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The Fastnet storm—a forecaster's viewpoint

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Summary

The 1979 Fastnet Race is remembered for the exceptional weather conditions which were experienced to the south of Ireland and caused havoc among the competitors. The origin and development of the storm are reviewed on the basis of the data available at the time to the forecasters in the Central Forecasting Office at Bracknell. In particular, the guidance from the various numerical models is discussed, together with its interpretation by the forecasters.

1. Introduction

At 1230 GMT on Saturday 11 August 1979, 303 yachts sailed from Cowes, Isle of Wight at the start of the biennial Fastnet Race. This race, which is organized by the Royal Ocean Racing Club (RORC), forms part of the series of international yacht races counting towards the Admiral's Cup trophy. The course takes the competitors to the Fastnet Rock and then back to Plymouth via Bishop Rock (Fig. 1). On the same day a small depression (identified as low LY) was centred just south of Nova Scotia and it was the arrival of this low over southern Ireland on the night of 13/14 August that was to have such dramatic and tragic consequences. During that night the competitors, who were mostly located between Fastnet Rock and the Isles of Scilly, caught the full force of the storm. Of the 303 starters only 85 finished the race, 24 yachts were abandoned and 15 crew members were lost.

Besides describing the development of the storm, this paper also discusses the basic observational data available at the time, the guidance from the numerical models and the forecast material which was actually issued.

2. Saturday 11 August

(a) *Synoptic situation*

Fig. 2 shows the surface and 300 mb analyses for 12 GMT on Saturday 11 August, close to the time of the start of the Fastnet Race. A broad upper ridge was moving slowly eastwards over the British Isles and was associated at the surface with a good deal of warm and very moist air originating from near the Azores, behind the warm front WX. Ironically, the main problems worrying competitors at the start of the race were possible lack of wind and increasing likelihood of sea fog. A major surface low LX and its associated upper vortex were drifting north-eastwards to the south of Greenland whilst another vortex was almost stationary over Hudson Bay. On the southern flank of these two upper vortices a strong westerly flow was propagating forwards over the central North Atlantic with maximum wind speeds of

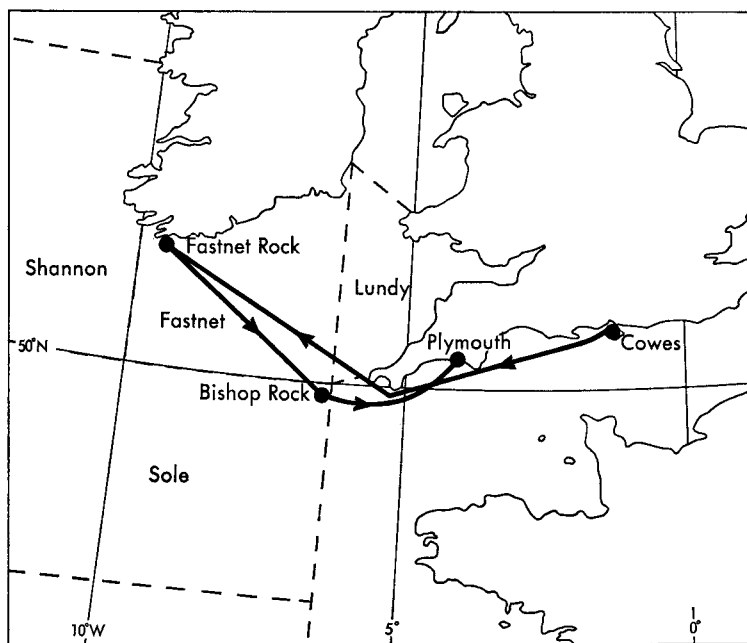


Figure 1. The course of the Fastnet Race.

the order of 120–130 kn. Low LY, which had broken away three days earlier from a shallow area of low pressure over the north-western United States, was well documented at this stage. The centre was located 150–200 n. mile south of the jet axis and, with the vorticity advection term obviously small, its eastward movement at about 30 kn was mainly controlled by the thermal steering with little change in the central pressure. In fact some slight filling of the centre from 1002 to 1005 mb was apparent during the second half of Saturday.

(b) *Forecast guidance*

Numerical forecasts from the coarse-mesh (octagon) version of the Meteorological Office 10-level model gave consistent advice during these early stages in the life of low LY. Even the guidance produced on Friday 10 August for four and five days ahead suggested that the depression would deepen later in the period as it approached the British Isles.

On Saturday 11 August the 48- and 72-hour numerical forecasts reinforced this advice and were subsequently supported by the 500 mb products from the United States. The models showed the upper ridge over the British Isles declining and moving away as the strong westerly jet over the Atlantic extended eastwards. Numerical forecast charts for midday on the 14th indicated substantial development and sharpening of the upper trough associated with LY as it approached 20°W, helped by a veering of the flow over the western Atlantic as the upstream ridge amplified near Labrador. This is well illustrated in Fig. 3(a) which shows the 72-hour forecast at 500 mb from the 10-level model, based on data for 12 GMT on 11 August. The corresponding forecasts of surface pressure showed LY running rather quickly eastwards at about 30–35 kn during the first 48 hours with no development—quite the reverse,

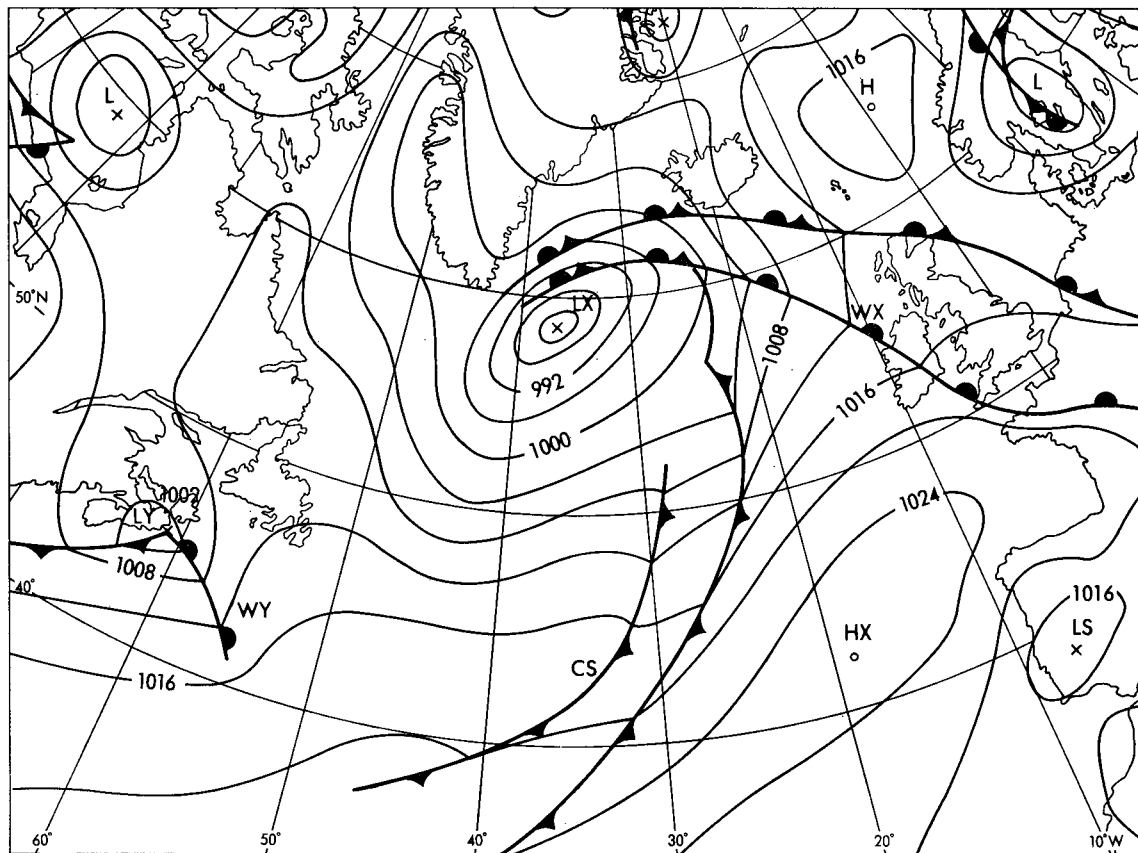


Figure 2(a). Central Forecasting Office (CFO) surface analysis for 12 GMT, 11 August 1979.

in fact, with the 48-hour forecast for 12 GMT on 13 August giving no discrete centre associated with the low, merely a trough implying a wave of about 1012 mb near 48°N 30°W. However, after 72 hours a significant change had taken place in the forecast field as the low moved into the well-marked diffluent area ahead of the sharpening upper trough. On the forecast chart for 12 GMT on 14 August (Fig. 3(b)) a separate low centre had been developed to the west of Ireland with a closed circulation and a central pressure of 1003 mb.

The medium-range guidance issued on 11 August followed the general developments predicted by the model—not surprising in view of the plausibility and consistency of the solutions produced by the computer. The forecasters were particularly impressed by the massive upper trough generated behind LY on the 72-hour prognoses and the highly developmental nature of the pattern. Experience has shown that in this type of situation the model frequently underestimates the deepening of the associated surface low. Consequently, on the subjective prognoses the forecasters considerably accentuated the depth of the low as it moved over the eastern Atlantic, encouraged also by the rapid deepening suggested by the model in the latter stages of the forecast period. The 72-hour forecasts based on data for 00 and 12 GMT on 11 August produced by the medium-range forecaster are shown in Figs 3(c) and 3(d)

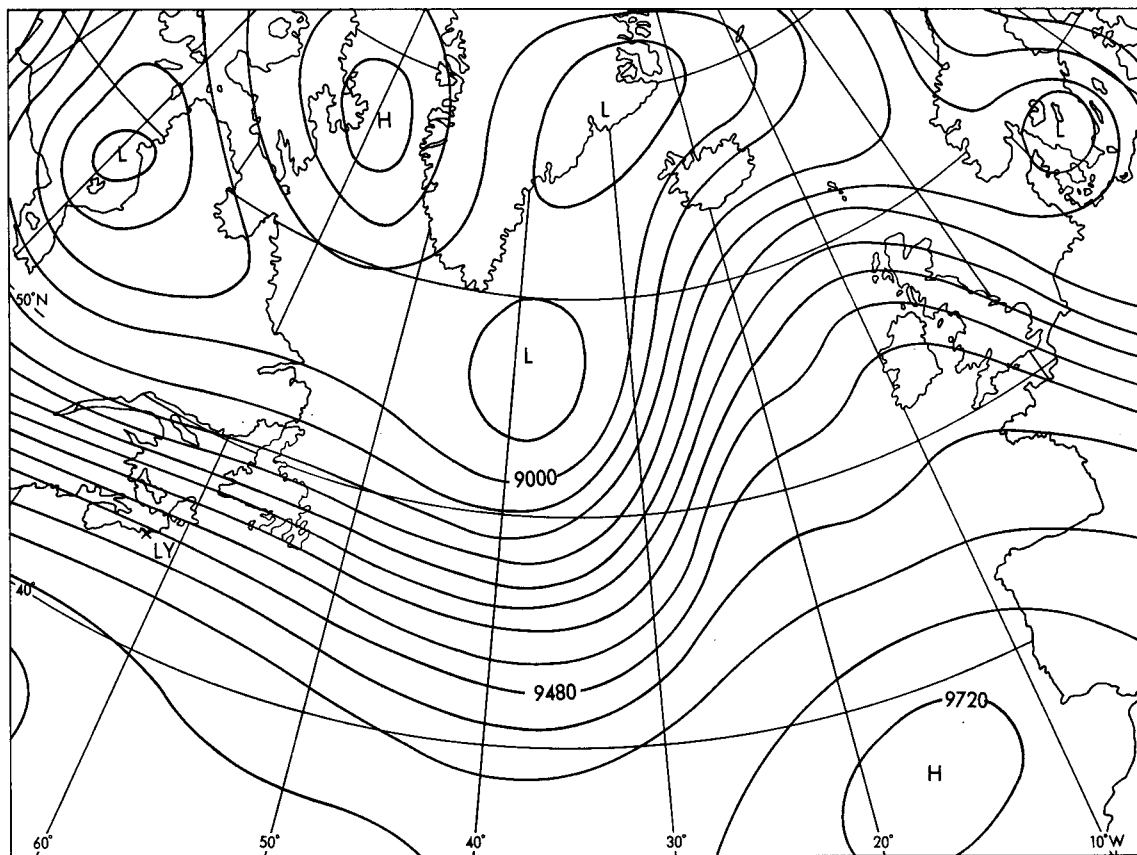


Figure 2(b). CFO 300 mb analysis for 12 GMT, 11 August 1979. Values in geopotential metres.

respectively. Although these charts were originally drawn at intervals of 8 mb, intermediate isobars at 4 mb have been interpolated so that the subjective prognosis in Fig. 3(d) may be directly compared with the original numerical forecast (Fig. 3(b)). It is noteworthy that the central pressure of LY in Fig. 3(d) is about 17 mb deeper with a resultant marked increase in the pressure gradients.

Both sets of medium-range forecasts issued on 11 August proved to be slow as far as the eastward movement of LY was concerned. Even so there is no doubt that they provided useful guidance and correctly conveyed the idea of a vigorous low with pressure gradients strong enough to produce gales or severe gales approaching western Ireland by early on 14 August (although the track was expected to be further to the north-west than actually occurred).

Southampton Weather Centre had been asked by the RORC for an extended forecast to be prepared about seven hours before the start of the race. The advice included an outlook until 23 GMT on 13 August (about the time when the first severe effects of the storm were to be felt) and was written after consultation with the medium-range forecaster in the Central Forecasting Office (CFO). When the situation was discussed the 72-hour forecast chart shown in Fig. 3(c) was still being prepared and, since it was thought that the main wind strength in Fastnet would develop after the end of this particular

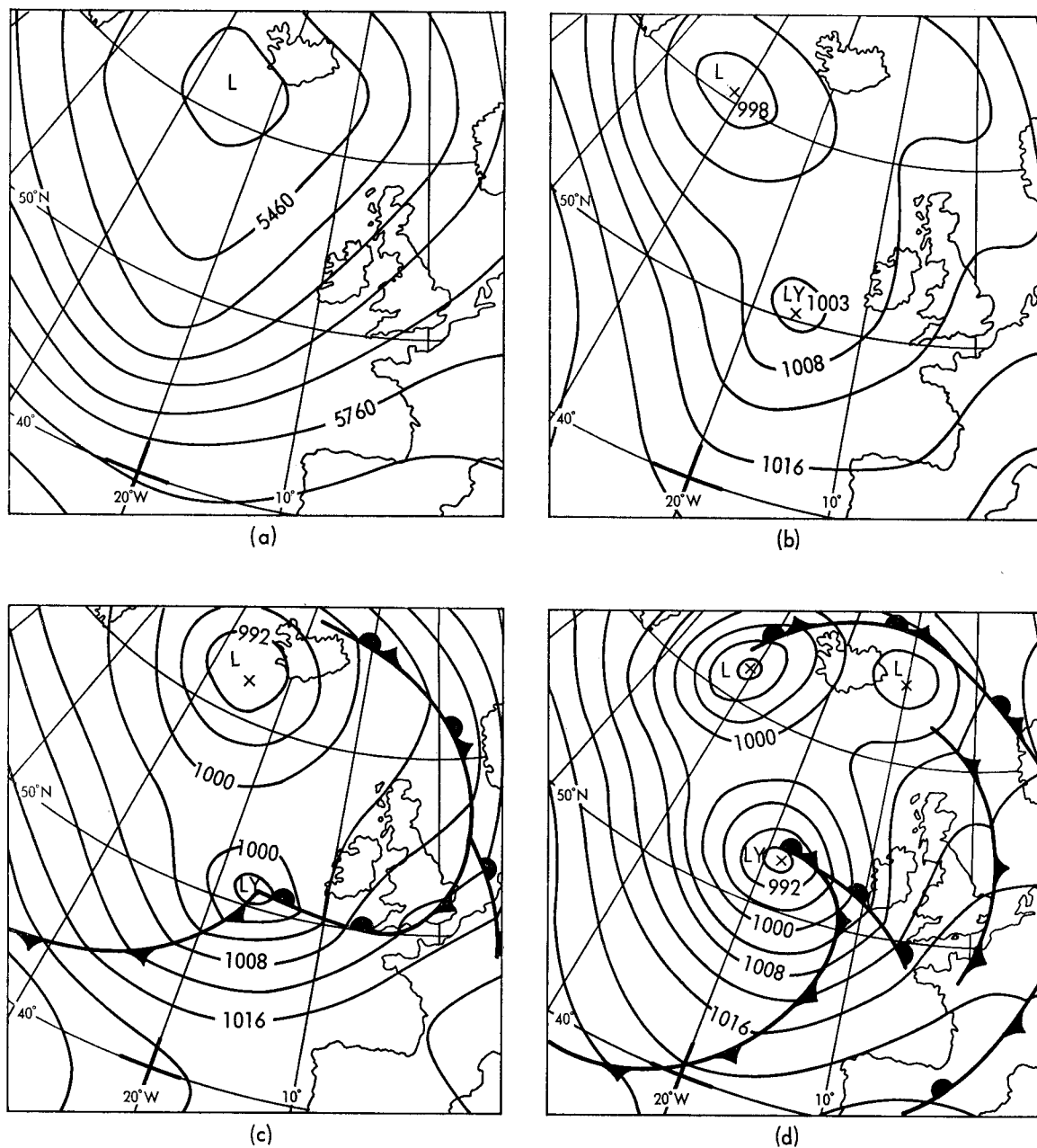


Figure 3. (a) Octagon 72-hour 500 mb forecast for 12 GMT, 14 August 1979. Values in geopotential metres. (b) Octagon 72-hour surface forecast for 12 GMT, 14 August 1979. (c) Medium-range 72-hour surface forecast for 00 GMT, 14 August 1979. (d) Medium-range 72-hour surface forecast for 12 GMT, 14 August 1979.

forecast period, the advice issued by Southampton did not reflect the potential vigour of LY. The RORC made no arrangements to receive updated forecasts during the race because they had no means of transmitting the information to the competitors once they had sailed. The British national team were also briefed by a member of the Meteorological Office acting on a private basis. At the final briefing which took place shortly before the start of the race (again after consultation with CFO) the possibility was indicated of winds reaching gale force (Beaufort force 8) at times from Tuesday 14 August onwards.

3. Sunday 12 August

(a) Synoptic situation

During Sunday 12 August developments proceeded along the lines expected earlier. Low LY continued on a general easterly track with ship observations giving a reasonable fix on the position and depth, at least until midday when the centre was approximately 300 n. mile east of Newfoundland (Fig. 4). Continuity charts (Fig. 5) indicated that the system was accelerating at this stage as its track slowly became closer to the jet axis, the mean speed between midnight and midday being about 40 kn. There was still no discernible deepening and the upper trough associated with the low remained as a minor perturbation in the strong zonal flow.

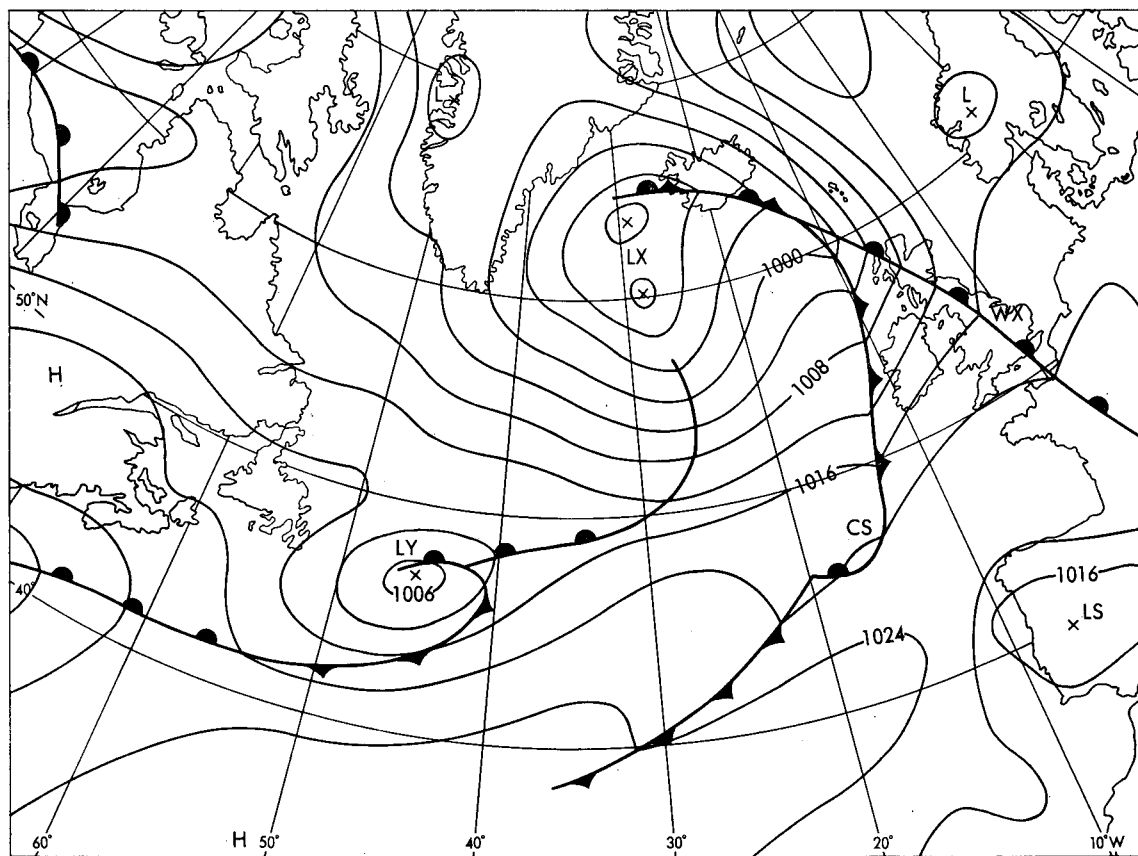


Figure 4. CFO surface analysis for 12 GMT, 12 August 1979.

(b) Forecast guidance

The run of the numerical model based on data for 00 GMT on 12 August maintained the same general evolution as previous runs and the medium-range forecaster again accentuated the depth of LY on his 48- and 72-hour forecast charts, developing a low of 986 mb off western Ireland (12 mb deeper than the model).

During the day the senior forecaster became increasingly unhappy with the detail of the numerical guidance as far as the 24-hour prognoses were concerned. By now low LY was just appearing on the forecast charts produced from the fine-mesh (rectangle) version of the model (these charts extend only as far as 35°W over the North Atlantic). The two versions of the model gave similar solutions, suggesting that LY would be near 50°N 30°W at midday on the 13th with central pressure around 1010 mb. This represented a slight *filling* of the low and an average speed of only 25 kn. Such movement appeared much too slow considering the strength of the upper flow, the recent observed acceleration of the system and the evidence from satellite pictures (which showed the associated cloud mass extending very quickly eastwards across the Atlantic). Moreover, it was expected that some deepening would be initiated as the low became located in an increasingly diffluent pattern on the cold side of the jet. The models had clearly not made the low deep enough, since even in the 12-hour forecast for 12 GMT that same day the central pressure was 7 mb higher than the analysed value, despite a satisfactory numerical analysis.

In his subjective prognosis for 12 GMT on 13 August (Fig. 6(a)), the senior forecaster therefore deepened the low to 998 mb (12 mb deeper than the model) and moved the centre quickly east-north-east to near 50°N 20°W. This turned out to be close to the position suggested by the later rectangle run based on 06 GMT data. The main intention behind this prognosis was to portray the start of vigorous cyclonic development with geostrophic winds up to 50 kn round the low. In the accompanying Synoptic

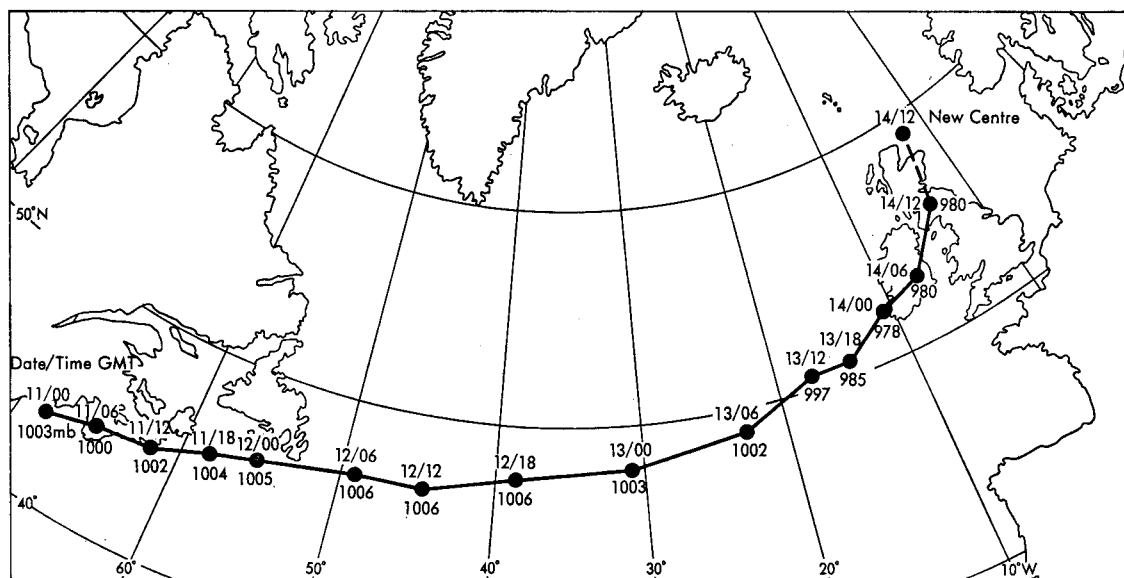


Figure 5. Track and depth of Low LY from 00 GMT, 11 August to 12 GMT, 14 August 1979.

Review the comment was made: 'Low LY is expected to start deepening substantially tomorrow as it engages the very cold air now extending south over mid-Atlantic'. The reference to 'very cold air' was especially pertinent since the analysed 1000–500 mb thickness values near 55°N 35°W were close to the 25-year (1951–75) extreme minimum of 534 decageopotential metres. This had produced very strong baroclinicity over the central North Atlantic near 50°N and AIREPs (aircraft reports) indicated that the associated jet was slowly strengthening, maximum wind speeds of around 150 kn being reported by early on Monday 13 August. The flow pattern was in many ways appropriate to a winter situation and the potential was obviously there for major cyclonic development.

Numerical guidance based on midday data received later on 12 August presented few surprises. After showing no development in the first 24 hours the 36-hour rectangle forecast for 00 GMT on 14 August (Fig. 6(b)) at last showed the low starting to deepen more noticeably. However, both the rate of deepening and the eastward movement of the centre were about 12 hours slower than the senior forecaster's prognosis which had just been issued (Fig. 6(a)).

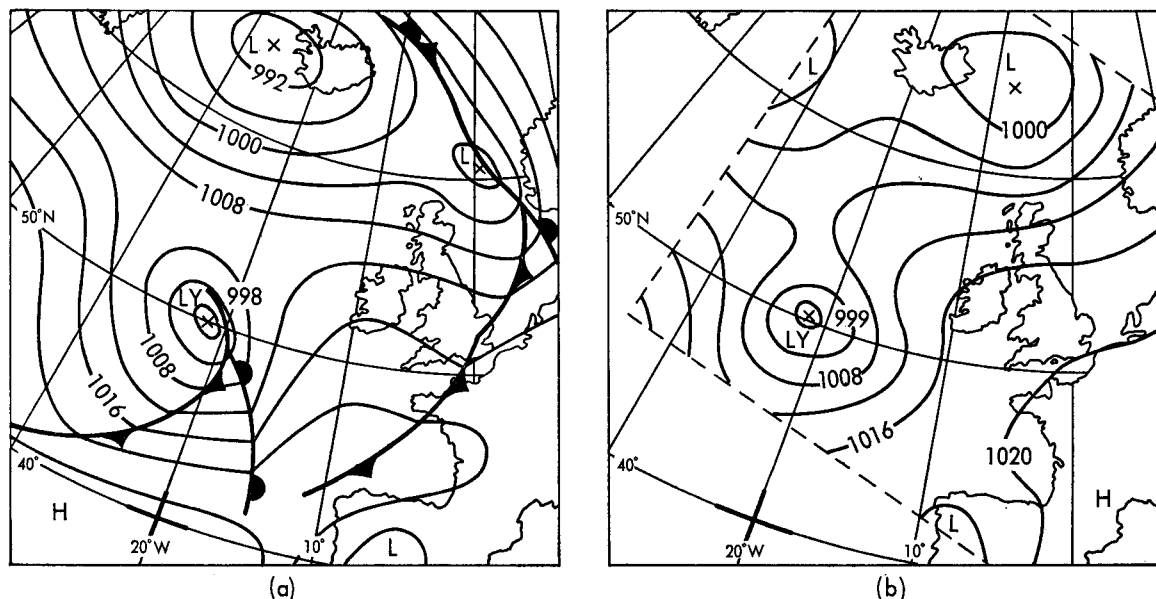


Figure 6. (a) Subjective 24-hour surface forecast for 12 GMT, 13 August 1979.
(b) Rectangle 36-hour surface forecast for 00 GMT, 14 August 1979.

Thus, throughout Sunday 12 August the general feeling continued that LY would be a notably vigorous system as it approached Ireland, probably much more so than indicated by the models. A forecast prepared by Southampton Weather Centre for Offshore Instruments Ltd in connection with the Fastnet Race included the possibility of severe gales (force 9) on the 14th, in line with the medium-range guidance and outlooks issued from CFO. However, the shipping forecasts which were the main source of weather information for the yachtsmen contained no such information, since the major intensification of LY was expected to take place after the 24-hour period covered by the forecast.

4. Monday 13 August

(a) 00–12 GMT

When the senior forecaster came to draw the midnight surface analysis in the early hours of Monday 13 August he was faced with a complete dearth of information in the area of the North Atlantic where low LY was located. No observations were available within about 350 n. mile of the estimated position of the centre, the nearest being from Ocean Weather Ship 'C' (52.7°N 35.5°W) which was outside the circulation of the low and gave little clue to its depth. The analysis therefore had to rely heavily on continuity with the centre of the low estimated at 1006 mb near 48°N 32°W. In contrast, the flow pattern at 300 mb (Fig. 7) was well defined by AIREPs with a maximum wind speed of 150 kn at 33 000 feet just north-east of the estimated position of the low centre, decreasing rapidly to 40–60 kn in a classic left-exit region near the British Isles.

Despite the uncertainty over the depth and exact position of LY, it was clear from satellite pictures that the very strong upper flow was bringing the low eastwards much faster than indicated by the model, as had been anticipated on the previous day. Moreover, it was considered that with the jet also propagating forwards quickly, the major development of the low would occur later and further east than expected previously. In his draft 24-hour prognosis for 00 GMT on 14 August, the senior forecaster ran

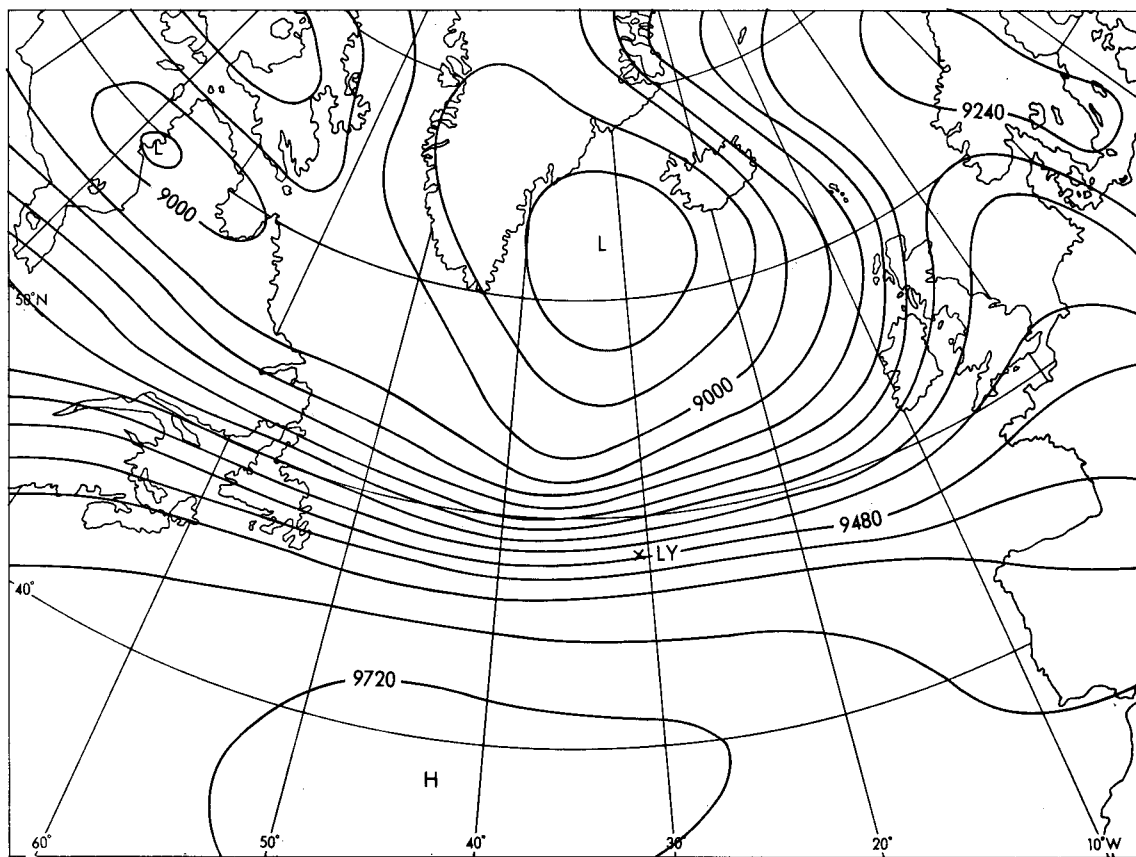


Figure 7. CFO 300 mb analysis for 00 GMT, 13 August 1979. Values in geopotential metres.

LY quickly towards the north-west of Ireland with only slight deepening. As it happened, when the new numerical guidance based on midnight data was received, it supported these ideas and the forecast chart shown in Fig. 8 was issued with LY kept more as an open wave than hitherto. It is true, of course, that the numerical analysis also suffered from the lack of data over mid-Atlantic and this aspect has been investigated by Day (1981). However, although the initial analysis was very poor for the rectangle run, rectification of this for the octagon forecast did not result in any greater development.

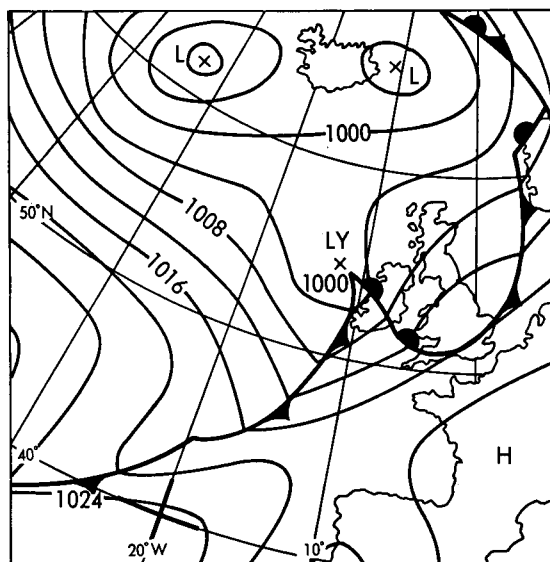


Figure 8. Subjective 24-hour surface forecast for 00 GMT, 14 August 1979.

A complex situation existed near the British Isles with the weather during the coming day expected to be controlled by frontal waves on the cold front CS. One particular wave which had been identified at 46°N 20°W at 12 GMT on the 12th (Fig. 4) was moving towards south-west England and was destined to complicate the picture throughout the day. By the end of the night it appeared that the upper pattern was pushing so far eastwards that this small wave was going to be the deepener rather than low LY (pressure falls in the south-west approaches were then significantly larger than at Ocean Weather Ship 'R' ahead of LY).

Doubts about the surface analysis persisted through the morning, the only ship observation on the chart for 06 GMT closer than 400 n. mile to the low centre being that from Ocean Weather Ship 'R' (47°0'N 16°9'W). This report just ahead of the associated warm front seemed fairly innocuous with a surface pressure of 1013·4 mb, a falling pressure tendency of 2·2 mb in three hours and a wind of 210°, 16 kn. Satellite pictures helped to estimate the centre of the low near 49°N 25°W and, with no evidence for any significant deepening, the story followed the general lines adopted overnight.

In the late morning the surface analysis was reviewed when some delayed ship observations for 06 GMT were received. Amongst these (see Fig. 9) was an observation from the Panamanian-registered *Carmelita* (call-sign 3EJE) giving the first report of a gale and suggesting some deepening of the low. For clarity only the coded pressure and wind have been plotted in Fig. 9. However, just 40 n. mile to the north-west of this ship was another observation from the British vessel *Resolution Bay* (call-sign GXEV)

with a wind of only 18 kn and a slightly higher pressure. *Resolution Bay* is a ship noted for the excellent quality of its observations and the 06 GMT analysis was subsequently revised accepting its observation rather than that from the Panamanian vessel. Thus, only very slight deepening of LY was diagnosed although it was clear that further acceleration of the system had occurred overnight, the mean speed of movement of the low in the 12 hours up to 06 GMT being about 50 kn!

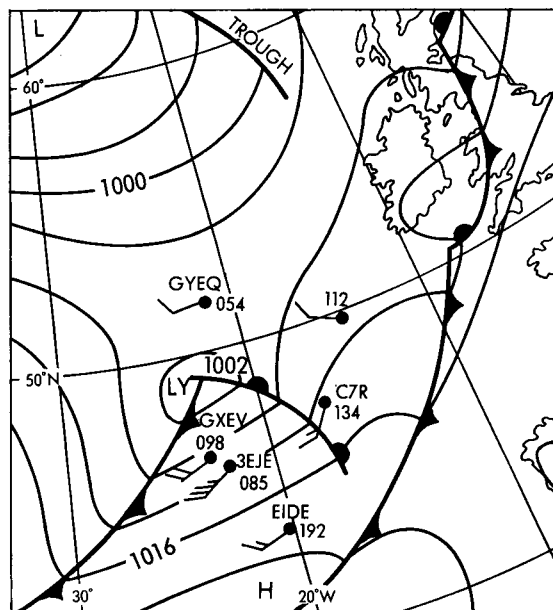


Figure 9. Finalized CFO surface analysis for 06 GMT, 13 August 1979.

(b) 12–18 GMT

Around midday, the pressure falls at Ocean Weather Ship 'R' which had averaged a modest 2 mb in three hours for most of the morning suddenly accelerated to 5 mb in three hours with an equally abrupt increase in surface wind from around 20 to 31 kn between 11 and 12 GMT. In addition, the rectangle forecast received in the early afternoon, based on 06 GMT data, indicated rather more development of LY than the run based on midnight data with the 30-hour forecast (Fig. 10(a)) showing a low of 996 mb near eastern Scotland. Comparison of the 6-hour forecast with the current midday analysis revealed that the model already had the low much too shallow. The apparent discrepancy was around 10 mb, arising partly from errors in the analysis (3 mb) but mainly from spurious filling of the low in the early stages of the forecast. Again there was some uncertainty over the exact position and depth of the low on the midday analysis, with no ship reports closer than about 180 n. mile to the estimated position of the centre. However, the evidence that the model had probably underestimated the development of LY, combined with the increasing wind and pressure falls at Ocean Weather Ship 'R', encouraged the senior forecaster to make the low a much more vigorous feature on his 24-hour forecast for 12 GMT on 14 August (Fig. 10(b)). This was the first prognosis produced on Monday 13 August which correctly developed very strong pressure gradients around LY as well as keeping it on a track over southern Ireland.

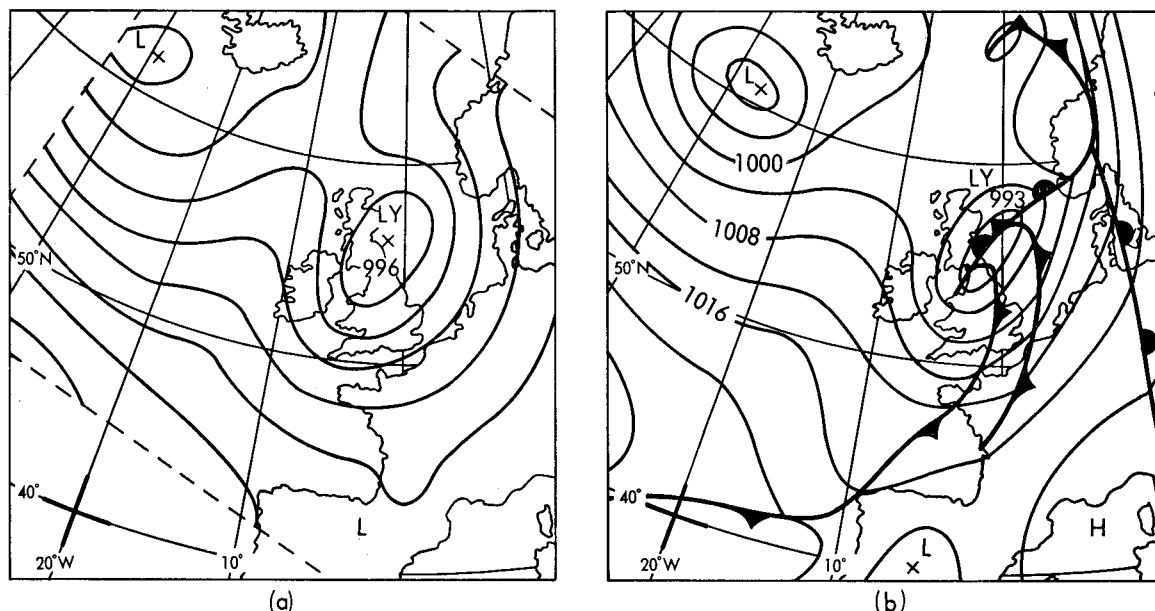


Figure 10. (a) Rectangle 30-hour surface forecast for 12 GMT, 14 August 1979.
(b) Subjective 24-hour surface forecast for 12 GMT, 14 August 1979.

With the wind at Ocean Weather Ship 'R' continuing to increase to 40 kn, it was now clear that the low was starting to slow down and deepen. The Synoptic Review issued at 1525 GMT added the further qualification: 'With LY now engaging the cold trough at 30°W considerable deepening is now expected. . . . Winds are now expected to be even stronger than indicated on the 1200 prognosis'. The TIROS N satellite picture received in the late afternoon (Plate I) gave further evidence that LY was deepening. The cloud was developing a marked 'comma' shape indicating increased circulation, with signs of a significant trough already forming in the cold air.

The finalized CFO surface analysis for 12 GMT on 13 August (Fig. 11) differed little from the preliminary drawing, none of the late ship reports being in a position to help define the centre of the low better. However, inspection of the tracking in Fig. 5 suggests that the centre may well have been slightly further to the south-west as it entered the deepening stage and slowed down. The wind, coded pressure value and tendency are plotted in Fig. 11 for a selection of key observations. In retrospect, the outstanding impression is how ordinary the low looked at that time with only one report of a gale and generally light or moderate winds in Fastnet and to the south-west of Ireland. Pressure tendencies were by no means exceptional; indeed by 15 GMT pressure falls over the southern Irish Sea ahead of the developing wave on cold front CS were larger than those in south-west Ireland (3.3 mb in three hours at Valentia). So even after the event it is difficult to isolate any features on the surface charts which should have given firm warning of such explosive development as actually occurred. Lack of ship reports near the low centre at the crucial time meant that the only real clue lay in a qualitative assessment of the upper pattern (which, as stated before, was exceptionally favourable for cyclonic development). Further guidance from the numerical model was not available during the afternoon, owing to the breakdown of both the IBM 360/195 and 370/158 computers, which also disrupted the supply of plotted charts to CFO.

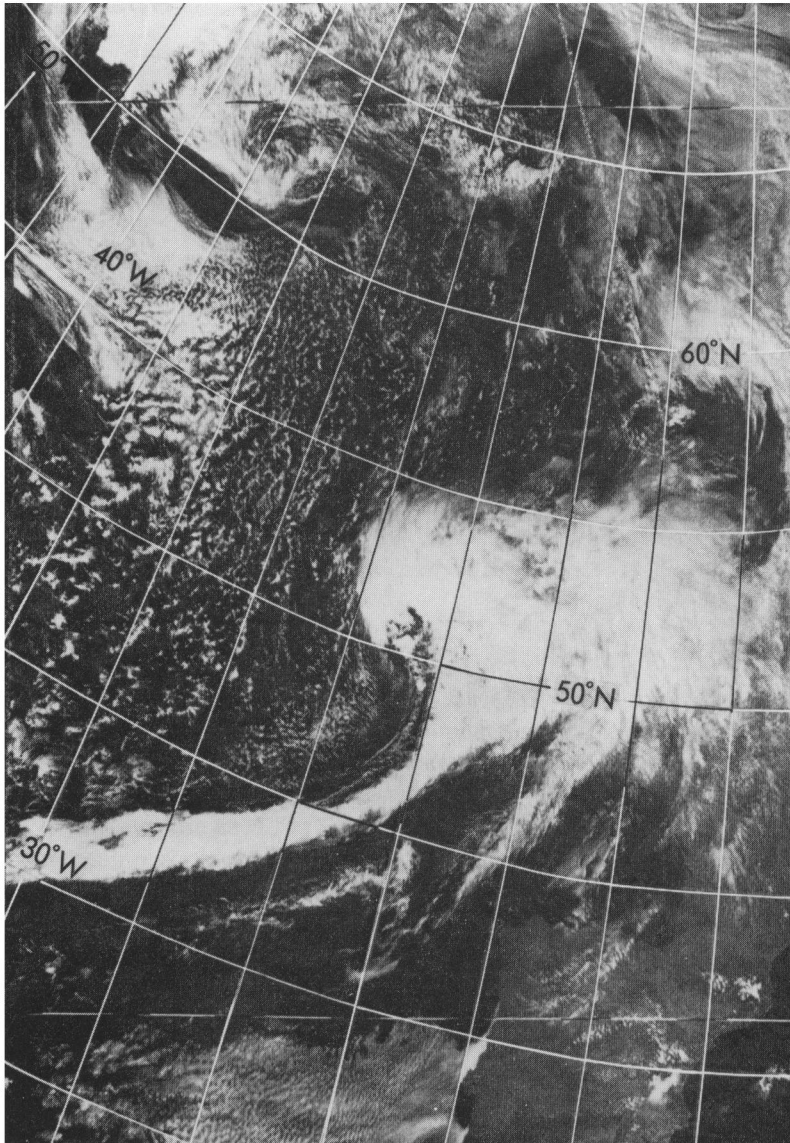


Plate I. TIROS N visible satellite picture received on the afternoon of 13 August 1979.

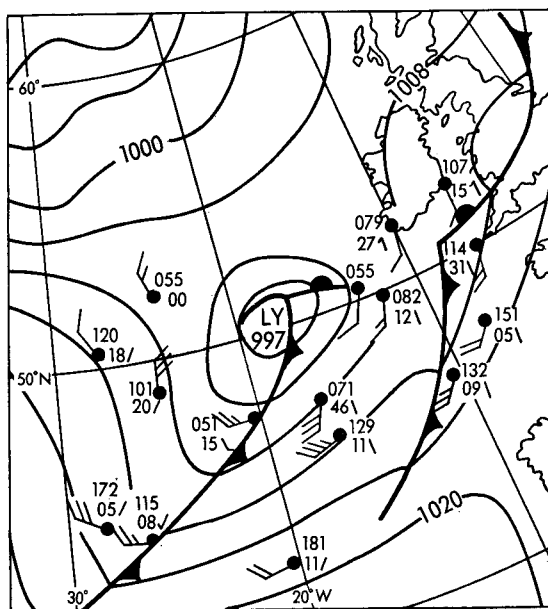


Figure 11. Finalized CFO surface analysis for 12 GMT, 13 August 1979.

(c) 18–24 GMT

During the early evening of 13 August, steadily accelerating pressure falls over south-west Ireland confirmed the vigorous nature of the low, although similarly increasing falls were also evident ahead of the developing wave on the cold front CS as it moved northwards over the Irish Sea. This wave was still occupying some attention from the senior forecaster, since by now it was associated with a broad area of moderate or heavy rain and the need for FLASH messages was being actively considered.

With the computer complex now back in service, new guidance from the fine-mesh model was received around 20 GMT confirming what was already apparent, namely that LY was going to deepen substantially. However, even at 2015 GMT when the senior forecaster came to draw the 18 GMT surface chart, the analysis was still in doubt. Fig. 12 shows that the three ship reports closest to the low centre (call-signs KGCW, D5MI and UITO) had pressure values which almost certainly were wrong or incorrectly coded. Without knowing this, it was possible to draw the low as a much shallower feature but then no satisfactory explanation could be given for the very strong winds reported from ship KGCW (55 kn) and Ocean Weather Ship 'R' (40 kn). The most likely solution appeared to be that the pressure reports from ships KGCW and D5MI had been erroneously coded in whole millibars. The resultant analysis produced in CFO that evening was very similar to Fig. 12 which was constructed by Painting (personal communication) after the event using all available data. The low had deepened, therefore, by around 12–13 mb between midday and 18 GMT, an exceptional rate of development for August, whilst its speed of movement had halved to about 25 kn. In the Synoptic Review issued at 2235 GMT, considerable stress was placed on the strength of wind to be expected in the unstable westerlies on the southern side of the low (particularly in gusts); in addition, a warning was sent to Ministry of Defence Headquarters of severe weather conditions (heavy rain and severe gales) which might call for military aid to the civil community.

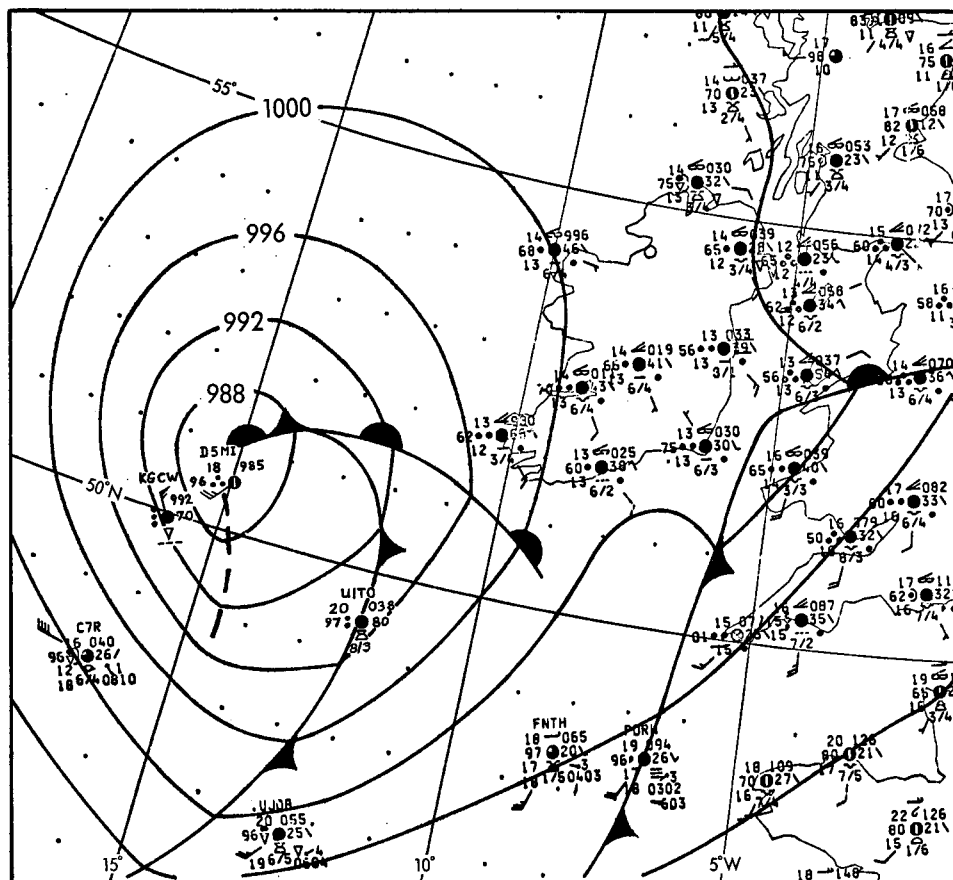


Figure 12. Retrospective surface analysis for 18 GMT, 13 August 1979.

5. The storm

Figs 13 and 14 show the retrospective surface analyses constructed by Painting for 00 and 06 GMT on 14 August, spanning the period when the majority of the race competitors thought the weather was at its worst. It is outside the scope of this paper to attempt any detailed analysis of the climatological aspects of the storm. However, a few points are worth noting to put the occasion in perspective.

As shown in Fig. 13 the strongest winds were undoubtedly located in the unstable westerly flow behind the trough extending southwards near 9°W. Painting's investigation concluded that storm-force winds with very high seas reached Fastnet Rock just before 23 GMT on 13 August and spread rapidly eastwards across the race area during the next three hours. He estimated mean wind speeds reaching 50–55 kn with gusts up to 68 kn (the upper reaches of force 10) and waves as high as 15 metres at times. Another important point to come out of Painting's work was the sudden veer and abrupt increase of wind which occurred with the passage of the trough, accompanied by enhanced gustiness and very high seas. This may well explain why the majority of race competitors estimated the wind speed as force 11 or more. The report prepared for the Royal Yachting Association and the RORC (1979) pointed out that

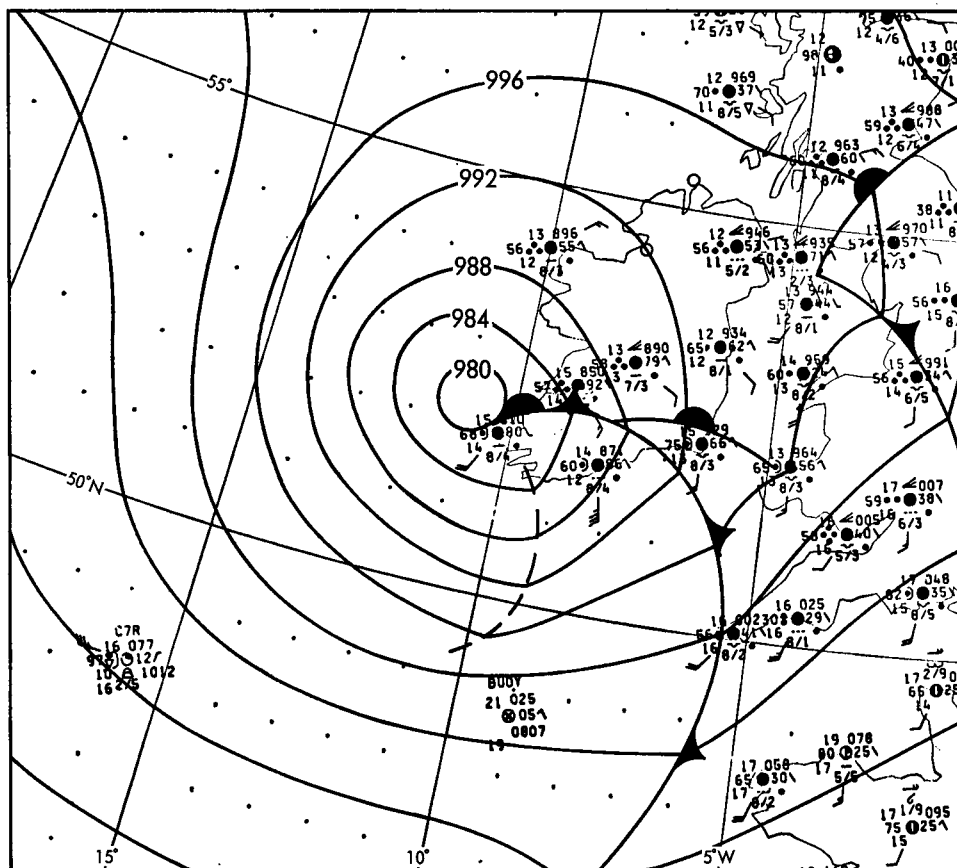


Figure 13. Retrospective surface analysis for 00 GMT, 14 August 1979.

the rapid wind veer would result in wind and waves coming from different directions, making conditions particularly difficult during the hours of darkness. Apparently many experienced competitors stated that the wind strength was not unusual but the sea conditions were the most dangerous they had ever experienced.

The storm went on to cause considerable damage over land during the day, especially in Wales and the west Midlands where many roads were blocked by fallen trees and camping sites were devastated. The highest steady wind speed reported at a land station was 50 kn from Mumbles in South Wales at six consecutive hours from 06 to 11 GMT. Many stations inland over England and Wales had gusts of 50 kn or more, several places recording their highest gust speed for any August. The maximum gusts reported were 65 kn at Milford Haven and 74 kn at Hartland Point, although the latter must be treated with some reserve because of its peculiar exposure. However, the belt of exceptionally strong winds was of very limited lateral extent since, as pointed out by Littlejohns (personal communication), many stations in south-west England and southern Ireland did not even report a mean wind of as much as gale force (although gusts between 43 and 50 kn occurred widely).

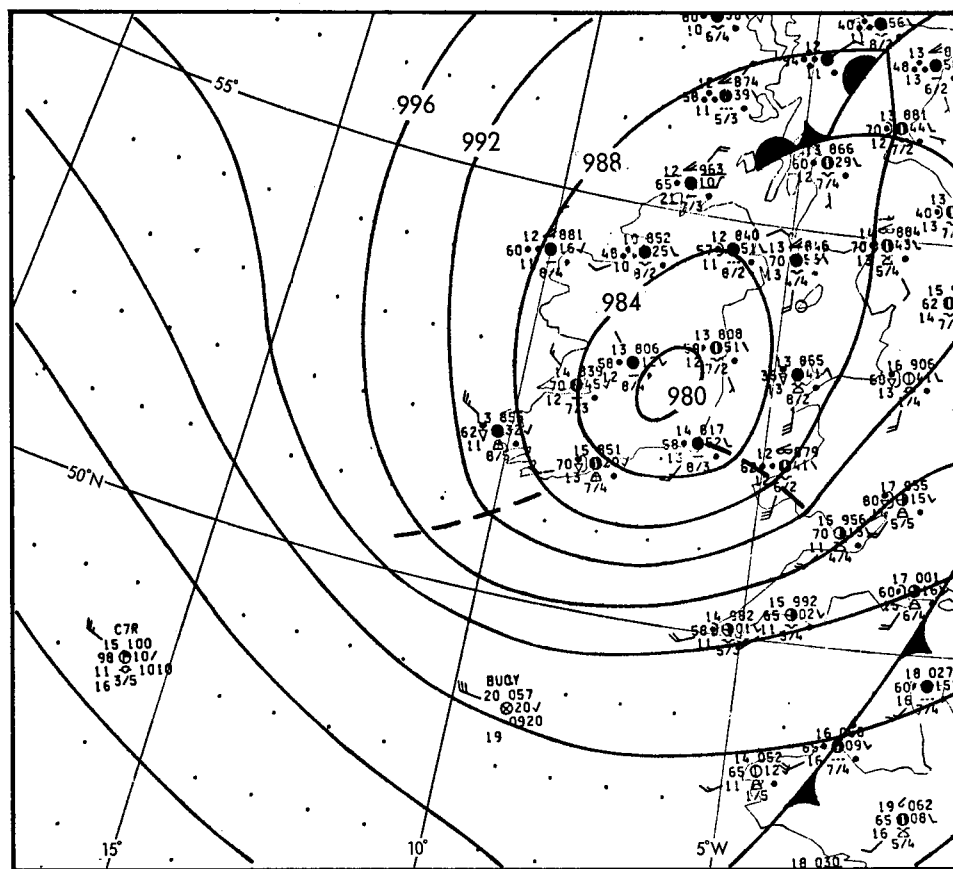


Figure 14. Retrospective surface analysis for 06 GMT, 14 August 1979.

During Tuesday morning the low turned on a more northerly track and became complex with a second centre developing off eastern Scotland. This was another surprising feature of the storm, viz. despite the massive deepening which occurred there was no major deviation of the track to the left until after 06 GMT on 14 August (presumably because of the resistance of the very strong upper flow to buckling). Although the storm was unusually severe for August it was not without precedent. Painting (personal communication) has noted a depression of amazing similarity which also moved across southern Ireland, on the night of 15/16 August 1970, and gave severe gales in many parts of the British Isles.

6. Conclusions

(a) Guidance for 48 and 72 hours ahead from the 10-level model gave firm indications that low LY was likely to deepen as it approached western Ireland, although the surface pressure forecasts seriously underestimated the amount of deepening by 20–25 mb.

(b) The medium-range forecasters made substantial improvements to the numerical guidance, deepening the low by an extra 12–17 mb, thereby indicating a distinct possibility of gales or severe gales

in the Fastnet area. This was an outstanding example of the contribution that the forecaster can still make to the so-called 'man-machine mix'.

(c) Retrospective analysis of the storm indicates that the belt of exceptionally strong winds (force 9 or more) was of very limited lateral extent, probably of the order of 100 miles wide. Bearing in mind the grid length of the model and the enormous distance travelled by the low, it would appear unrealistic at present to expect reliable medium-range forecasts of the development and location of such features.

(d) Fine-mesh forecasts for 24 and 36 hours ahead failed to give advance warning of the sudden deepening and exceptional vigour of the low. Forecasts of the depth of LY at the peak of the storm were generally in error by 20 mb or so (even if we exclude the run from 00 GMT on 13 August which was affected by a very poor analysis).

(e) Twenty-four hour subjective forecasts for the period when the storm was at its height showed some improvement over the corresponding fine-mesh product. Nevertheless, forecast winds in the race area were underestimated at this stage.

(f) Although it was recognized that conditions were generally very favourable for cyclonic development, the short-term assessment of the timing and magnitude of the deepening proved much more difficult. Apart from the complications introduced by the forward wave in the South-west Approaches, the lack of and discrepancies between observations near the low centre undoubtedly delayed recognition of the start and the rapidity of the major deepening. This case-study clearly demonstrates the vital importance of reliable and correctly coded ship observations, even in this era of computers and satellite data.

7. Acknowledgements

I am indebted to my colleagues in CFO for their recollections of the situation at different stages in the development of the storm. I am also grateful to Mr W. B. Painting for various information and data which have been used in the preparation of this paper.

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