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A Case Study of the Detection of Fog at Night

Using AVHRR Channels 3 and 4

by

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Introduction

Eyre et al (1984) described a new technique for the detection of fog at night using two of the infra-red channels on the Advanced Very High Resolution Radiometer (AVHRR), flown on the TIROS-N series of polar-orbiting satellites. The technique allowed the areas covered by fog to be delineated by using the fact that the water droplets constituting the fog have a lower emissivity at 3.7 microns than at 11 microns and therefore have different brightness (equivalent black-body) temperatures at these two wavelengths. Surface features such as land and sea have very similar emissivities in these two channels. By examination of the brightness temperatures at these two wavelengths, it was shown to be possible to isolate the fog-covered areas by considering those pixels for which the channel 3 (3.7 micron) brightness temperatures were significantly colder than those for channel 4 (11 micron).

The initial paper included an example from August 1981 in which a composite image had been created to show the areas covered by fog or low stratus in shades of grey together with the surface temperatures in the clear areas in various colours. This paper describes a new case study which attempts to relate the difference in brightness temperature deduced from measurements of the radiances in two infra-red channels to the horizontal distribution of the fog, to its vertical thickness and to the horizontal visibility.

The technique

In the earlier paper, the AVHRR data were processed by calibrating the digital counts from channels 3 and 4 to obtain brightness temperatures by using data from the space view and on-board calibration targets. The two brightness temperatures at each pixel were then compared and the following code used to indicate fog coverage according to the degree to which the channel 3 brightness temperature was lower than that for channel 4.

0 : $dT < 0.5$
1 : $0.5 < dT < 1.5$
2 : $1.5 < dT < 2.5$
3 : $2.5 < dT$

These four categories were chosen empirically, but were found to be effective in giving an impression of varying thicknesses of fog, with category 0 being clear, 3 showing thick fog and the intermediate categories showing mist or shallow fog. The mode of display chosen was to construct an 8-bit image consisting of two bits to indicate fog or mist in shades of grey and 6 bits to indicate the surface temperatures in clear areas.

For this study it has been decided to concentrate on the fog discrimination aspects alone, rather than to try and combine different data, such as fog and surface temperatures, into a composite image. For this reason, it was decided to use the simple difference between the brightness temperatures of channels 3 and 4 as the main tool in this investigation, rather than to split the data into the four categories listed above. This allowed small differences in brightness temperatures to be examined in detail and also allowed the differences at specific locations to be extracted using the graphics display in Met O 19.

Background to the case study

The example documented in this note was selected following a search for suitable cases by examination of the operational charts held at the Meteorological Office Archives. The aim was to find a case in which there was patchy fog across the country rather than widespread coverage since it was felt that one of the strongest features of the detection of fog using satellite techniques was that much more detail could be provided on the spatial coverage than was possible using conventional data. Having decided on the case, the raw AVHRR data were then obtained on computer compatible tape from the University of Dundee and processed on the HERMES system within Met O 19. HERMES consists of a DEC VAX 11/750 mini-computer and a powerful graphics display system which is used for a number of different applications in satellite remote sensing. For a detailed discussion of the HERMES system see Turner et al (1985). Following the selection of the case all relevant hand and machine-drawn charts were then obtained for the period of the study and significant quantities of surface and upper air observations were extracted from the synoptic data bank (SDB).

THE CASE STUDY - 23 October 1983

Synoptic Situation

The general situation at 0600Z on the 23 October 1983 is shown in figure 1. A large anticyclone with mean sea-level pressures up to 1039 mb was centred over south-east Europe with a ridge extending west-north-westwards into central and southern England. A warm front lay across Northern Ireland and north-east Scotland. This front moved eastwards to cross most of the UK during the 23rd, closely followed by a cold front.

The sequence of UK surface charts every hour from midnight on the 23rd shows strong to gale force south-westerly winds in the north of Scotland. Over central and southern England, however, the winds were mainly south to south-easterly, with speeds of 5 knots or less.

The time of the satellite pass from which the fog image was created was 0433Z. The UK charts for 0400 and 0500Z are shown in figures 2 and 3. These show virtually no cloud reported over England, Wales and northern France. The only exceptions were Anglesey with 7/8 stratocumulus with a base at 1600 feet on the edge of a sheet of cloud extending from south-west Ireland to north-east England, Aberporth reporting 1/8 of stratocumulus and Swansea with 1/8 of cumulus at a base of 2000 feet.

The screen temperatures from the 0400Z UK chart were analysed for central and southern England and are shown in figure 4. The highest temperatures occurred near the coasts, particularly in the south and south-west. Inland, temperatures below freezing were found in a belt extending from south and west Dorset, through London and the Home Counties to the Wash and the Welsh border region. To the west of London, the temperatures were generally higher with temperatures above freezing being found from Somerset to Berkshire and the south Midlands.

Analysis of the fog cover

a) From surface observations

At midnight, fog was reported only from Coltishall and Gatwick, both with sky visible, although these was mist reported in the North of England, in Dorset and in a belt through East Anglia to Central England. Large areas of England had small or zero dew-point depressions at this time. These are shown in figure 5 and reveal a close correspondence with the areas covered by mist or fog.

There was very little increase in the size of the areas covered by fog until after 0200Z. At 0300Z, Yeovilton, Southend, Bedford, Hurn and Stansted all began reporting fog. By 0500Z, reports of fog were received from Boscombe Down, Brize Norton, Upper Heyford, Luton, Birmingham, Shawbury, Alconbury and Coningsby.

Thus, of all the stations where observations were made at 0400Z and 0500Z, six, (Yeovilton, Gatwick, Southend, Stansted, Bedford and Coningsby), reported fog at 0400Z and five more, (Shawbury, Birmingham, Coltishall, Alconbury and Luton), developed fog between 0400Z and 0500Z. From observations made at Shawbury, it is believed that the fog first formed around 0447Z - after the time of the satellite pass.

Since variations in visibility can occur on a scale much smaller than that of the synoptic network, it is extremely difficult to produce an accurate analysis of fog coverage from the surface reporting stations alone. Figure 6 shows an attempt to analyse the observations of visibility over England and Wales at 0500Z. There are, apparently, three main areas of fog; over the Somerset/Dorset area, on the north-east coast of East Anglia and in an arc through Northampton, London and Surrey. The south, east and western coasts generally had good visibility at this time, but in central areas of

England, the visibilities reported were very variable.

b) From the satellite imagery

On the 23rd October 1983, a south-bound NOAA-7 pass over the UK occurred at 0433Z. The complete AVHRR data for this pass were obtained from the University of Dundee and processed on the HERMES system. The data stream was split into its constituent channels, and images formed from the data in each infra-red channel. These were calibrated into brightness temperatures by using the data from the calibration targets in the instrument. Since the measurements of radiance were calibrated over a range of 25.5 K and are represented by eight bits, the smallest detectable change in the scene temperature is about 0.1 K, approximately the level of the radiometric noise of the long-wave detectors of the instrument.

An image can be formed from the difference in the brightness temperatures viewed by the two channels for each pixel. However, Allam (1986) has shown that the procedure of taking the difference between the brightness temperatures in channels 3 and 4 for each pixel in the scene produces an artifact, apparently due to a mis-registration of the fields of view of the two channels by about one quarter of a pixel. This artifact is sufficiently large to cause uncertainty in the interpretation of the resulting image. Allam found that shifting one image by one quarter of a pixel before subtraction virtually eliminates the artifact. Accordingly, the image used for this study and shown in figure 7 was produced using this method.

The contrast in this image has been selected to display a range of the temperature differences of about -4.0 K to +4.5 K in steps of 0.03 K. Light areas in Figure 7 are where the channel 3 brightness temperatures are less than those for channel 4 and, from the previous study, indicative of fog covered areas. In areas of semi-transparent cirrus the channel 3 brightness temperature is often greater than that for channel 4 and appears dark in Figure 7.

c) Comparison of conventional data with imagery.

In order to compare the distribution of fog inferred from the satellite image with conventional observations and local topography, a method was adopted of locating the pixel in the satellite image containing each observation site. Using information from the ephemerides issued by NESDIS, the geometry of the scanning pattern of the instrument and the time as recorded on the satellite, an estimate was obtained of the mapping between image coordinates and geographical location.

A correction to this estimate was obtained by superimposing the positions of twelve prominent coastal features as computed using the mapping, and comparing them with their actual positions in the image. The linear shift of the coordinate framework relative to the image was determined that produced the smallest displacement, in a least-squares sense, between the framework and the image. It was estimated that following this procedure, a point with a specified latitude and longitude within the area of interest could be located to an accuracy of two pixels, or approximately 3 kilometres.

The observations of weather and of horizontal visibility for each station reporting at 05:00Z were compared with the difference in brightness temperature between the two AVHRR channels. Since there were uncertainties of about two pixels in the location of the observing station within the image, it was decided to use an average temperature difference over the nine pixels closest to that predicted to contain the station. The mean of the nine pixels could easily give a distorted average in an area with a few anomalous values. Use of the median to represent the average avoids such distortions.

Another difficulty in comparing the conventional data with the satellite image is that they represent the situation at different times. This could be crucial at a time in which the visibility is changing rapidly. Accordingly, observations at both 04:00Z and 05:00Z were recorded and an estimate of the visibility at 04:33Z deduced by interpolation, bearing in mind that the observations are actually made at about ten minutes before each synoptic hour.

Figure 8 shows the median temperature difference for the nine pixels closest to the predicted point of observation plotted against the horizontal visibility deduced for 04:33Z, assuming that the logarithm of visibility varied linearly with time. A hand-drawn curve that fits the points is also shown. A general increase in the value of the temperature difference is noted as the visibility decreases. At high visibilities, the mean value of the difference is about 0.4 K, suggesting that the emissivity of the land is slightly different at the two wavelengths. If there were no difference in the emissivity, the mean temperature difference should be slightly negative, since a pixel containing objects with different brightness temperatures would appear warmer at 3.7 um than at 11 um. (See Saunders, 1986)

It is clear from figure 8 that no clear threshold in the difference between the brightness temperatures of the two channels can be applied to distinguish visibilities below 1000 metres from those above it, however, a difference of 1 K appears to be able to discriminate between visibilities above and below about 200 m, assuming that the two isolated points with visibilities greater than 200 m and differences greater than 1 K are due to noise in the validation technique.

d) Discussion

It should be emphasised that the bi-spectral method of detecting fog is based upon the characteristics of the liquid water in the field of view, and especially upon the drop-size distribution and total amount. While it is clear that both of these factors will also affect the horizontal visibility, it is not clear that changes in them will affect equally the radiation in the two infra-red regions used in the technique and that in the visible region used to estimate the visibility.

Areas of shallow fog may occur that are sufficiently thick to produce a significantly different spectral signal from surrounding areas, yet may not be deep enough to cause a significant deterioration of visibility measured at the eye level of an observer. It is also plausible, particularly at night, that significant areas of fog may remain undetected by the observer.

Furthermore, the positions of most of the stations reporting fog at 05:00Z were situated away from the regions of coherent areas of light pixels. The fog observed was of limited vertical extent, since in all cases, the sky was not obscured.

The satellite data are effectively averages over space. Even the pixels produced by the AVHRR, which at best are approximately 1 km square, could be expected to contain areas both with and without fog. It is unlikely that the details of the spectral signal that is characteristic of such regions will be unravelled using the conventional observing network, but might be possible using some sort of mathematical simulation.

e) Further validation

Validation of the product is also possible in an indirect sense, since the spatial distribution of the bright areas revealed by the technique should correspond to the known properties of fog. Referring again to the image shown in figure 7, a number of areas of interest can be related to the local topography and conventional observations.

In the extreme south of England where the winds were very light, the bright areas occur in valleys, shallow depressions and gaps in ridges.

The conurbation of London itself is virtually clear of bright areas, even though they are present in the estuary of the Thames. As an urban area, its higher surface roughness can increase the depth through which turbulent mixing occurs, preventing or delaying the onset of fog formation. Also, the temperatures in the urban areas tend to be higher than in the country, with the same effect.

To the north of London, there is a perceptible flow of air from the south. Bright areas are shown within the small valleys that dissect the Chilterns and their continuation into East Anglia, producing the dendritic pattern in the image. The bright areas cease northward of the ridge in a strip about fifty kilometres wide. It is plausible to suggest that a combination of a katabatic drainage flow down the sides of individual valleys, coupled with the light general flow from the south, would cause cold air to ascend each valley to the top of the ridge, cooling as it did so. On reaching saturation, fog could form. North of the ridge, the air would descend and warm adiabatically, preventing further condensation. Since some water would be deposited on the upslope, the warming of the air could be enhanced by a "Foehn" effect.

The distribution of the bright areas in the north of East Anglia is more problematical, since the lack of significant topography would seem to preclude not only any lifting of moist air, but also any concentration of cold air through katabatic drainage flows. It is possible that local variations in relative humidity are important in such cases.

The Somerset Levels are another area of interest. This area, bounded by the Mendip, Quantock and Blackdown hills is very flat and low lying with numerous dykes for drainage (the sea in fact at one time reached inland as far as Glastonbury). It is an area prone to fog and shows up well in figure 7, with the white area following the Parrett river and around the south-east end of the Quantocks along the Tone valley to west of Taunton.

The topography around Hindhead in Surrey is also well depicted with the rather square shaped hill on which Hindhead itself is situated shown as dark grey, and the surrounding low-lying areas showing grey to white, but coming to an abrupt end at the South Downs. Note that the small gap caused by the river Arun can be seen as a bright area.

Other topographical features can be picked out: the shape of the Vale of Kent between the North Downs and the Weald along the Medway valley is shown, as is the Thames valley area south-west and west of London.

A thin strip of lighter pixels lying north to south through Lincolnshire is also of interest. It coincides with the valley lying just to the east of the narrow ridge running through Lincoln.

Other minor low-lying areas can be distinguished by comparing figure 7 with a detailed topographical map.

Clearly shown on figure 7 are the dense white areas over the Brecon Beacons in south Wales and over Herefordshire and the Macclesfield area of Cheshire. These are probably areas of cloud. Unfortunately, there are no observations to confirm or deny this, although an observation from Cilfynydd near Merthyr Tydfil in south Wales at 0300Z reported 2/8 of cumulus with a base of 2000ft. The small amounts of cloud at Swansea and Aberporth at 0500Z have already been mentioned earlier in the text. These areas are all over or near high ground and do not follow any valleys. The pressure gradient was slightly stronger over much of Wales, and it is thought possible that these white areas could be cloud formed by upslope effects, or may have drifted north-east from such an area where cloud would form.

In all these examples, the light areas correspond to regions in which fog would be expected to occur.

Conclusion

It is proposed that there is evidence, both direct and indirect, to support the proposition that the areas of the image in which the brightness temperature seen in AVHRR channel 4 exceed those in channel 3 significantly are probably the sites of significant banks of water droplets, some of which could be deep enough to reduce the horizontal visibility to less than 1000m.

In the light of the scatter of the points in figure 8, particularly towards low visibilities, it would be folly to exaggerate the quantitative aspects of this study. It should be noted that the case was by no means an optimum one for the technique and shows some of the complications to be expected in an operational environment. In particular, the fog was thin and patchy, both of which increase the problems of interpretation. Further case studies are being examined where the fog is more uniform and it is hoped that these will increase our understanding of the quantitative aspects of the technique.

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Turner J, Eyre J R, Jerrett D, and McCallum E	1985	The HERMES System. Met Mag 114 161-173
Allam R J	1986	On a slight mis-registration of AVHRR channels 3 and 4. (Submitted to Int J Remote Sensing)
Saunders R W	1986	Removal of cloud contamination from AVHRR radiances. (Submitted to Int J Remote Sensing)

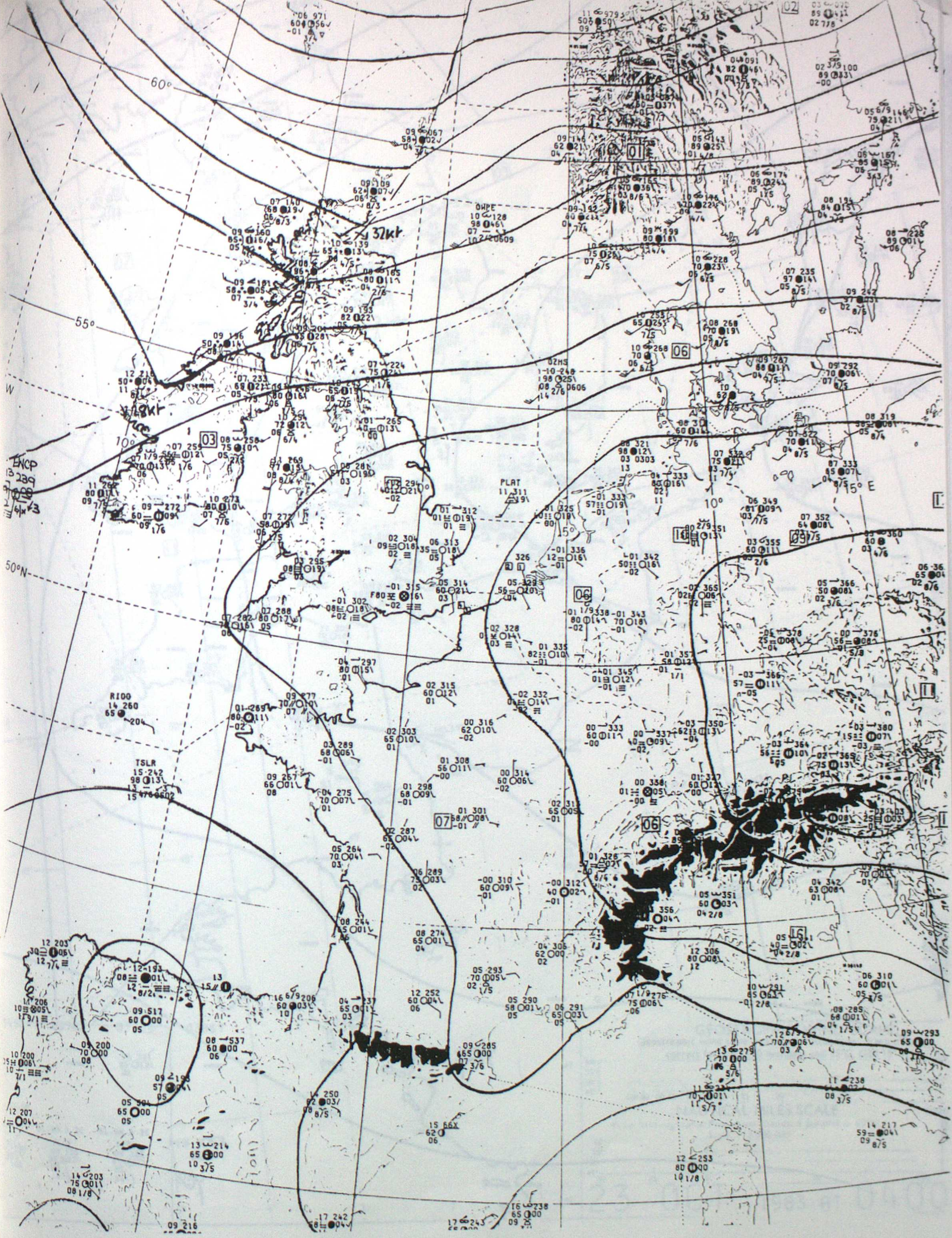

Fig. 1 Surface analysis and observations for north west Europe - 23 October 1983 at 0600 G.M.T.

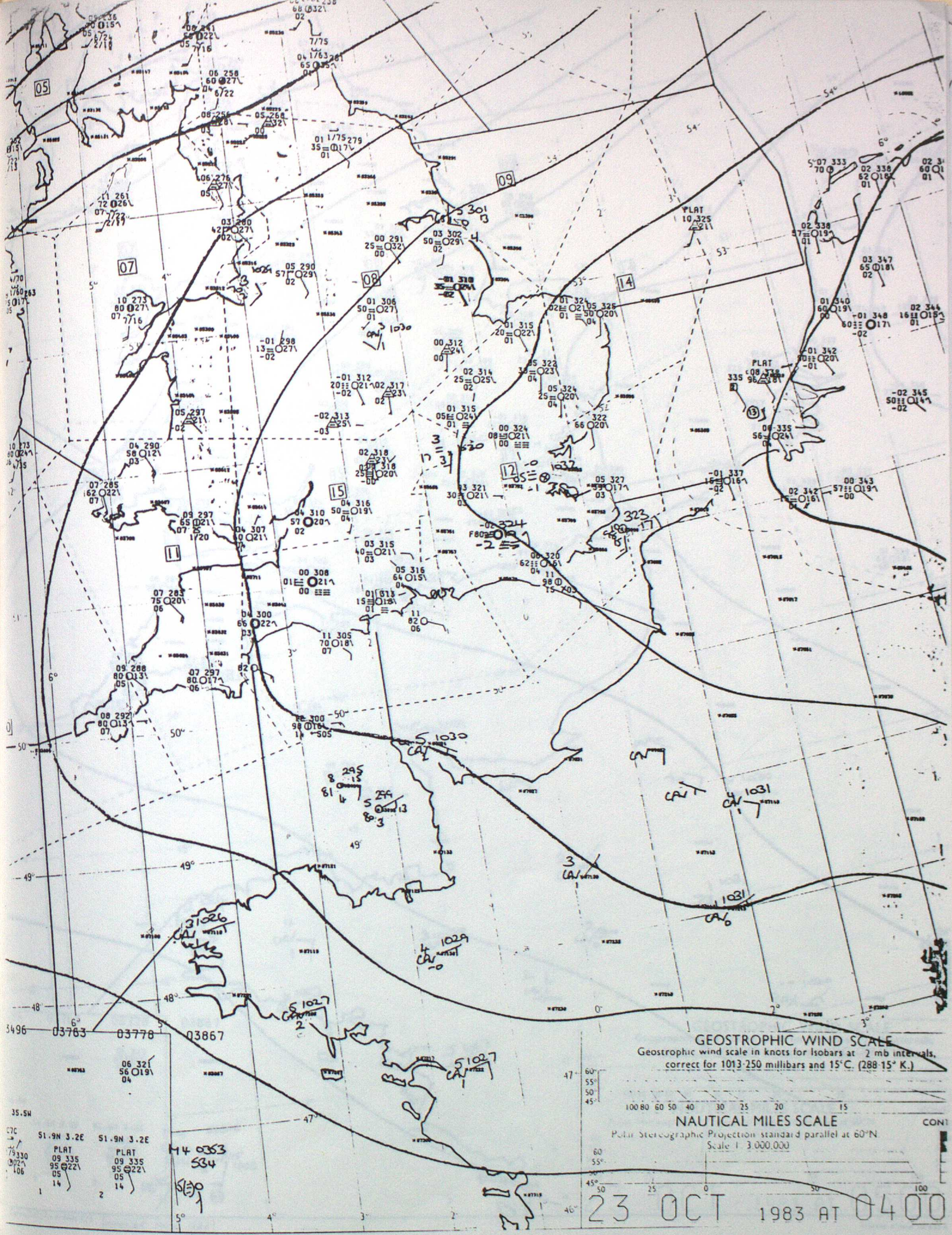

Fig. 2 Surface analysis and observations for the U.K. - 23 october 1983 at 0400 G.M.T.

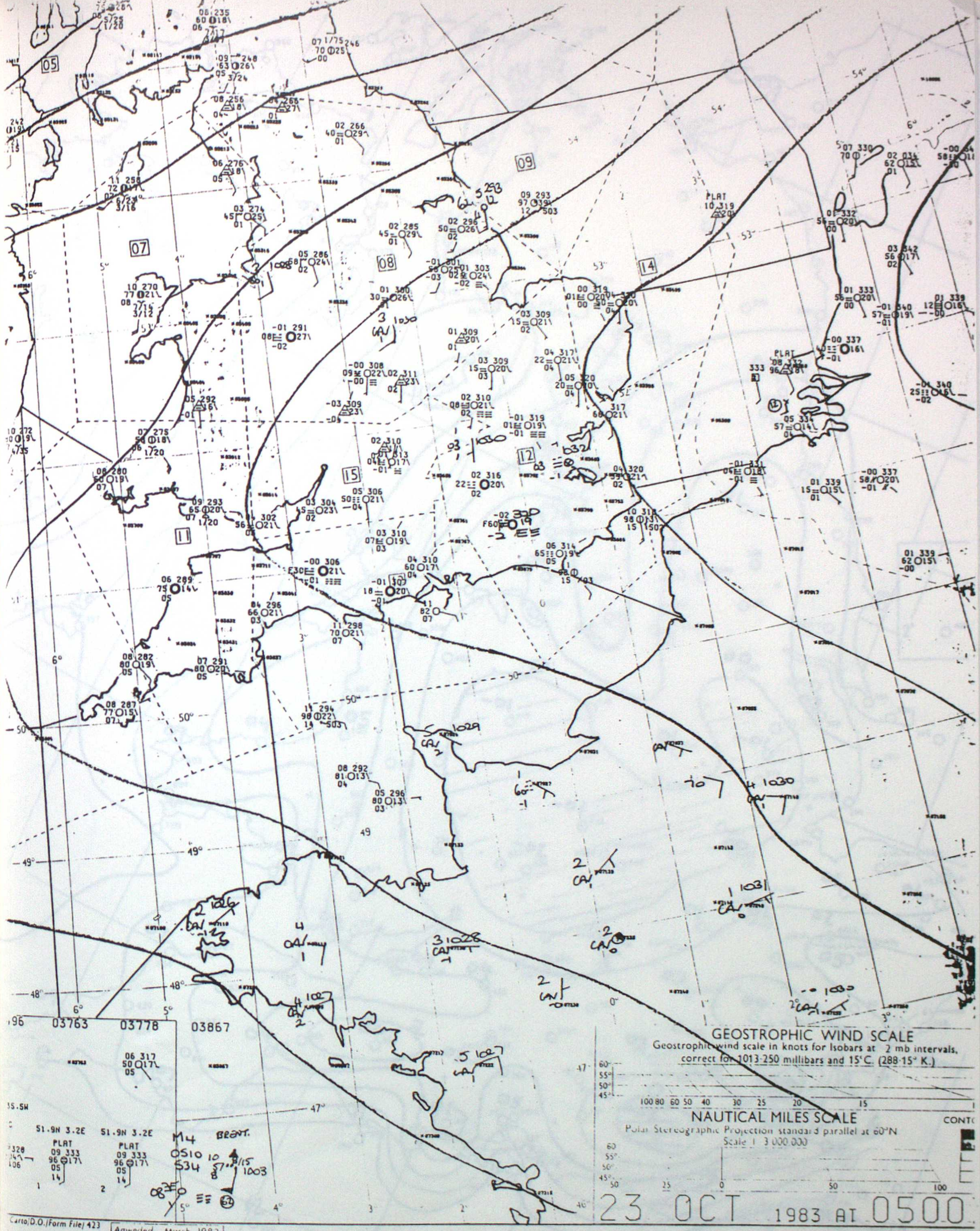

Fig. 3 Surface analysis and observations for the U.K. - 23 October 1983 at 0500 G.M.T.

Fig. 4 Analysis of reported screen temperatures
- 23 October at 0400 G.M.T.

Fig. 5 Analysis of reported dew point depressions
- 23 October 1983 at 0000 G.M.T.

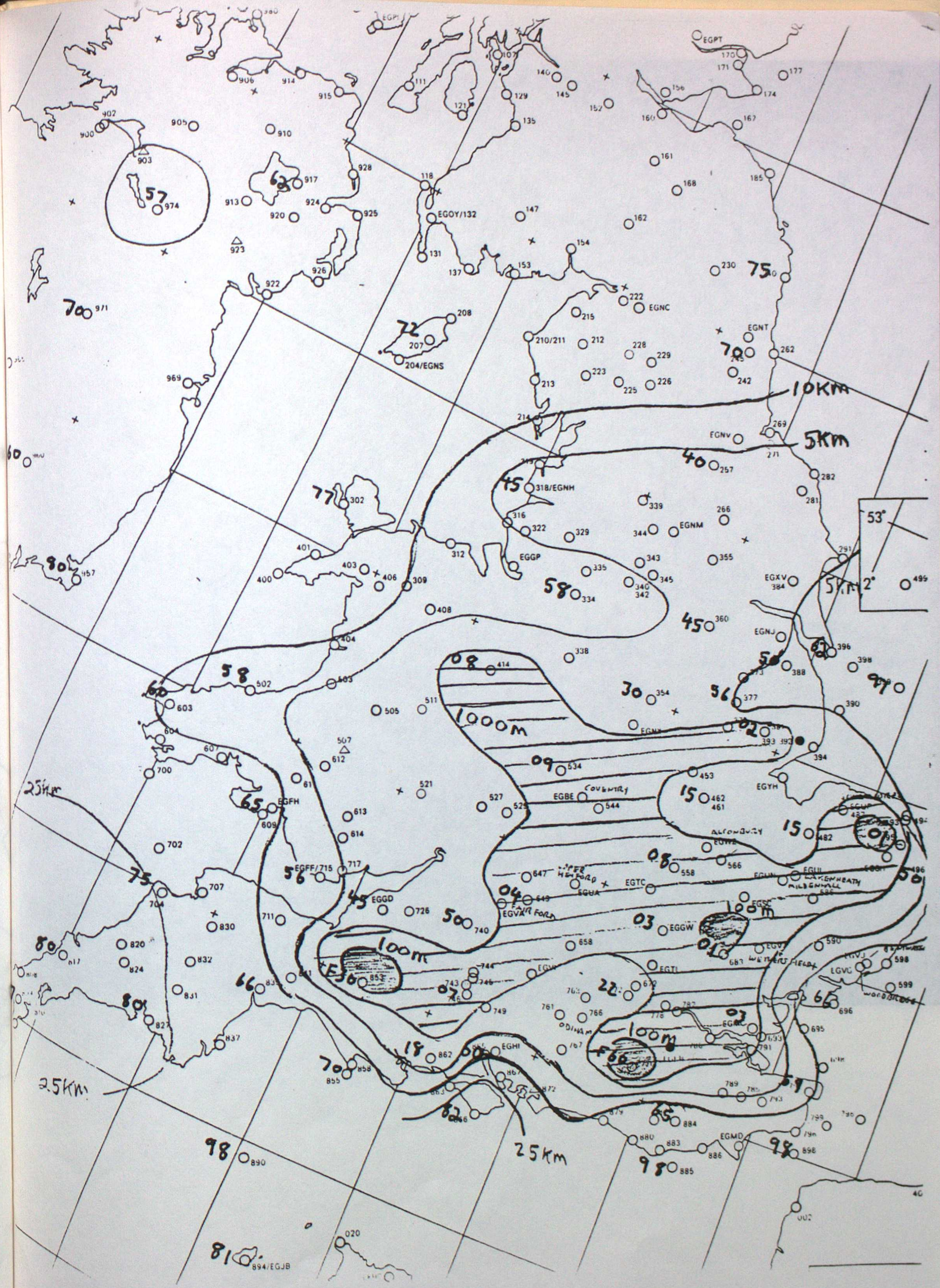

Fig. 6 Analysis of reported horizontal visibilities - 23 October 1983 at 0500 G.M.T.

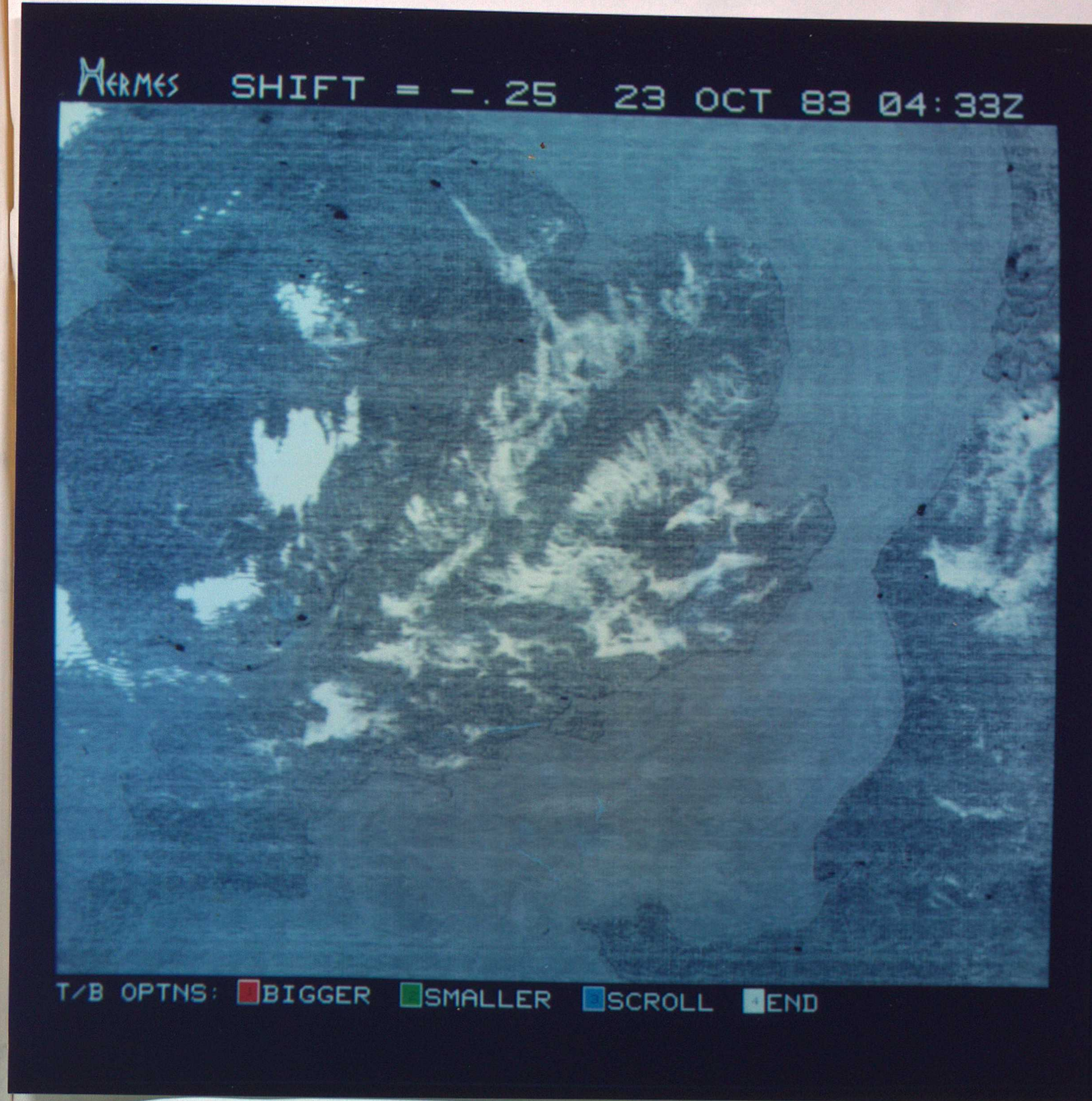

Fig. 7 A photograph of an image created by taking the NOAA-7 channel 4 - Channel 3 difference and then applying a 1/4 pixel shift to counteract effects of mis-registration - 23 October 1983 at 0433 G.M.T.

Fig. 8 Graph of (log) reported horizontal visibility (assumed at 23 Oct 1983 at 0433 G M T), against brightness temperature difference (median of 9 pixels surrounding station).