (knots)	Relative Humidity (%)
18Z	mesoscale	1.7	6.2	10.3
18Z	fine-mesh	1.9	7.3	11.7
6Z	mesoscale	1.9	5.8	9.4
6Z	fine-mesh	2.2	6.9	10.8

Table 6 Comparison of errors between finemesh and mesoscale forecasts

The mesoscale model, like the fine-mesh model, performs substantially better for inland stations than the above figures for all 200-plus UK synoptic stations would suggest.

The mesoscale model also attempts to forecast low cloud and fog. Fog forecasts made during the early part of this winter were generally disappointing. The model tended to forecast fog three times as often as it was observed. The favoured fog spots in the model were coastal estuaries and valleys in the model topography which often did not coincide with relevant real features on a finer scale. The excessive humidity at the surface is as big a problem in the mesoscale model as it is in the fine-mesh model. As well as contributing to the overforecasting of fog, the surface moisture bias also has an adverse effect on the low cloud forecasts. A third of all forecasts have cloud bases below 600 feet compared with an observed frequency of less than 10%. The presence of cloud (> 4 octas) is, however, forecast with an accuracy of around 70%. The 30% of incorrect forecasts are much more likely to be when cloud is observed but none is forecast. Further details of the recent performance of the mesoscale model are given in Bell (1985).

References

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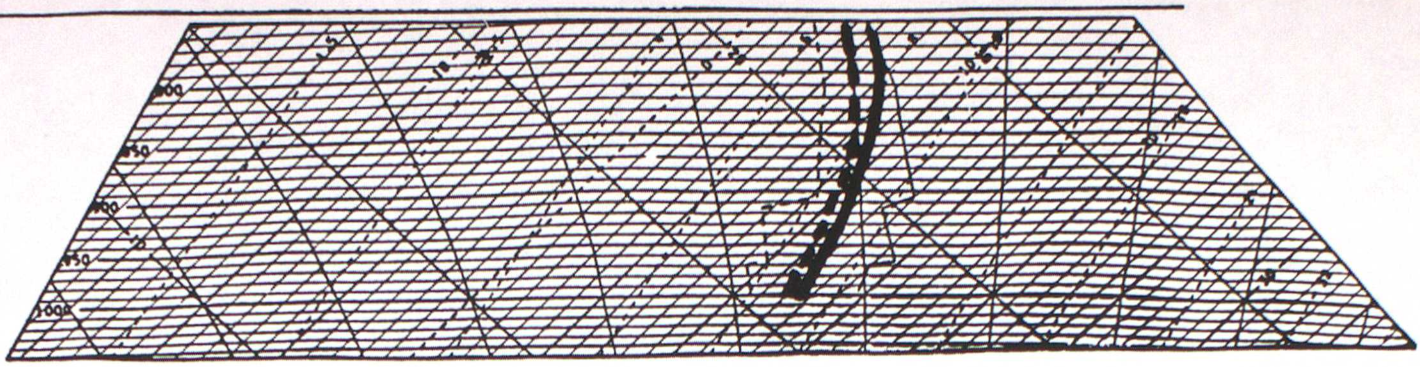
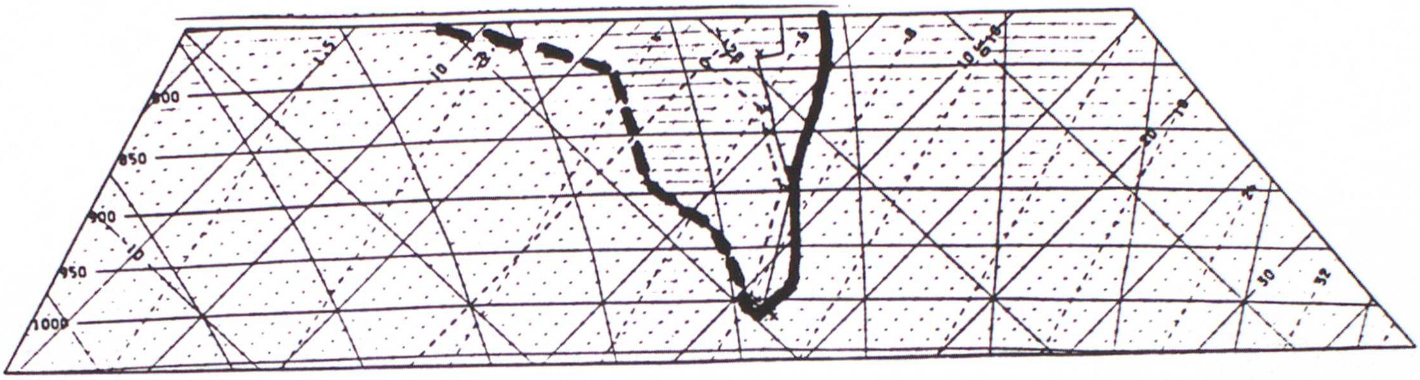
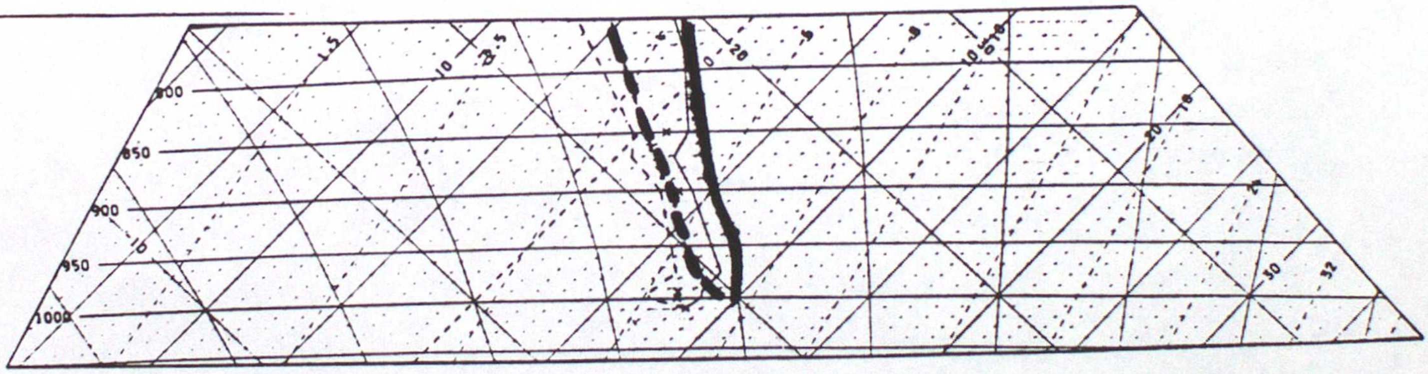
Kitchen, J.E.	1986	An implicit version of the Operational Model Boundary Layer Routine. Met. Office, Met O 11, TN 222.
Richards, P.J.R.	1980	The Parametrization of Boundary Layer Processes in General Circulation Models. PhD Thesis, Univ. Reading.



a) Camborne 12Z 2.12.85



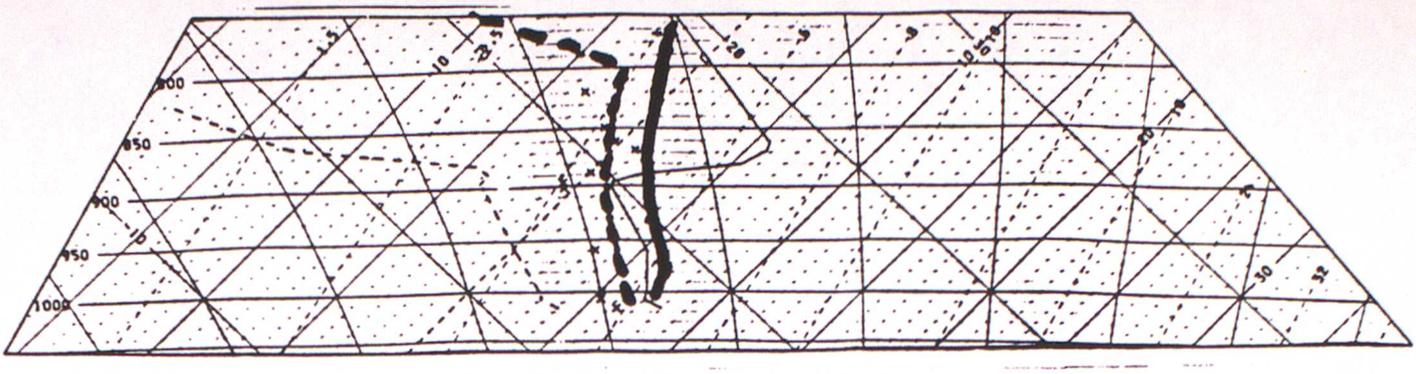
b) Camborne 12Z 13.12.85



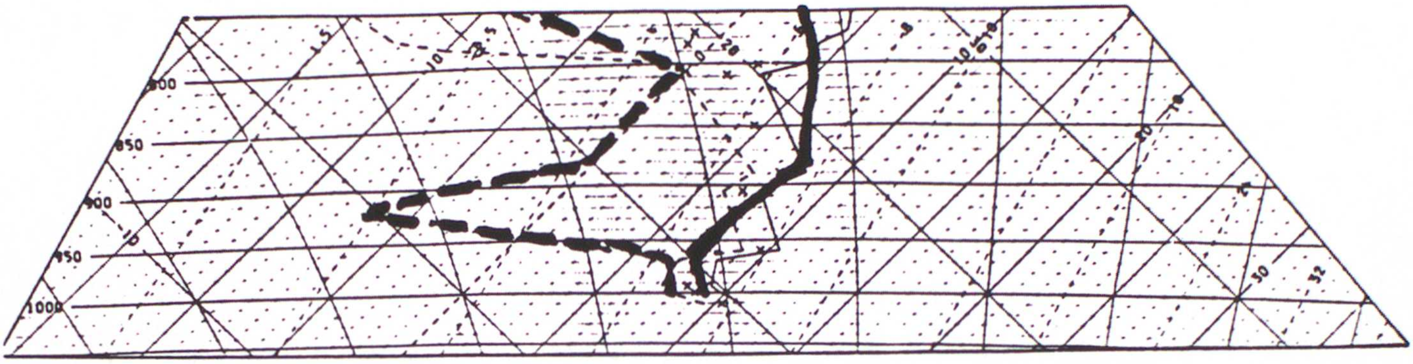
c) Stornaway 12Z 17.12.85

d) Hemsby 12Z 10.12.85

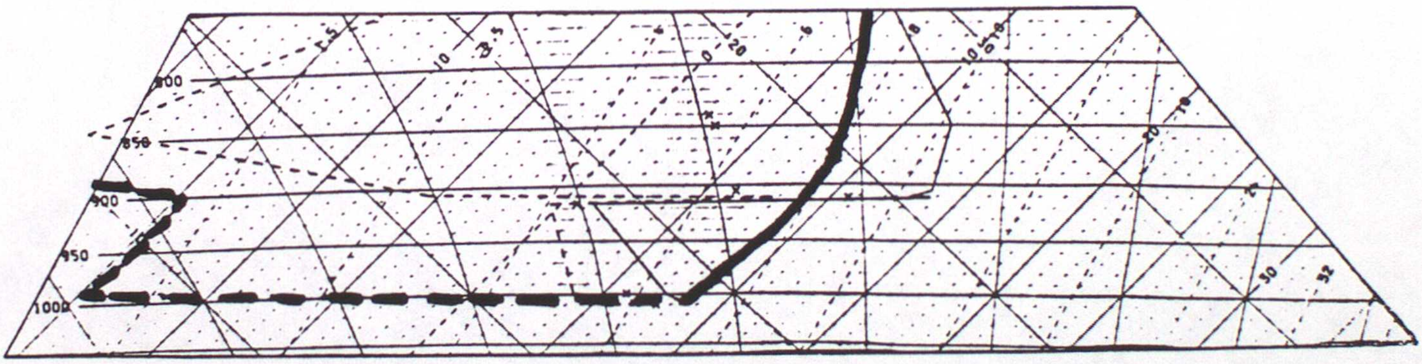
Fig. 1   Radiosonde profiles with 24 hr finemesh forecast profiles superimposed.



a) Shanwell 12Z 13.12.85



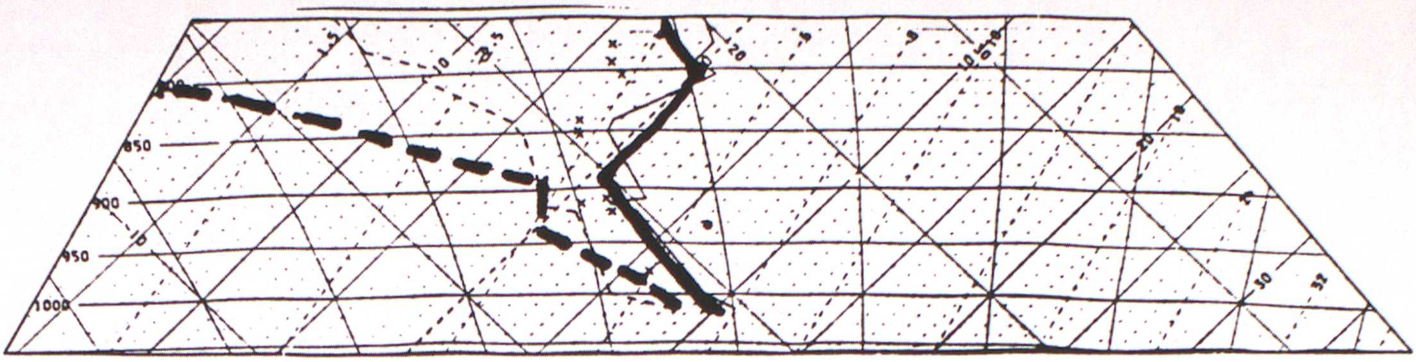
b) Crawley 12Z 15.12.85



c) Crawley 12Z 16.12.85

d) Crawley 12Z 17.12.85

Fig. 2 Radiosonde profiles with 24 hr finemesh forecast profiles superimposed.



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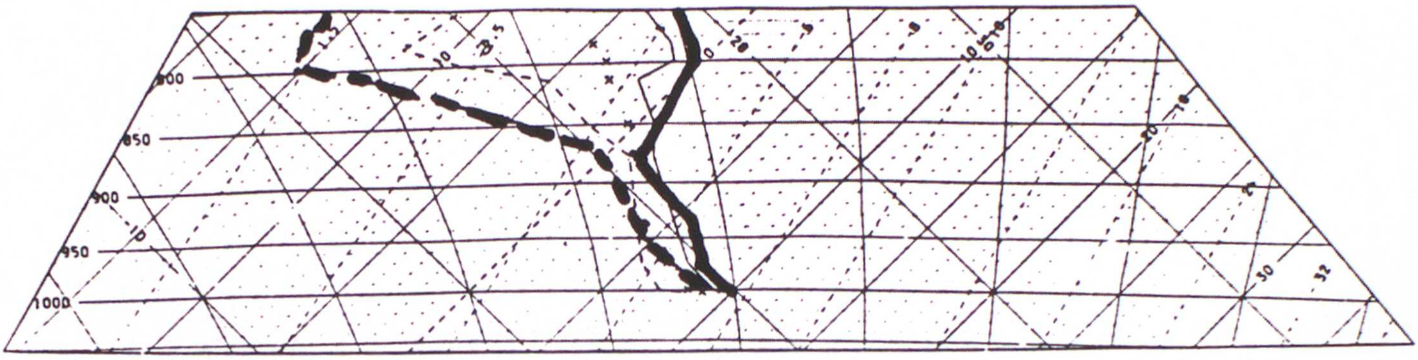
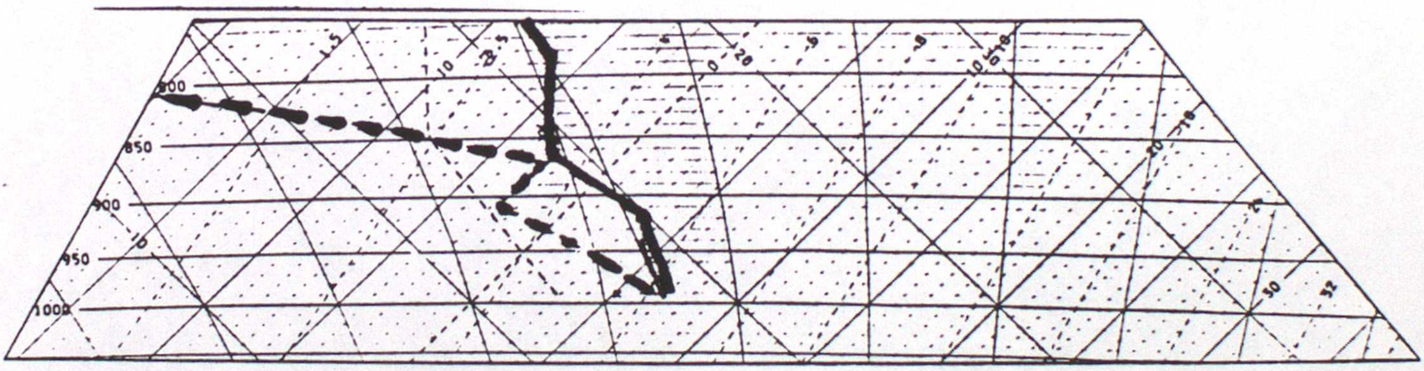
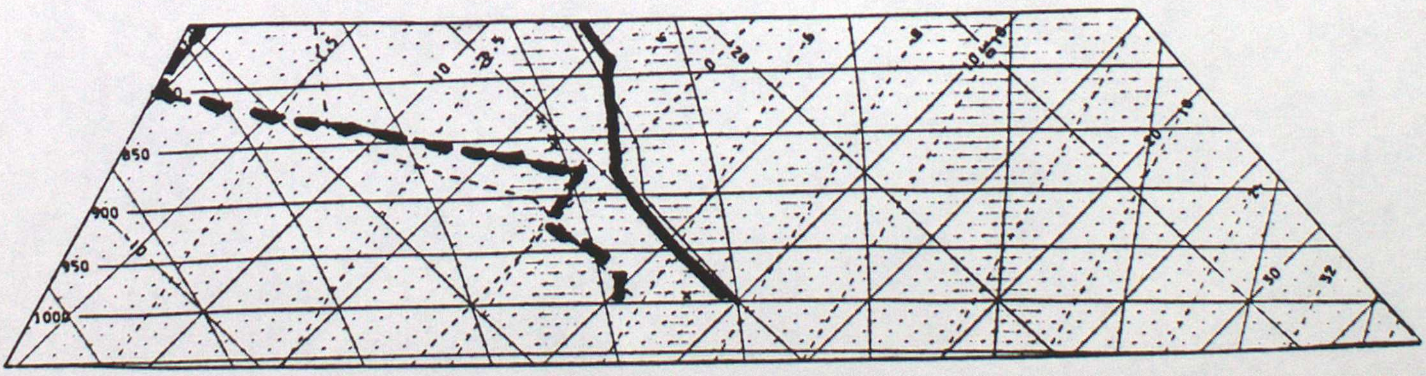


b) Crawley 12Z 20.12.85



c) Long Kesh 12Z 22.12.85



d) Camborne 12Z 22.12.85

Fig. 3 Radiosonde profiles with 24 hr fine mesh forecast profiles superimposed.

Figure 4   Diagnosed boundary layer depth at 12z 13/12/85

T+24

BOUNDARY LAYER DEPTH (metres)
VALID AT 12Z ON 13/12/85 DATA TIME 12Z ON 12/12/85
LEVEL: SURFACE

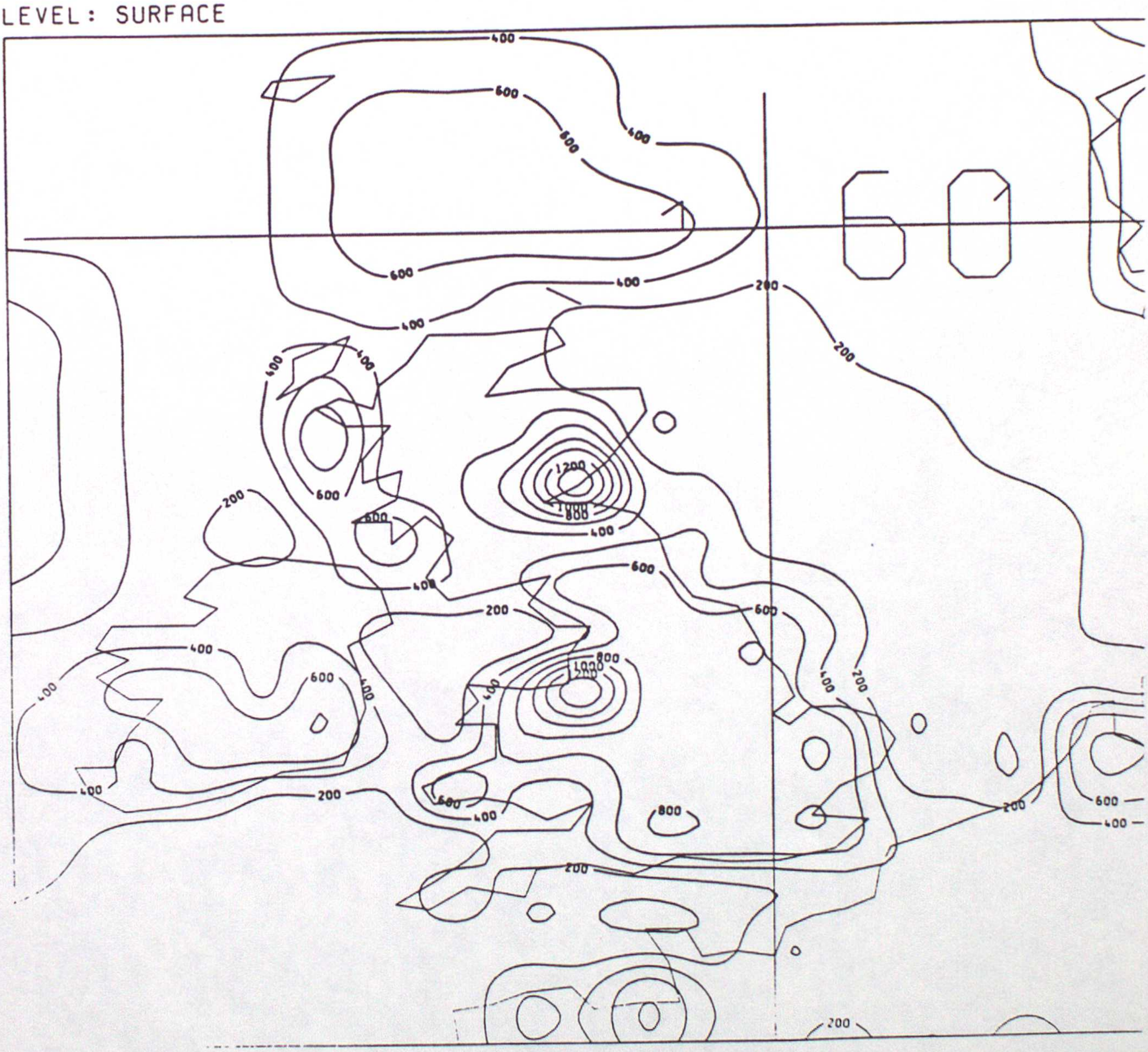


Figure 5 Mean forecast temperature error at 18z during January 1986 (deg C)

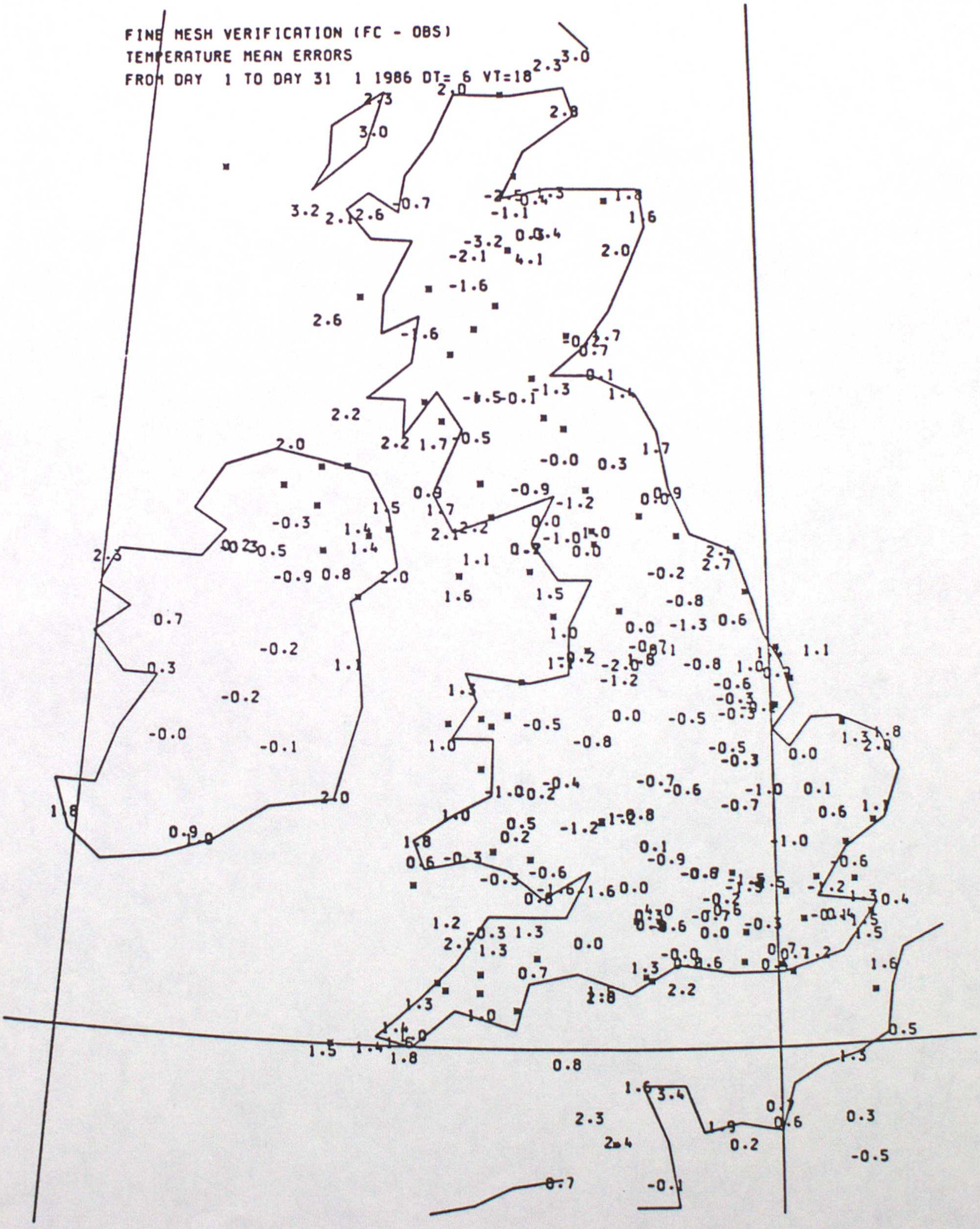


Figure 6 R.M.S. forecast temperature error at 18z during January 1986 (deg C)

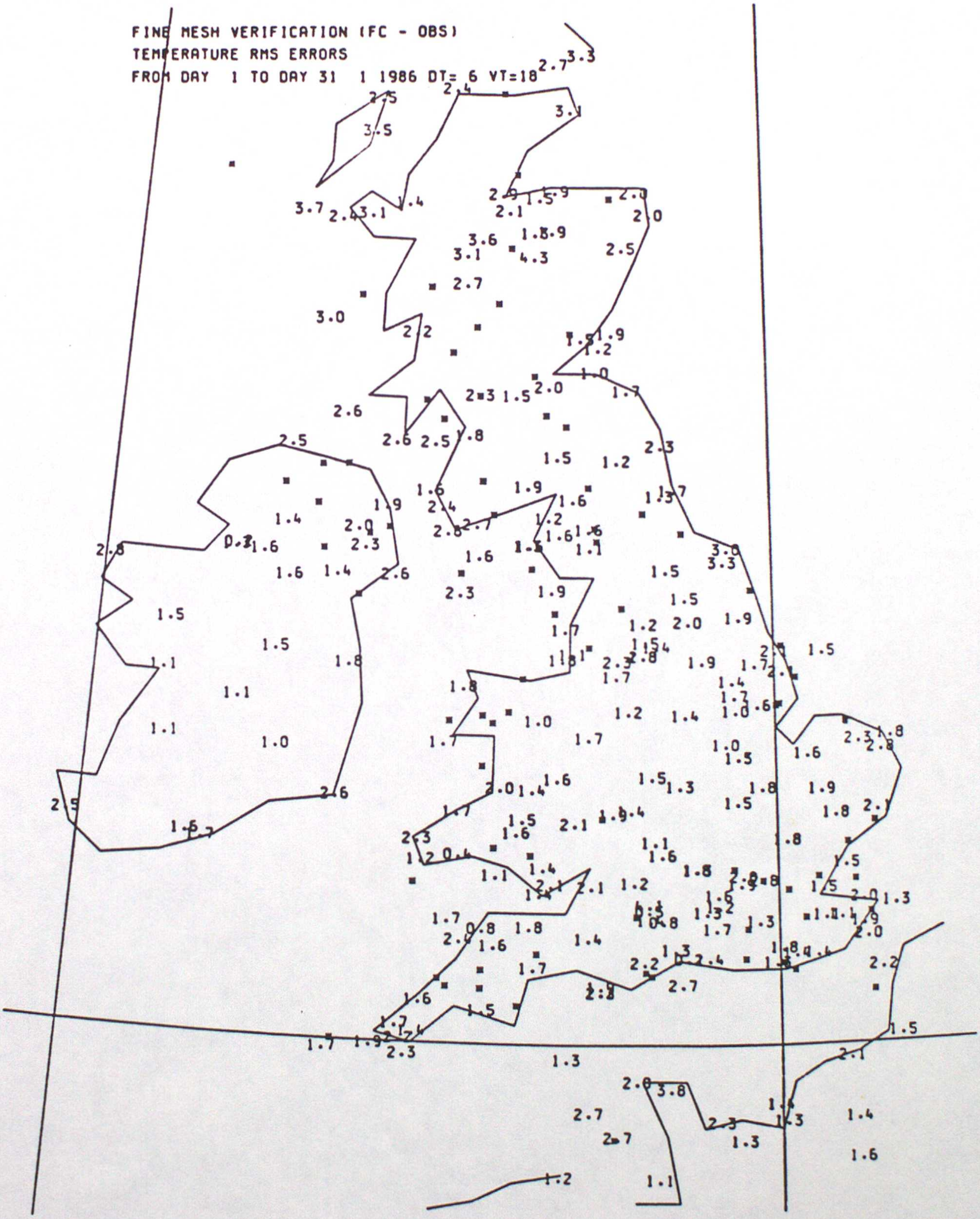


Figure 7 Frequency of large temperature error (≥3C) at 18z during January 1986

Figure 8 Mean forecast relative humidity error at 18z during January 1986 (%)

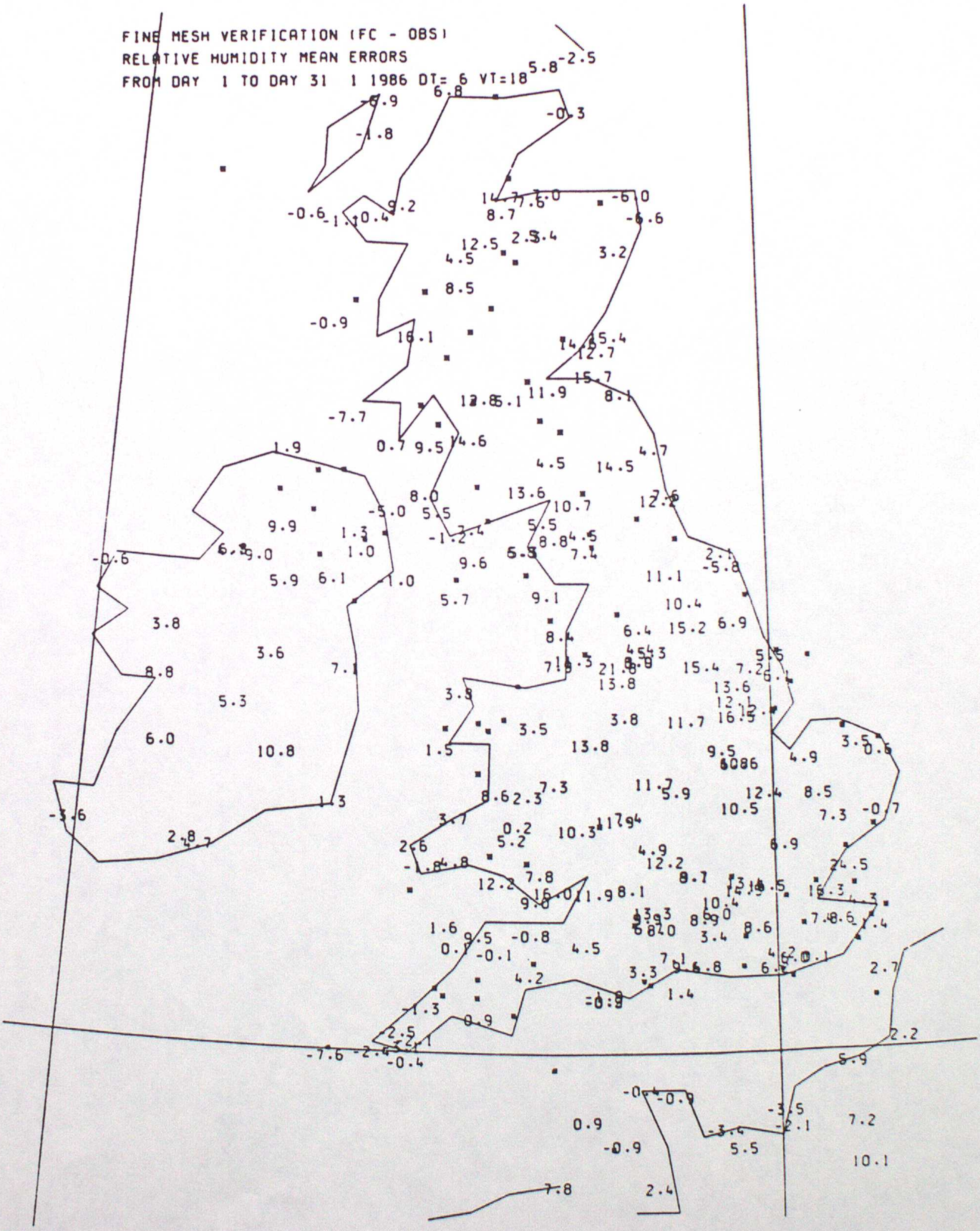


Figure 9 Mean forecast windspeed error at 18z during January 1986 (knots)

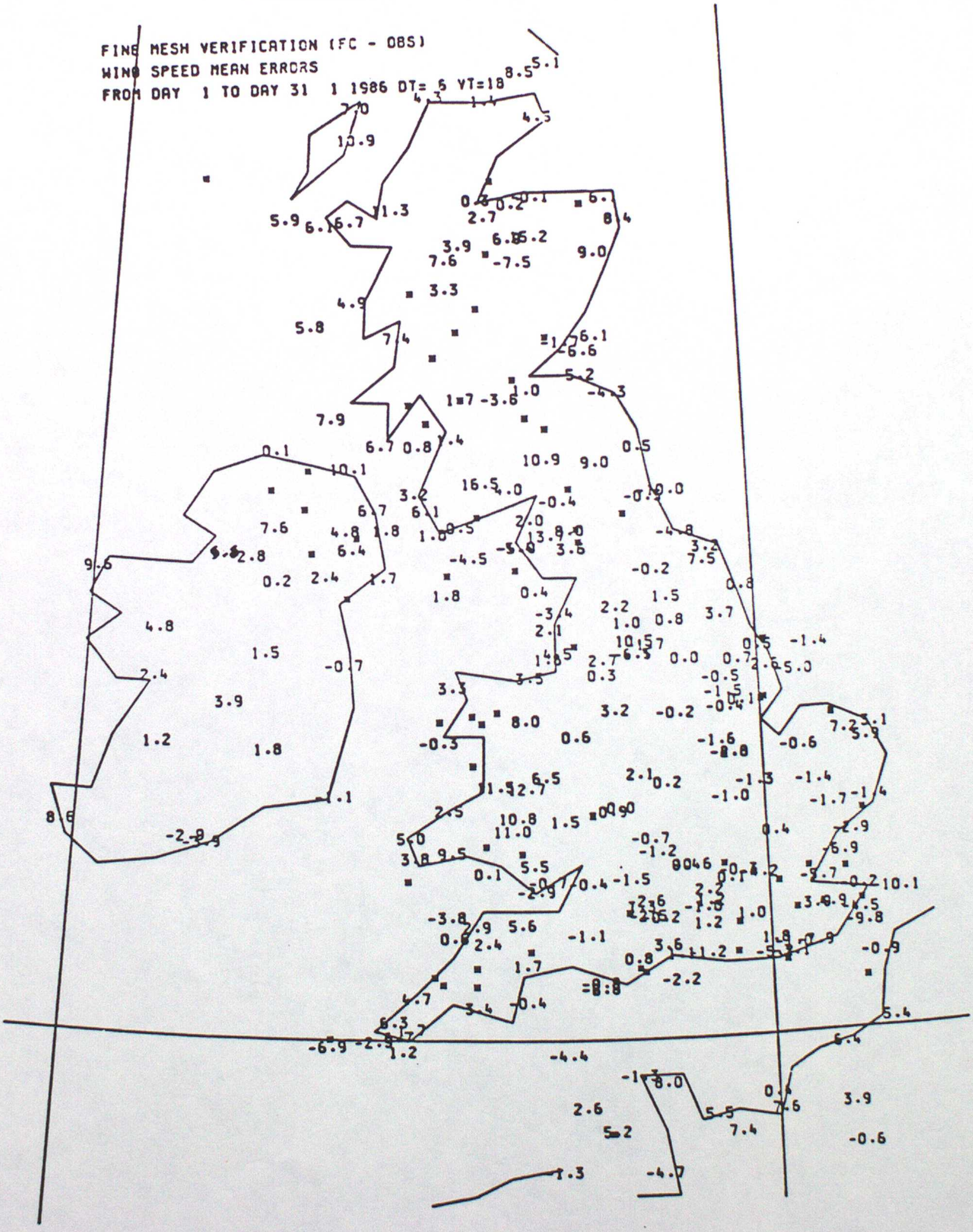


Figure 10 R.M.S. forecast windspeed error at 18z during January 1986 (knots)

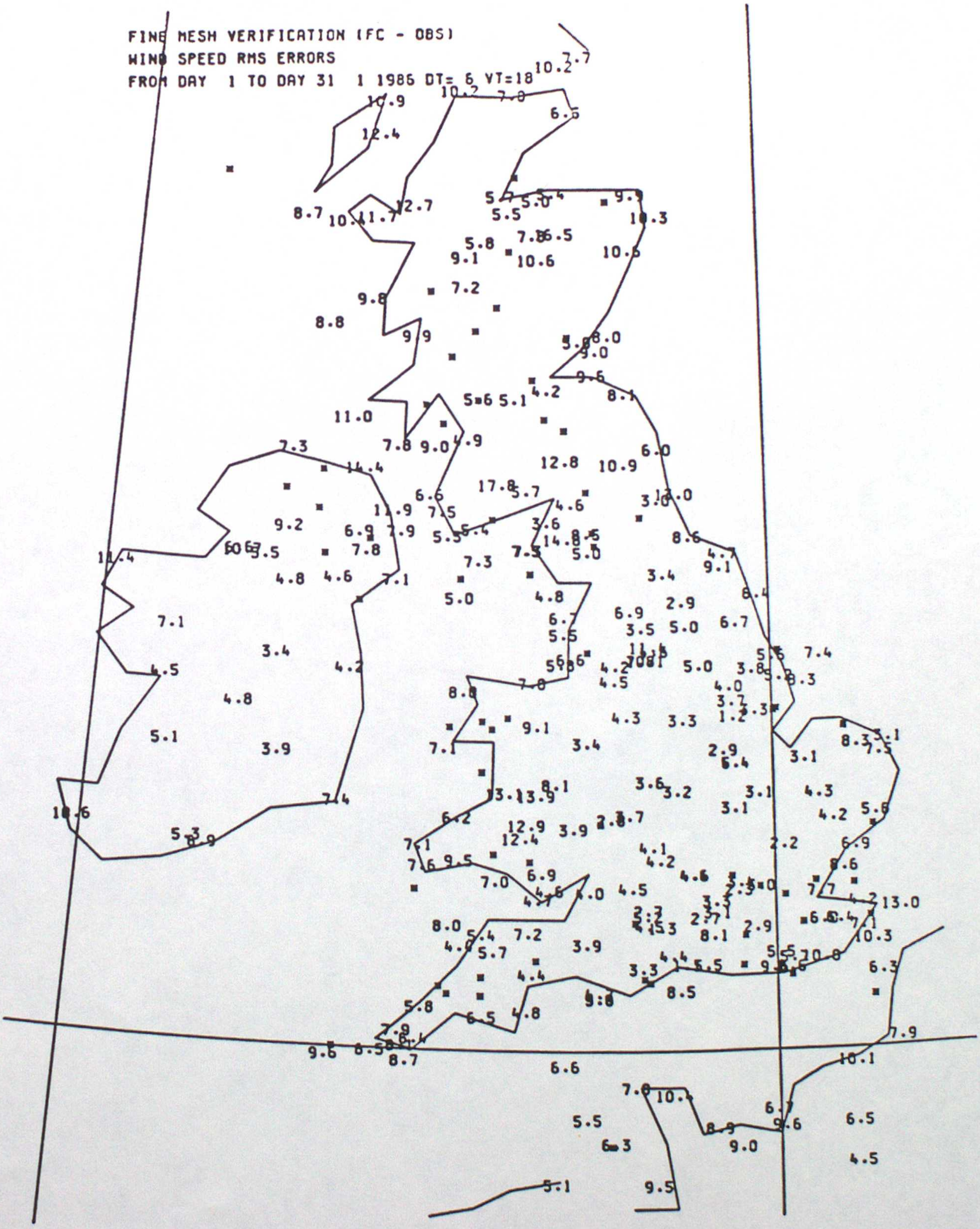


Figure 11 Frequency of significant windspeed error (>1 Beaufort Force category) at 18z during January 1986