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May 1982

NATURAL ENVIRONMENT RESEARCH COUNCIL

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CONTENTS

1. INTRODUCTION

A storm crossing south-west Britain on the evening of 13th December 1981, coinciding with high water of a spring tide, caused coastal flooding in the Bristol Channel. The area affected stretched along the south side of the Channel east of Bideford extending up the River Severn almost as far as Gloucester. The worst flooding occurred on the west-facing coast between the mouth of the River Parrett and just north of Weston-Super-Mare. Substantial damage was caused to property, agricultural land and machinery and there were considerable losses of livestock. Notable industrial installations affected included the C.E.G.B. power station at Hinkley Point and the Esso oil terminal at Avonmouth. A valuable account of the flooding from Avonmouth upstream to Gloucester is given in SEVERN-TRENT-WATER AUTHORITY (1981).

This report deals with the meteorological and oceanographic aspects of the floods and examines the surge predictions produced by the operational west coast forecasting system.

2. THE METEOROLOGICAL SITUATION

A notable feature of the meteorological situation during December 1981 was that the North Atlantic jet stream (the upper air flow which guides the paths of depressions producing storm surges around the British Isles) moved much further south than is usual. The result was that depressions which would normally pass eastward between Scotland and Iceland followed more southerly tracks, several vigorous low pressure systems moving eastward across or close to southern Britain. The very cold air, which came behind these depressions in a strong northerly airstream from the Arctic areas north-east of Greenland, contributed to the exceptionally low temperatures which made it the coldest December in England since 1890 (RATCLIFFE 1982). One of the most vigorous of these depressions crossed South Wales and Southern England on 13th and 14th December.

The following account of the meteorological development is based on the daily weather summaries produced by the London Weather Centre and an analysis of wind speeds and directions carried out by the Marine Climatology Branch (Met. O3c) of the Meteorological Office at the request of I.O.S. (Appendix). Figure 1 shows the tracks of depressions referred to in the text and Figure 2 gives more detailed weather charts for 13th December.

On 12th December, an anticyclone was centred over England. During the day a depression, identified by the letter Y in Figure 1, moved SE from a position

50^{o}N, 10^{o}W crossing the Bay of Biscay and SW France into the Mediterranean. Further north, a depression (T) south of Iceland was moving slowly south. At midday, a complex depression (X) was situated in mid-Atlantic and a secondary depression (B), which was to produce the surge, formed on the cold front SW of its centre. The main depression (X) moved fairly quickly east, merging with low (T) and deepening to 975mb by 0000GMT on 13th December. During the next 36 hours it became slow-moving NW of Ireland, deepening further to 968mb by midday on 13th December.

In the early hours of 13th December the anticyclone over England began to decline and move away SE into central Europe leaving a ridge extending north over eastern England and Scotland (see Figure 2a). The strong pressure gradient between this ridge and the depression (X + T) was giving south to south-easterly gales over the west of Ireland by 0600GMT. The secondary depression (B) had by now intensified and was rapidly approaching SW Ireland. Ahead of the warm front the pressure gradient steepened with the approach of the depression (Figure 2a and 2b) and the resulting south to south-easterly winds increased in strength. By midday (Figure 2b) when the depression, with central pressure now 966mb, reached SW Ireland, the south-easterly winds were estimated to be stronger than 50 knots (26 m/s) over the central English Channel and St. Georges Channel and locally in excess of 60 knots (31 m/s) off the north Cornish coast. In the southern Celtic Sea, the winds were veering to westerly with the approaching cold front, with speeds again estimated to be in excess of 50 knots in places.

Low B continued to move quickly east across southern Ireland deepening further to 962mb by 1800GMT when it was situated between Rosslare and Fishguard (Figure 2c). The frontal system and associated areas of strong wind also moved east, the 60 knot south-easterlies affecting the outer Bristol Channel for a time in mid-afternoon before the winds veered to the west. By early evening west to north-westerly gales were established over the whole of the Celtic Sea with speeds in excess of 50 knots over a large area. As the depression moved east across south Wales, the west to north-westerly gales extended into the Bristol Channel and Severn Estuary with speeds exceeding 40 knots (21 m/s) as far east as Flatholm by 2100GMT. By midnight the depression had reached central England, its central pressure increased to 968mb, and the west-north-westerly gales over the Celtic Sea and Bristol Channel had moderated.

It is of interest to compare the development just described with the characteristics given by LENNON (1963) as identifying those depressions likely to give large surges at Avonmouth. These characteristics are summarised by Lennon as follows:

1. A deepening and well-developed secondary depression approaches the country,

in the zone indicated, so that its right-rear quadrant has latitude to act upon the water surface en route to the port or ports.

2. The speed of approach of this depression is of the order of 40 knots.

3. The depression can be represented by an independent and roughly concentric system of isobars up to a radius of 150 to 200 nautical miles.

4. The depression is likely to reach a depth of approximately 50 mb over the country, and will be associated with a pressure gradient of approximately 30 mb in 250 nautical miles in its right-rear quadrant.

where the zone of approach is shown in Figure 3. In the present case the first criterion is satisfied except that the track of the depression after it crossed St. Georges Channel was far to the south of the danger zone indicated by Lennon. The speed of approach as determined from Figure 1 during the period from 1200GMT on 13th to 0000GMT on 14th was only about 25 knots, substantially below the 40 knots required in 2. The depression was certainly an independent feature, as required in 3, though its size might be considered small. The small extent in the NE - SW direction probably compensates for the southerly track of the depression by bringing effective winds to bear on the Bristol Channel. The final requirement, 4, was satisfied quite well. Overall, the slow approach speed and southerly track of the depression might well have led to its being classed as 'not dangerous' under the criteria given by Lennon.

3. TIDES AND SURGES

3.1 Observed sea levels and predicted tides

Tide gauge records for the period of interest were obtained from the nine ports in and close to the Bristol Channel shown in Figure 4. Of the nine gauges, three failed on the 13th or 14th December. The clock on the Fishguard gauge stopped during the early afternoon of 13th December, and with it the rotation of the drum. However, the vertical movement of the pen was unaffected so that the maximum level reached could be read from the chart, though the time at which it occurred is not known. The clock was restarted on the morning of 14th December. The stilling well on the Avonmouth gauge was overtopped about ½ hour before high water of the evening tide on 13th, during which the flooding occurred, and the float jammed a few minutes later. Information from the nearby Royal Portbury Docks gauge was used to estimate the maximum level reached. A power failure affected the gauge at Hinkley Point about 2 hours after high water, presumably associated with the flooding of parts of the power station. In addition, the tidal predictions were based on a preliminary analysis of only one month of data and would not normally be considered adequate for such a shallow water site. This means that separation of the tide and surge components of the observed levels can only be approximate for Hinkley Point.

A summary of the predicted tides and observed levels at the nine gauges for the evening tide on 13th December is given in Table 1. The tidal levels were not exceptionally high, corresponding to high spring tide conditions such as might be expected to be equalled or exceeded more than 20 times in a year. At Avonmouth, for example, the predicted tidal high water level was about 0.4m above mean high water for spring tides (MHWS) but 1.0m below highest astronomical tide (HAT). The predicted times of tidal high water range from 1803GMT at St. Marys becoming progressively later up the Channel to 2049GMT at Avonmouth, covering the period when the centre of the depression which generated the storm surge moved from St. Georges Channel into south-east Wales. This coincidence of the passage of the storm with tidal high water in the Bristol Channel had a vital influence on the levels produced.

Table 1 also gives the height and time of the corresponding observed maximum water levels. The actual maximum levels exceeded the predicted tidal maxima by between 0.48m at Newlyn and 2.16m at Newport (Table 1). The observed high waters occurred close to the times predicted except at Milford Haven and to a lesser extent at Newlyn. The water level curve at Milford Haven was perturbed around high water leading to the time discrepancy. An indication of the frequency of occurrence of the recorded levels is given in Table 2. The first column relates to the analyses of annual water level maxima carried out by GRAFF (1981). Return periods range from 2 years at Newlyn to well in excess of 250 years in the upper estuary. Since Graff's 1 in 250 year level at Avonmouth is known to have been equalled or exceeded four times in the last 100 years, the results of his analyses for Swansea, Newport and Avonmouth appear to be unrealistic. In the light of the levels recorded on 13th December 1981 and at the request of the Wessex and Welsh Water Authorities, the analyses for Newport and Avonmouth were re-worked, incorporating annual extreme levels not available to Graff or rejected by him as 'abnormal'. The new results, given in the last column of Table 2, indicate that the maximum levels reached in the upper estuary were such as are likely to occur, on average, once in 100 years. The reason for the considerable difference in return period between Newlyn and the upper Channel is discussed in the next section.

The above findings are consistent with reports of the flooding on 13th December, outlined in the Introduction.

3.2 The storm surge

In order to examine separately the contribution of the storm surge to the flooding, the available records from the nine tide gauges in Figure 4 were digitised at hourly intervals and the corresponding predicted tides subtracted to give the surge component of the observed levels. These are plotted in Figure 5.

The gaps in the time series for Avonmouth and Fishguard correspond to the periods when these gauges were out of action, except that a value for Avonmouth at 2100GMT on 13th December based on the Royal Portbury Dock gauge is included to cover the time of tidal high water there. The values for Hinkley Point were extracted from a copy of the chart covering the period 1000GMT to 2200GMT on 13th December kindly supplied by the Wessex Water Authority. However, as pointed out earlier, the quality of the tidal prediction possible with the limited span of data from this new gauge makes the probable accuracy of the residuals rather poor. More accurate residuals may be derived from these data when a complete year's record has been collected from the gauge and a tidal analysis of it carried out.

Residuals derived in the manner described above are susceptible to errors arising in a number of different ways. Table 3 gives a list of some of these sources of error and the effects they can produce in the residuals. Many of the faults could introduce a spurious tidal signal in the residuals. This is unfortunate since, especially in shallow water, a genuine tidal signal can occur in the residual due to surge-tide interaction. There is then a problem in trying to decide whether such an oscillation is genuine or not. Perhaps the only way of deciding this question is to examine the residuals derived from nearby ports - genuine interaction effects might be expected to occur over a region such that they would be coherent at neighbouring stations, whereas the errors producing the same effect on the residuals might not be expected to occur together at a number of gauges.

Before proceeding to describe the surge it is prudent to examine the time series for evidence which might indicate the presence of some of these errors. At the gauges in deeper water (St. Marys, Newlyn, Milford Haven and Fishguard) the residuals vary smoothly with time. An exception occurs at St. Marys where a clear semi-diurnal oscillation with amplitude 0.25m starting at 0900GMT on 14th December can be seen in Figure 5. The start of this oscillation coincides with the tide gauge chart being changed, suggesting that the new chart may not have been correctly located on the drum and the oscillation was due to the associated timing errors. Small but distinct oscillations of tidal period occur at Fishguard with nothing to suggest that they are other than genuine. At all the remaining gauges, located in shallower water within the Bristol Channel, oscillations of tidal period appear in the residuals and at Avonmouth and Newport significant spikes and sudden changes in residual elevation also occur. The oscillations at Avonmouth, Newport and Swansea seem reasonably coherent, being of similar amplitude (about 0.5m) with peaks coinciding in time at

Avonmouth and Newport and 2 to 3 hours earlier at Swansea, suggesting that they may be, at least in part, genuine interaction effects. However, the fact that these oscillations persist even during relatively calm periods such as occurred on 11th and 12th December would seem to indicate that they are not genuine, but associated with the problems of tidal prediction. The difference between the mean level of residuals at Newport and at Avonmouth also suggests an error of about 0.4m in the datum used for the tidal predictions, most probably at Newport.

To illustrate some of the difficulties in predicting tides in the Bristol Channel, recorded low waters at Avonmouth and Newport during the period 11th to 14th December are plotted in Figure 6. The curves from Avonmouth contain flats at low waters around 1.0m above tide gauge zero (TGZ) associated with siltation of the tide gauge well. At Newport, the rate of change of water level between falling and rising tide depends on the low water level (Figure 6b). On large spring tides, when low water falls to about 7 feet above tide gauge zero, the transition is very sharp introducing a discontinuity in rate of change of level with time. On smaller tides with low water more than about 8 feet above TGZ, the transition is smooth. At both ports the tide rises linearly with time over much of the range. A fundamental problem arises in that it is not possible to fit variations with discontinuous slopes or straight lines of constant slope, as described above, with a finite number of harmonic functions as used in the harmonic method of tidal analysis. By attempting so to do, errors will be introduced in the harmonic constituents derived which may affect the accuracy of the predictions at other stages of the tide. In other words, the tidal predictions using the harmonic method are probably inadequate at shallow water ports such as Newport and Avonmouth, so that spurious tidal signals and other effects must be expected to appear in the residuals. Some of the spikes and sudden changes in the residuals from these two sites, shown in Figure 5, can certainly be identified with the factors described above. A clear example is the residual at 0300GMT on 13th December at Newport (near low water as can be seen in Figure 6b) which falls about 0.5m below the values on either side of it, indicating that the predicted tide does not reproduce the shape of the bottom of the observed tidal curve.

The tidal oscillations in the residuals at Ilfracombe (see Figure 5) are different in character from those at the other shallow sites, being more regular, of larger amplitude (about 1.0m) and almost out of phase with those at the other gauges. In addition, the Tide Gauge Inspectorate report independent observations of the tides at Ilfracombe differing substantially from those predicted, even in calm conditions. It therefore seems probable that the tidal signal in the residuals there is mainly spurious being introduced as a result of poor tidal predictions.

To summarise, the surge residuals derived for St. Marys (up to 0900GMT on 14th December), Newlyn, Milford Haven and Fishguard are probably reliable. Those from Swansea are probably reasonably good, being consistent with the Milford Haven data apart from the oscillations of tidal period. The Ilfracombe data are almost certainly unreliable. At Hinkley Point, Avonmouth and Newport the residuals are of doubtful accuracy. In particular a constant of about 0.4m should be subtracted from the residuals at Newport.

In the light of the above criticism, it is difficult to arrive at a description of the surge development in the Bristol Channel based on the observations alone. At St Marys, Newlyn, Milford Haven and Fishguard the surge levels increased with the strengthening south to south-easterly winds during the morning of 13th December. A peak elevation of ~0.75m was reached at St. Marys between 1100GMT and 1200GMT shortly before the warm front passed and the winds veered to westerly, though the surge decreased only slowly during the afternoon. At Newlyn the surge peak of 1.0m occurred at 1300 GMT. This was a very large surge for Newlyn, approximately a 1 in 50 year event on the basis of the work of PUGH and VASSIE (1978). The tide gauge operator there reported being unable to gain access to the tidal observatory until 1600GMT because "mountainous seas" were breaking over it. However, the surge peak occurred close to tidal low water, and this explains the rather modest return period associated with the observed total water level, given in the previous section. The surge at Milford Haven remained above or close to 1.0m between midday and 1900GMT falling quite rapidly in the next hour as the depression passed and winds veered to north-westerly. Rather similar behaviour occurred at Swansea though slightly later.

The surge at all the ports mentioned above (St. Marys, Newlyn, Milford Haven, Swansea and Fishguard) appears to have been generated in response to the south-easterly winds either directed onshore, as at Newlyn, Swansea, Milford Haven and (possibly?) St. Marys, or alongshore with the coast on the right of the direction towards which the wind was blowing, as at Fishguard. This latter situation might be expected to produce a wind-driven longshore flow into the Irish Sea with the Earth's rotation giving a tilting of the sea surface up to the right leading to a positive surge at Fishguard.

The situation towards the head of the Bristol Channel is less certain because of the problems discussed earlier. However, the indications are that here the surge was generated in the 2 to 3 hours before tidal high water as the winds veered to westerly. A significant contribution was probably associated with the effects of atmospheric pressure. The track of the depression so close to the Bristol Channel brought the pressure below 970mb over the upper reaches just around the time of tidal high water. If the hydrostatic approximation were valid this would account for 0.4 to 0.5 metres of surge at high tide. The peak of the surge seems to have occurred close to tidal high water perhaps also suggesting that local forcing was dominant, leaving no time for significant interactions to develop, which might have shifted the surge peak away from high water. If this is the case then the timing of the passage of the depression relative to tidal high water can be seen to have been crucial.

The absence of reliable observations along the south shore of the Bristol Channel gives no indication as to whether the surge developed in the outer Channel during the afternoon propagated upstream. It may be that surge levels on the north facing coasts of Cornwall and Devon were lower than those observed at Swansea and Milford Haven because the south-easterly winds were directed offshore. It is hoped that model studies may help to cover some of the questions which cannot be answered on the basis of observations alone.

3.3 The surge forecasts

Since the winter of 1978-79, a storm tide warning service has operated for ports on the west coast of England and Wales. The surge forecasts have been based on a numerical sea model covering the continental shelf (CSM - shown in Figure 7) intended primarily to provide information for the North Sea (FLATHER 1979). The forecast procedure employs wind and pressure information taken from an atmospheric weather prediction model operated at the Meteorological Office, grid points of which are also shown in Figure 7. It has been felt for some time that the CSM could not be expected to provide forecasts of the required accuracy on the West Coast, and a second higher resolution sea model (WCM - shown in Figure 8) intended to give improved results has been established (FLATHER 1981). During the 1981-82 season, an operational test of the new model, running in conjunction with the established system at the Meteorological Office, was carried out. We now examine the forecasts produced by these models for the period of the Bristol Channel floods.

Tables 4 - 12 give hourly surge residuals for each of the nine ports in Figure 4 derived (i) from the operational forecasts produced at the Meteorological Office, (ii) from subsequent model studies using observed meteorological information and (iii) from the tide gauge observations. The operational system produces two forecasts each day starting at midday and midnight (referred to as the forecast initial data time). Each forecast covers a 36 hour period and is accompanied by a 'hindcast' extending back 12 hours from the start of the forecast. The information from a given hindcast and forecast becomes available to the Storm Tide Warning Service roughly 6 hours after the initial data time of the forecast giving up to 30 hours of advanced warning. Only hours 6 to 36 of the forecast are transmitted to the Water Authorities. Data from the forecasts with initial data times 12Z on 12th (issued at ~ 18Z on 12th) and OZ on 13th (issued at ~ 6Z on 13th) should have contained information useful for warning purposes. The WCM was not run for the next two forecasts (initial data times 12Z on 13th issued at 18Z and OZ on 14th issued at 6Z) because of power supply problems affecting the computers at the Meteorological Office. These forecasts would, in any case, not have been issued in time to be of any practical value.

Examining the Tables, and in particular comparing columns headed a), b), c) and d) containing the potentially useful forecasts with the observations, it can be seen that neither the CSM nor the WCM was successful in predicting the surges. This applies at all ports. Taking, in particular, Avonmouth (Table 8) both models predicted surges of only 0.24 to 0.29m at 2100GMT on 13th December, shortly after tidal high water, when the observed residual was 1.89m. The "last minute" CSM forecast issued at ~18Z on 13th only about 3 hours before the high water (column e)) was still only 0.39m and the hindcast (column f)) 0.52m. The results were equally disappointing at the other ports.

In view of the dominant influence of the wind and pressure fields on the computed surges, the atmospheric model forecasts were compared with the observed meteorological development to assess their accuracy. In particular, atmospheric pressure distributions based entirely on observations and synoptic charts produced by London Weather Centre were constructed by fitting a surface to the available values. A similar procedure was applied to the forecast grid point values of surface pressure from the atmospheric model. Comparisons of the distributions at 1800GMT and 2100GMT on 13th December based on the observations and on the model forecast with initial data time OZ on 13th (this being potentially the most useful forecast) are shown in Figure 9. The outline of the CSM coast serves to indicate the location.

Clearly, the depression as represented in the atmospheric model is a much shallower feature than observed, making much less a distinct low than in the observations and appearing more as a trough extending south-east from the main depression. The whole pattern in the model fields is shifted to the south as compared with the observations, indicating that the centre of the trough would pass across Cornwall and Devon rather than across South Wales as observed. The main difference as far as the winds are concerned, vital for the development of the surge in the Bristol Channel, is that the atmospheric model gives rather weak winds over the Bristol Channel and Celtic Sea north east of a line from Lands End to SW Ireland. The tight isobars over this area in the observed fields (Figure 9) suggests that the winds were very strong, and this is borne out by the wind analyses mentioned in Section 2 (see Appendix).

In order to examine the probable influence of these errors in the atmospheric model forecasts, sea model calculations have subsequently been carried out using surface winds derived empirically from the 3-hourly observed pressure distributions as shown in Figures 9b) and 9d). The procedure for estimating the surface winds has been described previously (FLATHER 1979). Although the resulting wind estimates may not be as accurate as one might wish, they should be of roughly the right strength and direction over the north-east Celtic Sea and Bristol Channel. Surge results from these computations using CSM and WCM are given, as appropriate, in columns headed g) and h) of Tables 4 - 12. There are considerable differences between the models in the Bristol Channel, as would be anticipated when strong local forcing occurs. Surges of order 1.5m are obtained at Avonmouth, approaching the observed magnitude. The substantial surge at Newlyn at midday is still not reproduced in the CSM, and although many factors could contribute, it is possible that setup due to breaking waves may have been significant there.

Overall, it appears that given correct forcing by wind and atmospheric pressure variations the models would produce surges of roughly the right magnitude in the Bristol Channel. For useful comparisons between the sea models, it is necessary to have accurate meteorological information, and to this end work is in progress aimed at making use of observed winds from coastal sites and the wind analyses carried out by the Meteorological Office (see Appendix) in surge calculations. In addition to the CSM and WCM it is intended that higher resolution models of the Bristol Channel (BCM shown in Figure 10) and the Severn Estuary (SEM shown in Figure 11) will be used. The results of these experiments will be reported when they become available, possibly as a supplement to the present report.

4. SURFACE WAVES

4.1 Incoming wave energy

There would have been swell approaching from the west during the afternoon and evening of 13th December. For a point just south of Milford Haven, the Meteorological Office wave model predicted combined sea and swell values at noon of $H_s = 2.7$m $T_z = 6$ sec, where H_s is the significant wave height and T_z the mean zero crossing period. Of this, 1.7m was swell of 10 sec period and 2.1m was local sea of 6 sec period (wave trains are combined as the square root of the sum of their squares). St. Gowan Light Vessel (Figure 4) is near this Met Office grid point, and was carrying the only operational wave recorder in the area. At noon it measured a (combined sea and swell) wave height of 4.7m. By 1500GMT it had risen to 6.1m, falling to 4.5m at 1800GMT, rising again to 5.9m by 2100GMT. The predicted wave heights were probably in error because the southerly local winds were more severe than had been forecast. (The wave model makes use of essentially the same meteorological information as the surge prediction model).

4.2 Locally-generated waves

Although by 1500GMT on 13th December an area of strong north westerly wind was beginning to develop and travel eastwards across the Celtic Sea, the winds at that time in the Bristol Channel were south easterly, nearly 50Kt at Ilfracombe, 35Kt at Weston, and 60Kt at St. Gowan in the centre of another local disturbance. From the wind-field analyses (Appendix) it can be seen that the locally-generated wave components in the St. Gowan and also the Sevenstones (Figure 4) wave records were not relevant to what happened on the north Devon and Somerset coasts during the evening high tide.

4.3 Total wave energy

Only the swell component as, for example, predicted by the Met. Office model, would have penetrated to the Weston area, but that model stops at about Milford Haven. Calculation of the swell height arriving off Weston is difficult without a comprehensive refraction study. However, if the Met. Office model swell estimates for Milford Haven of about 1.7m at noon, and decreasing, are correct (they are probably the best estimates available) and if these waves lost a large part of their energy before reaching Weston (this is likely) leaving a swell height there of, say, 0.5m, then their enhancement of locally-generated wave heights at Weston soon after about 2000GMT would have been small, perhaps 10 - 15% and by 2100GMT it would have been negligible. These swell waves would have taken from 2 - 3 hours to travel from Milford to Weston. Combining swell and sea, the significant wave height of the wave conditions off Weston as deduced from the wind analyses (see Appendix) and the Darbyshire/Draper coastal wave prediction curves, would probably have been as given in Table 13 and plotted in Figure 12.

From this it can be seen that it would not have been until about 2000GMT that the locally-generated waves would have become important along the north Somerset coast, including the Weston area, but from that time on they rapidly become dominant.

A further effect on the waves, and one which is difficult to quantify, is the effect of the ebbing tide from about 2100GMT. This would rapidly have begun to hold back the approaching wave energy so that whatever damage did occur must have happened soon after high tide as the water level would have begun to drop, as would the wave heights. The decline in wave height would have been further enhanced by the lower mean water level and therefore more rapid energy loss by sea bed friction. It is therefore obvious that the wave heights off Weston after about 2200GMT would have been lower than those given in the table. Wave heights further up the Bristol Channel would have been lower than those arriving at Weston; at about Avonmouth, assuming a westerly fetch of about 10 miles and a mean wind speed of about 30 knots, the highest significant wave height would have approached 1 metre, and this would have occurred soon after high tide.

5. CONCLUSIONS

The floods were caused by a vigorous secondary depression which moved east across southern Ireland and South Wales on the afternoon and evening of 13th December. The depression did not conform to the characteristics given by LENNON (1963) as likely to produce dangerous surges at Avonmouth. There would appear to be grounds for re-examining the meteorological criteria used to indicate the possible danger of coastal flooding in the Bristol Channel.

The tides corresponded to large spring conditions, not exceptional in themselves. The coincidence in time of the passage of the depression across South Wales with tidal high water was, however, of crucial importance.

Substantial surges were generated on south facing coasts during the late morning and afternoon of 13th by the strong south to south easterly winds preceding the approaching warm front. The surge at Newlyn was approximately a one in 50 year event. These surges were accompanied by large waves with significant wave heights of order 6m being recorded. Only the swell component would have penetrated to the Weston area, taking some 2 - 3 hours to propagate from the mouth of the Channel. It would appear that these waves did not contribute substantially to the events near the head of the Bristol Channel during the evening high tide.

The westerly gales extending into the Bristol Channel from the Celtic Sea as the depression crossed South Wales in the few hours preceding tidal high water appear to have generated the main surge effect and the local sea which was the main component of the surface waves at the time of the flooding. Significant wave heights were estimated to be about 2m near Weston-Super-Mare and 1m in the region of Avonmouth. The local sea was not fully developed, in which case higher drag coefficients than generally used in the surge computations might have been appropriate (DONELAN 1982), with some effects on the surge generation. Substantially larger waves would have occurred if high water had been 2 or 3 hours later, with perhaps even greater damage to coastal defences. In the event, the ebbing tide and falling levels would have reduced the waves, suggesting that the damage they caused must have occurred close to high tide.

The peak surge of about $1\frac{1}{2}$ to 2m seems also to have occurred very close to the time of high tide, suggesting that local forcing was responsible. Had there been a substantial externally generated contribution, interaction between it and the tide might have been expected to shift the peak of the surge away from tidal high water. Although the surge was not in itself exceptional, its coincidence with high tide produced very high still water levels in the upper Bristol Channel. The extreme level analysis of GRAFF (1981) appears to be unrealistic there. A re-analysis carried out by I.O.S. suggests that levels at Newport and Avonmouth were such as might be expected to occur on average once in 100 years.

The surge forecasts produced by sea models operating at the Meteorological Office gave no indication of a danger of flooding. A major cause appears to have been poor meteorological forecasts which failed to predict the development and movement of the secondary depression correctly. Further model studies using observed or analysed atmospheric pressure and wind fields may shed more light on the surge generation and propagation. It is hoped that useful comparisons between the different sea models may be possible with the observed winds and pressures. It would also be of interest to investigate the influence of the surface waves on the surge development.

A significant factor making deductions about water levels based on the observations difficult is the poor accuracy and reliability of some of the tide gauge measurements. A program is under way to upgrade the 'Class A' network of gauges (which includes Fishguard, Milford Haven, Swansea, Ilfracombe, Newlyn and St. Marys) under the direction of the Tide Gauge Inspectorate. New equipment has been developed and when installed should eliminate the instrumental and operational errors listed in Table 3, providing much improved information. A gauge of 'Class A' quality near the head of the Bristol Channel, say at Avonmouth, seems highly desirable. A new tide gauge installation on the north Cornish coast, if feasible, could help in understanding the characteristics of surge propagation into the Bristol Channel.

There remain the problems associated with tidal analysis and prediction in an area of large highly non-linear tides such as the upper Bristol Channel. These problems impose severe restrictions on our ability to study and understand surges in the region and require urgent attention if progress is to continue.

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Port	Predicted tidal high water		Observed high water		Exceedence of tidal HW	Maximum surge (hourly sampling)	
	height m.ODN	time GMT	height m.ODN	time GMT	m	height m.ODN	time GMT
St. Marys	2.90	1803	3.54	1800	0.64	0.72	1100 1200
Newlyn	2.55	1807	3.03	1750	0.48	1.00	1300
Ilfracombe	4.82	1926	5.61	1930	0.79	1.28	2200
Hinkley Point	6.10	2014	7.40	2025	1.30	1.34	2200
Avonmouth	7.09	2049	8.80 †	2048 †	1.71	1.89	2100
Newport	6.24 §	2047	8.40	2045	2.16 §	2.22 §	2000
Swansea	4.83	1949	5.73	1940	0.90	1.01	1700 1800
Milford Haven	3.60	1945	4.46	1908	0.86	1.17	1600
Fishguard	2.47	2046	3.21	*	0.74	0.85*	1200*

Table 1 : Predicted tide, observed levels and maximum recorded surges during the Bristol Channel floods on 13th December 1981.

* Clock stopped at 1338GMT 13/12/81 - time of maximum recorded level not known.

† Stilling well overtopped at 2020GMT and float jammed at 2028GMT 13/12/81. Maximum level and time estimated from Royal Portbury Dock gauge.

§ Probably affected by an error of about 0.4m in the datum of the tidal predictions.

Port	Return Period (years)	
	a)	b)
Newlyn	2	-
Avonmouth	250 + 0.37m	100
Newport	250 + 0.52m	100
Swansea	250 + 0.02m	-
Milford Haven	30	-
Fishguard	12	

Table 2 : Return periods associated with the extreme levels attained in the Bristol Channel on 13th December 1981 according to a) Graff (1981); b) re-analysis of available annual maxima carried out by I.O.S. at the request of the Wessex and Welsh Water Authorities.

Source of error	errors in record	probable symptom in surge residual
Instrumental :		
Clock slow or fast	timing	tidal signal present
Sloppy pen location	timing/height	tidal signal present
Sticking floats or pullies	height	spikes or sudden changes - tidal signal if sticks permanently
Operational :		
Bad location of chart on drum	timing/height	tidal signal/datum shift
Blockage of orifice	height	spikes or sudden changes if blockage temporary - tidal signal if prolonged
Siltation of well	height - flat on record at low tide	Peak in residual at low water on tides affected
Temperature or humidity effects causing chart shrinkage	height	complex (errors up to 0.25m reported due to chart shrinkage/expansion at Avonmouth)
Data Processing :		
poor or inadequate tidal predictions	timing/height	tidal signal/datum shift/ spikes
Failure to correct known errors	depends on error	depends on error

Table 3 : Possible sources of error in residuals derived from tide gauge records.

St. Marys

date	time	b)	d)	h)	observation
13/12	0000	0.12	0.09	0.07	0.20
	0100	0.12	0.07	0.03	0.21
	0200	0.13	0.07	0.10	0.21
	0300	0.14	0.13	0.13	0.22
	0400	0.14	0.16	0.12	0.27
	0500	0.15	0.17	0.12	0.29
	0600	0.16	0.17	0.09	0.40
	0700	0.17	0.17	0.08	0.43
	0800	0.18	0.21	0.10	0.40
	0900	0.18	0.24	0.08	0.55
	1000	0.20	0.27	0.07	0.59
	1100	0.21	0.30	0.10	0.72
	1200	0.23	0.30	0.07	0.72
	1300	0.24	0.27	0.05	0.65
	1400	0.25	0.27	0.16	0.68
	1500	0.25	0.27	0.28	0.64
	1600	0.25	0.27	0.37	0.59
	1700	0.24	0.27	0.35	0.61
	1800*	0.23	0.26	0.46	0.64
	1900	0.21	0.24	0.51	0.53
	2000	0.21	0.23	0.45	0.54
	2100	0.22	0.25	0.51	0.46
	2200	0.22	0.27	0.54	0.36
	2300	0.22	0.28	0.49	0.27
14/12	0000	0.23	0.28	0.49	0.25
	0100		0.28	0.49	0.31
	0200		0.28	0.47	0.26
	0300		0.28	0.48	0.31
	0400		0.28	0.48	0.21
	0500		0.24	0.49	0.18
	0600		0.23	0.51	0.18

Table 4 : Surge residuals (m) at St. Marys produced (i) in operational model forecasts (a)-f)), (ii) in subsequent model studies (g) & h)) and (iii) derived from observations.
a) CSM forecast with initial data time 12Z on 12/12 issued at ~18Z 12/12; b) same but from WCM; c) CSM initial data time 0Z on 13/12 issued at ~6Z 13/12; d) as c) but WCM; e) CSM hindcast and forecast initial data time 12Z on 13/12 issued at ~18z 13/12; f) CSM hindcast initial data time 0Z on 14/12 issued at ~6Z 14/12; g) CSM with winds derived from observed pressures; h) as g) but WCM.
Times in GMT. * indicates tidal high water.

Newlyn

date	time	a)	c)	e)	f)	g)	observation
13/12	0000	0.10	0.06	0.06		0.03	0.28
	0100	0.10	0.05	0.05		0.04	0.30
	0200	0.11	0.04	0.04		0.05	0.36
	0300	0.12	0.08	0.07		0.09	0.26
	0400	0.11	0.13	0.11		0.08	0.26
	0500	0.13	0.16	0.15		0.09	0.28
	0600	0.15	0.17	0.17		0.13	0.35
	0700	0.16	0.18	0.17		0.13	0.42
	0800	0.17	0.23	0.14		0.20	0.58
	0900	0.17	0.26	0.15		0.26	0.60
	1000	0.19	0.32	0.26		0.30	0.72
	1100	0.21	0.36	0.29		0.37	0.89
	1200	0.23	0.37	0.26	0.26	0.45	0.97
	1300	0.25	0.37	0.26	0.27	0.50	1.00
	1400	0.26	0.40	0.39	0.42	0.54	0.86
	1500	0.27	0.42	0.37	0.40	0.48	0.86
	1600	0.28	0.43	0.40	0.43	0.56	0.50
	1700	0.29	0.45	0.39	0.44	0.50	0.47
	1800*	0.28	0.48	0.41	0.45	0.46	0.43
	1900	0.26	0.44	0.40	0.37	0.46	0.36
	2000	0.25	0.40	0.36	0.32	0.34	0.38
	2100	0.25	0.40	0.32	0.35	0.28	0.31
	2200	0.24	0.39	0.34	0.37	0.29	0.25
	2300	0.24	0.39	0.36	0.36	0.26	0.28
14/12	0000	0.25	0.42	0.37	0.34	0.32	0.16
	0100		0.42	0.36	0.32	0.30	0.26
	0200		0.41	0.32	0.26	0.28	0.28
	0300		0.41	0.29	0.20	0.26	0.27
	0400		0.43	0.32	0.25	0.26	0.19
	0500		0.43	0.33	0.27	0.32	0.17
	0600		0.40	0.30	0.28	0.31	0.07

Table 5 : As Table 4 but for Newlyn.

Ilfracombe

date	time	a)	b)	c)	d)	e)	f)	g)	h)	observation
13/12	0000	0.10	0.07	0.08	0.05	0.08		0.04	0.11	0.37
	0100	0.13	0.13	0.11	0.14	0.11		0.04	0.16	0.21
	0200	0.14	0.14	0.12	0.13	0.12		0.03	0.09	0.08
	0300	0.12	0.12	0.09	0.09	0.09		0.12	0.06	-0.08
	0400	0.10	0.12	0.07	0.09	0.09		0.22	0.13	-0.22
	0500	0.14	0.11	0.18	0.13	0.20		0.15	0.14	-0.17
	0600	0.15	0.14	0.20	0.18	0.26		0.16	0.20	0.03
	0700	0.16	0.13	0.20	0.17	0.28		0.13	0.15	0.23
	0800	0.11	0.13	0.16	0.15	0.26		0.23	0.13	0.44
	0900	0.15	0.12	0.19	0.13	0.35		0.36	0.23	0.71
	1000	0.15	0.14	0.23	0.16	0.29		0.37	0.24	0.91
	1100	0.14	0.16	0.27	0.24	0.11		0.31	0.21	0.95
	1200	0.15	0.14	0.32	0.24	0.28	0.28	0.37	0.19	0.90
	1300	0.21	0.18	0.35	0.26	0.51	0.45	0.40	0.12	0.79
	1400	0.27	0.24	0.41	0.31	0.49	0.37	0.65	0.17	0.57
	1500	0.28	0.27	0.37	0.34	0.20	0.20	1.06	0.35	0.34
	1600	0.28	0.29	0.30	0.31	0.42	0.35	1.17	0.72	0.16
	1700	0.27	0.28	0.32	0.26	0.58	0.58	0.99	0.78	0.29
	1800	0.28	0.30	0.34	0.29	0.42	0.42	0.74	0.76	0.63
	1900	0.29	0.29	0.34	0.30	0.48	0.47	0.84	0.89	0.77
	2000*	0.28	0.31	0.27	0.29	0.39	0.40	0.86	1.08	0.89
	2100	0.28	0.31	0.33	0.29	0.31	0.38	0.68	0.89	1.11
	2200	0.28	0.29	0.35	0.32	0.24	0.36	0.48	0.87	1.28
	2300	0.29	0.26	0.32	0.28	0.22	0.38	0.46	0.61	1.20
14/12	0000	0.32	0.37	0.37	0.38	0.29	0.35	0.36	0.73	0.90
	0100			0.40	0.45	0.32	0.33	0.38	0.72	0.55
	0200			0.40	0.48	0.40	0.46	0.30	0.64	0.19
	0300			0.40	0.38	0.34	0.29	0.15	0.49	-0.08
	0400			0.39	0.42	0.30	0.22	0.17	0.53	-0.23
	0500			0.33	0.37	0.37	0.24	0.31	0.55	-0.30
	0600			0.27	0.29	0.39	0.28	0.33	0.58	-0.24

Table 6 : As Table 4 but for Ilfracombe.

Hinkley Point

date	time	b)	d)	h)	observation
13/12	0000	0.00		0.08	
	0100	0.02		0.09	
	0200	0.07		0.08	
	0300	0.15		0.01	
	0400	0.14		-0.01	
	0500	0.17		0.05	
	0600	0.11	0.10	0.07	
	0700	0.14	0.15	0.14	
	0800	0.12	0.14	0.08	
	0900	0.08	0.10	0.10	
	1000	0.08	0.07	0.12	0.47
	1100	0.08	0.06	0.04	0.73
	1200	0.08	0.07	-0.06	0.47
	1300	0.09	0.11	-0.11	1.14
	1400	0.12	0.16	-0.16	1.08
	1500	0.24	0.27	-0.22	0.72
	1600	0.27	0.31	0.01	0.69
	1700	0.36	0.38	0.51	0.33
	1800	0.29	0.27	0.80	0.46
	1900	0.31	0.30	0.86	1.23
	2000	0.34	0.34	1.28	1.24
	2100*	0.27	0.24	1.35	1.26
	2200	0.27	0.24	1.21	1.34
	2300	0.25	0.24	0.98	
14/12	0000	0.23	0.23	0.74	
	0100		0.27	0.74	
	0200		0.30	0.64	
	0300		0.45	0.70	
	0400		0.38	0.57	
	0500		0.53	0.67	
	0600		0.43	0.65	

Table 7 : As Table 4 but for Hinkley Point.

Avonmouth

date	time	a)	b)	c)	d)	e)	f)	g)	h)	observation
13/12	0000	0.00	0.01	-0.01	0.01	-0.01		0.01	0.10	-0.06
	0100	0.01	0.00	0.00	0.00	-0.00		0.03	0.08	-0.13
	0200	0.05	0.00	0.04	0.00	0.03		0.05	0.02	0.03
	0300	0.12	0.00	0.11	0.00	0.11		0.05	0.02	0.27
	0400	0.19	0.00	0.17	0.00	0.17		0.10	0.02	0.41
	0500	0.17	0.16	0.15	0.14	0.15		0.18	0.03	0.53
	0600	0.16	0.22	0.15	0.18	0.17		0.25	0.13	0.58
	0700	0.17	0.12	0.20	0.11	0.25		0.28	0.16	0.47
	0800	0.15	0.11	0.21	0.15	0.30		0.23	0.20	0.30
	0900	0.10	0.09	0.15	0.09	0.29		0.23	0.09	0.19
	1000	0.07	0.04	0.12	0.03	0.28		0.39	0.11	0.05
	1100	0.07	0.05	0.10	0.02	0.26		0.43	0.13	-0.01
	1200	0.08	0.05	0.11	0.03	0.19	0.19	0.37	0.10	0.09
	1300	0.08	0.05	0.14	0.14	0.02	0.10	0.36	0.01	0.05
	1400	0.10	-0.01	0.18	0.02	0.18	0.11	0.37	-0.01	0.09
	1500	0.17	-0.01	0.27	0.02	0.41	0.24	0.46	-0.01	0.45
	1600	0.31	-0.01	0.44	0.02	0.61	0.33	0.97	-0.01	0.42
	1700	0.36	0.23	0.46	0.26	0.59	0.31	1.40	-0.03	0.58
	1800	0.37	0.46	0.42	0.47	0.63	0.44	1.56	0.48	0.60
	1900	0.36	0.42	0.41	0.38	0.67	0.59	1.31	1.07	1.28
	2000	0.32	0.27	0.37	0.27	0.50	0.51	0.99	0.99	1.68
	2100*	0.25	0.29	0.24	0.29	0.39	0.52	0.83	1.53	1.89
	2200	0.20	0.24	0.18	0.18	0.25	0.46	0.47	1.46	
	2300	0.20	0.21	0.20	0.17	0.16	0.36	0.46	0.89	
14/12	0000	0.21	0.22	0.22	0.20	0.17	0.36	0.43	0.82	
	0100			0.23	0.18	0.19	0.35	0.39	0.70	
	0200			0.27	0.16	0.23	0.35	0.39	0.55	
	0300			0.34	0.00	0.33	0.40	0.38	0.00	
	0400			0.46	0.00	0.51	0.53	0.36	0.00	
	0500			0.53	0.18	0.56	0.52	0.30	0.27	
	0600			0.53	0.61	0.54	0.43	0.32	0.88	

Table 8 : As Table 4 but for Avonmouth.

Newport

date	time	b)	d)	h)	observation
13/12	0000	0.00	0.00	0.10	0.22
	0100	0.00	0.00	0.11	0.34
	0200	0.03	0.03	0.14	0.62
	0300	0.12	0.13	0.18	0.19
	0400	0.25	0.25	0.08	0.88
	0500	0.10	0.07	0.06	0.80
	0600	0.16	0.13	0.13	0.99
	0700	0.15	0.15	0.19	1.04
	0800	0.13	0.16	0.22	0.97
	0900	0.10	0.11	0.15	0.88
	1000	0.05	0.04	0.14	0.68
	1100	0.06	0.04	0.20	0.62
	1200	0.07	0.05	0.14	0.39
	1300	0.07	0.07	0.09	0.37
	1400	0.12	0.09	-0.04	0.87
	1500	0.12	0.16	-0.14	0.78
	1600	0.37	0.42	-0.15	0.94
	1700	0.23	0.24	0.36	0.92
	1800	0.39	0.38	0.79	0.95
	1900	0.40	0.36	1.05	1.66
	2000	0.28	0.28	0.92	2.22
	2100*	0.27	0.26	1.33	2.17
	2200	0.23	0.17	1.29	2.10
	2300	0.23	0.21	0.98	1.91
14/12	0000	0.24	0.23	0.86	1.39
	0100		0.22	0.68	1.05
	0200		0.25	0.69	1.07
	0300		0.31	0.73	1.01
	0400		0.54	0.64	0.17
	0500		0.42	0.55	0.77
	0600		0.56	0.77	0.70

Table 9 : As Table 4 but for Newport.

Swansea

date	time	b)	d)	h)	observation
13/12	0000	0.05	0.06	0.21	0.14
	0100	0.00	-0.05	-0.01	0.13
	0200	0.00	-0.05	-0.01	0.13
	0300	0.20	0.26	0.35	0.28
	0400	0.15	0.18	0.26	0.34
	0500	0.09	0.08	0.31	0.34
	0600	0.15	0.23	0.34	0.30
	0700	0.14	0.20	0.35	0.23
	0800	0.14	0.19	0.33	0.13
	0900	0.14	0.19	0.50	0.21
	1000	0.10	0.11	0.49	0.33
	1100	0.14	0.21	0.58	0.59
	1200	0.14	0.24	0.69	0.70
	1300	0.07	0.03	0.37	0.96
	1400	0.07	0.03	0.07	0.86
	1500	0.22	0.32	0.81	0.80
	1600	0.36	0.39	1.21	0.68
	1700	0.26	0.21	1.14	1.01
	1800	0.29	0.28	0.83	1.01
	1900	0.31	0.32	1.09	0.95
	2000*	0.30	0.26	1.02	0.88
	2100	0.36	0.32	0.89	0.71
	2200	0.24	0.24	0.63	0.73
	2300	0.32	0.33	0.86	0.71
14/12	0000	0.30	0.28	0.67	0.59
	0100		0.35	0.58	0.41
	0200		0.26	0.18	0.11
	0300		0.26	0.42	0.03
	0400		0.61	0.73	0.11
	0500		0.34	0.50	0.16
	0600		0.34	0.59	0.16

Table 10 : As Table 4 but for Swansea.

Milford Haven

date	time	a)	b)	c)	d)	e)	f)	g)	h)	observation
13/12	0000	0.11	0.09	0.09	0.08	0.09		0.05	0.15	0.44
	0100	0.13	0.12	0.12	0.12	0.12		0.08	0.16	0.30
	0200	0.15	0.15	0.15	0.15	0.15		0.13	0.16	0.34
	0300	0.13	0.12	0.13	0.12	0.13		0.21	0.19	0.35
	0400	0.15	0.13	0.18	0.16	0.19		0.24	0.22	0.32
	0500	0.16	0.15	0.21	0.24	0.24		0.24	0.27	0.49
	0600	0.18	0.17	0.27	0.29	0.30		0.24	0.28	0.49
	0700	0.17	0.16	0.27	0.30	0.34		0.24	0.28	0.55
	0800	0.17	0.16	0.27	0.27	0.39		0.34	0.30	0.55
	0900	0.18	0.19	0.29	0.30	0.37		0.39	0.33	0.63
	1000	0.19	0.18	0.35	0.30	0.34		0.45	0.33	0.73
	1100	0.19	0.17	0.38	0.32	0.39		0.51	0.38	0.79
	1200	0.22	0.20	0.41	0.33	0.48	0.48	0.55	0.36	0.97
	1300	0.24	0.24	0.44	0.40	0.48	0.49	0.74	0.51	1.02
	1400	0.26	0.26	0.44	0.42	0.45	0.45	0.83	0.55	1.05
	1500	0.28	0.27	0.38	0.30	0.47	0.46	0.99	0.65	0.99
	1600	0.28	0.31	0.35	0.36	0.48	0.45	0.95	0.74	1.17
	1700	0.28	0.30	0.33	0.30	0.47	0.43	0.80	0.76	1.00
	1800	0.28	0.29	0.33	0.29	0.46	0.45	0.64	0.57	1.00
	1900*	0.29	0.30	0.31	0.28	0.43	0.40	0.54	0.65	1.11
	2000	0.28	0.29	0.30	0.27	0.37	0.32	0.56	0.68	0.66
	2100	0.28	0.30	0.31	0.30	0.29	0.23	0.35	0.57	0.59
	2200	0.28	0.32	0.32	0.31	0.26	0.28	0.32	0.56	0.57
	2300	0.29	0.32	0.32	0.32	0.24	0.24	0.23	0.59	0.51
14/12	0000	0.31	0.44	0.33	0.44	0.24	0.27	0.26	0.65	0.50
	0100			0.33	0.36	0.27	0.29	0.21	0.52	0.34
	0200			0.34	0.40	0.28	0.25	0.13	0.48	0.28
	0300			0.34	0.41	0.29	0.25	0.15	0.54	0.21
	0400			0.32	0.31	0.29	0.21	0.13	0.44	0.18
	0500			0.28	0.33	0.32	0.22	0.22	0.56	0.19
	0600			0.24	0.26	0.33	0.24	0.22	0.56	0.20

Table 11 : As Table 4 but for Milford Haven.

Fishguard

date	time	a)	b)	c)	d)	e)	f)	g)	h)	observation
13/12	0000	0.09	0.10	0.07	0.07	0.07		0.05	0.16	0.35
	0100	0.11	0.10	0.09	0.08	0.08		0.09	0.17	0.26
	0200	0.13	0.12	0.13	0.12	0.12		0.09	0.12	0.23
	0300	0.14	0.15	0.17	0.16	0.15		0.06	0.11	0.20
	0400	0.17	0.16	0.17	0.18	0.15		0.23	0.15	0.24
	0500	0.18	0.18	0.24	0.22	0.22		0.23	0.21	0.28
	0600	0.17	0.18	0.24	0.26	0.22		0.29	0.25	0.37
	0700	0.17	0.16	0.31	0.25	0.34		0.28	0.27	0.44
	0800	0.16	0.17	0.30	0.27	0.37		0.28	0.25	0.47
	0900	0.20	0.18	0.32	0.28	0.42		0.36	0.24	0.56
	1000	0.21	0.20	0.37	0.34	0.41		0.42	0.29	0.60
	1100	0.21	0.22	0.42	0.37	0.35		0.47	0.16	0.77
	1200	0.24	0.23	0.47	0.41	0.50	0.50	0.44	0.26	0.85
	1300	0.24	0.24	0.51	0.45	0.53	0.48	0.78	0.37	0.83
	1400	0.25	0.23	0.51	0.42	0.46	0.38	0.79	0.45	
	1500	0.26	0.26	0.48	0.41	0.51	0.48	0.81	0.40	
	1600	0.27	0.27	0.39	0.33	0.49	0.47	0.70	0.36	
	1700	0.27	0.26	0.33	0.28	0.50	0.49	0.87	0.56	
	1800	0.28	0.29	0.30	0.28	0.40	0.38	1.01	0.67	
	1900	0.28	0.28	0.29	0.26	0.46	0.46	0.46	0.54	
	2000	0.28	0.28	0.26	0.27	0.42	0.41	0.59	0.61	
	2100*	0.27	0.28	0.30	0.28	0.31	0.25	0.40	0.68	(0.74)
	2200	0.29	0.28	0.30	0.26	0.35	0.30	0.41	0.60	
	2300	0.31	0.31	0.28	0.27	0.26	0.20	0.31	0.53	
14/12	0000	0.36	0.39	0.31	0.29	0.26	0.20	0.07	0.36	
	0100			0.29	0.27	0.27	0.36	0.27	0.42	
	0200			0.28	0.27	0.27	0.28	0.15	0.44	
	0300			0.31	0.30	0.26	0.25	0.02	0.46	
	0400			0.31	0.31	0.30	0.30	0.07	0.51	
	0500			0.32	0.30	0.31	0.21	0.07	0.48	
	0600			0.27	0.28	0.31	0.23	0.28	0.54	

Table 12 : As Table 4 but for Fishguard.

Time G.M.T. on 13th December	Local Sea (m)	Combined Sea and Swell (m)
1800	0	0.5
1900	0.2	0.5
2000	0.7	0.8
2100	1.8	1.9
2200	2.3	2.3*
2300	2.7	2.7*
2400	3.0	3.0*

Table 13 : Estimated significant wave height for wave conditions off Weston-Super-Mare on 13th December 1981.

* if near to high tide.

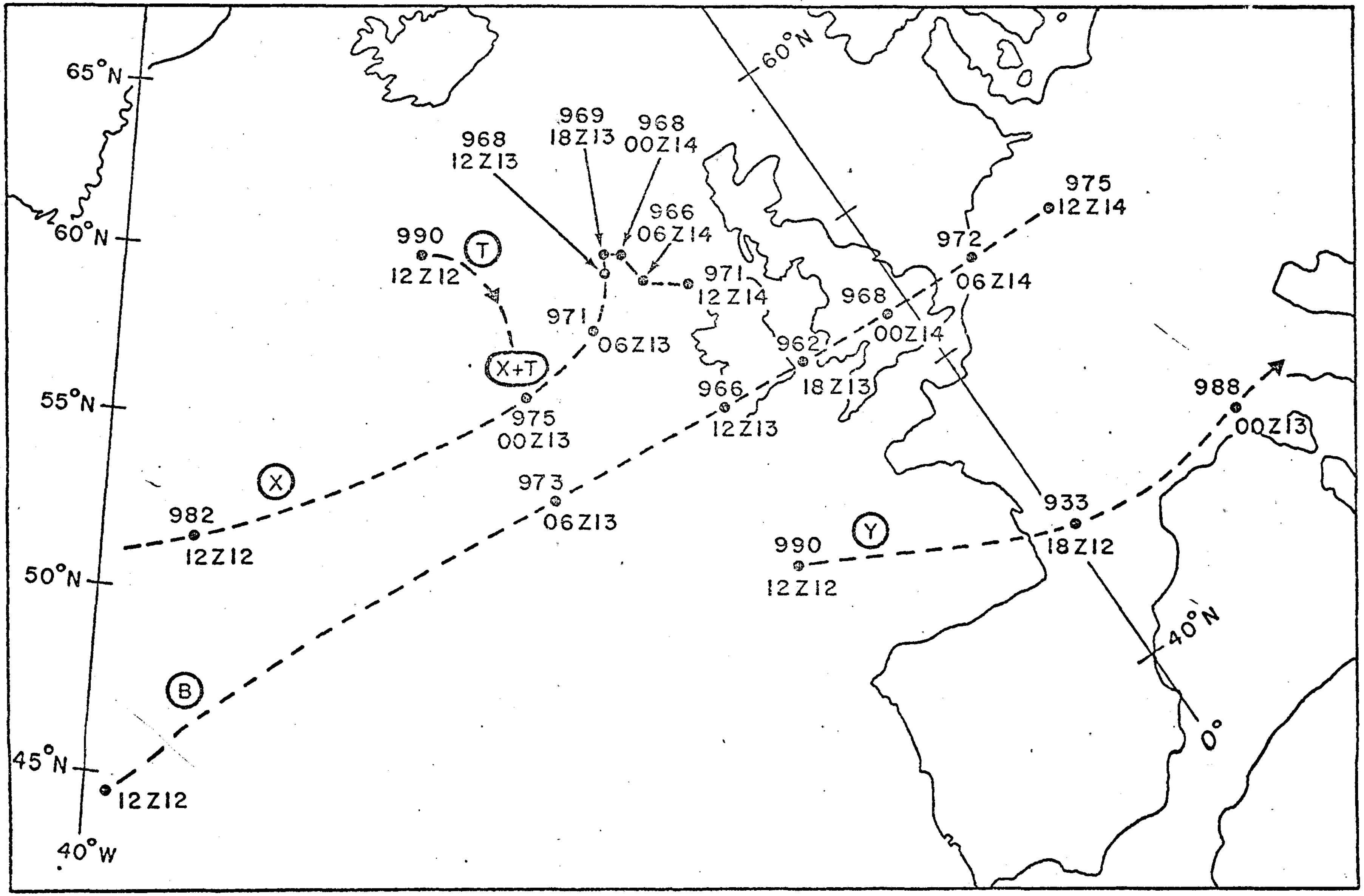


Figure 1 : Depression tracks during the period 1200GMT on 12th December (written 12Z12) to 1200GMT on 14th December (12Z14). Central pressures are given in millibars.

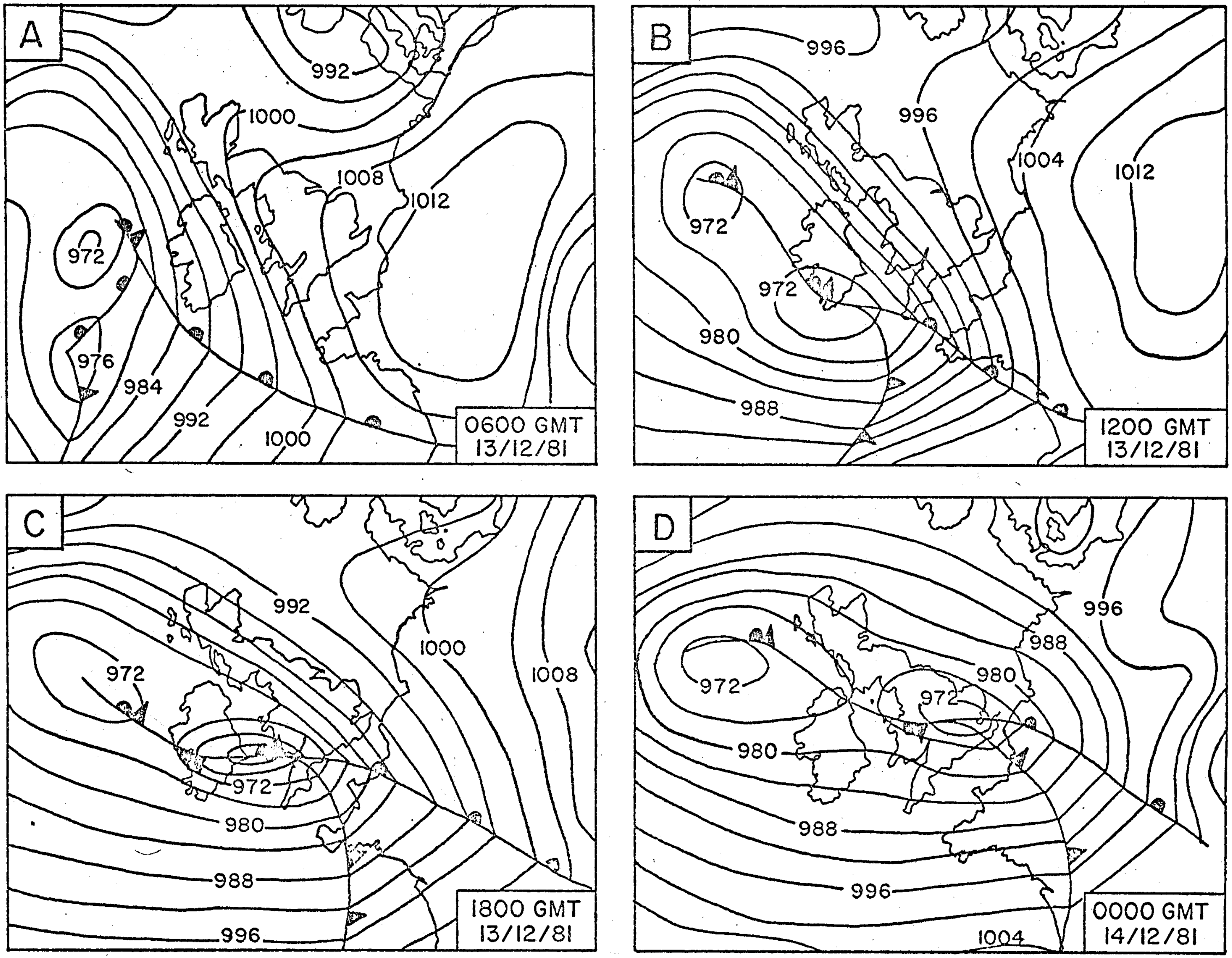


Figure 2 : Weather charts for 13th December 1981.

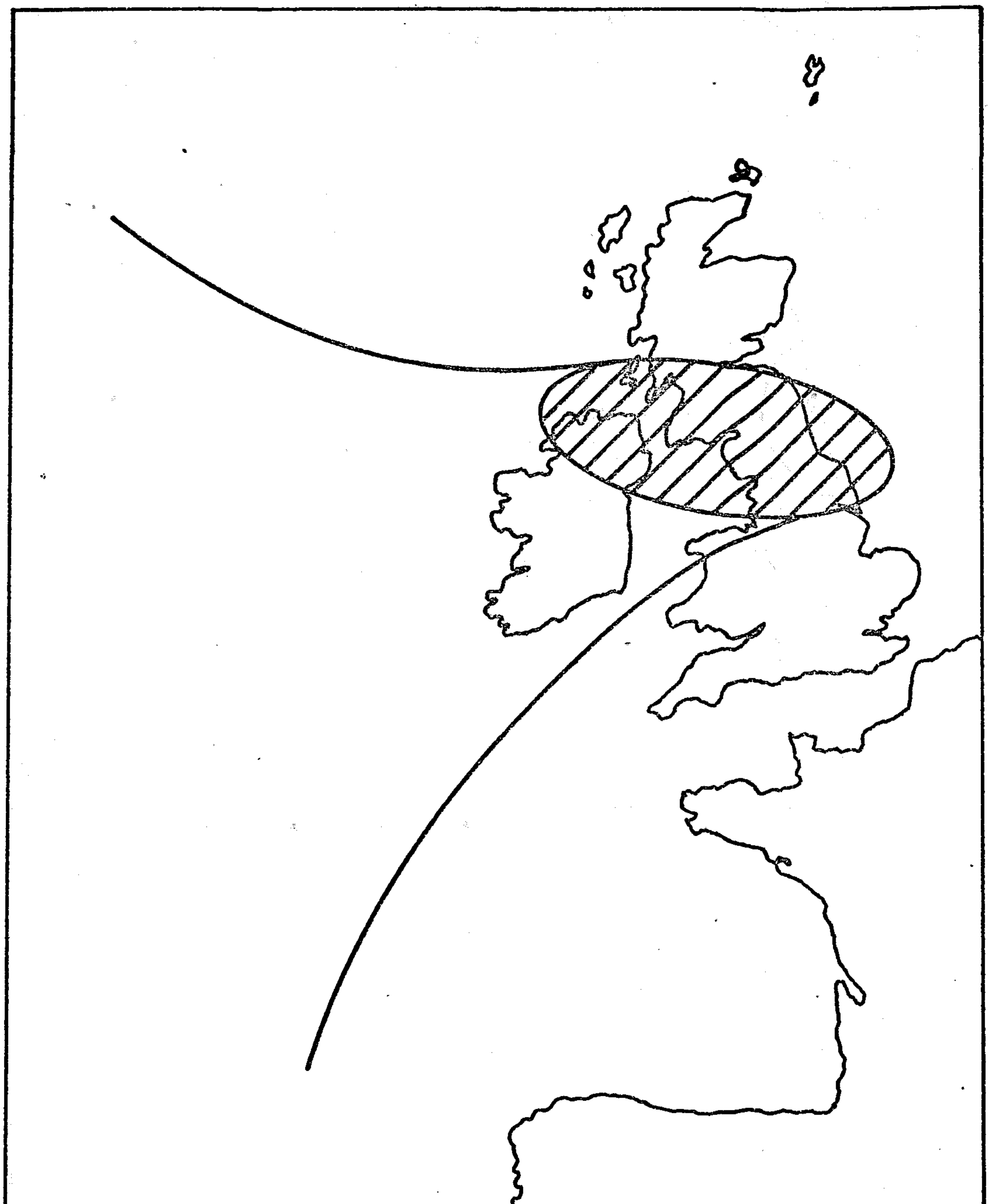


Figure 3 : Synthesis of depression tracks associated with large surges at Avonmouth. The hatched area contains the location of the centre of the depressions at the time of the peak surge. (Re-drawn from LENNON 1963)

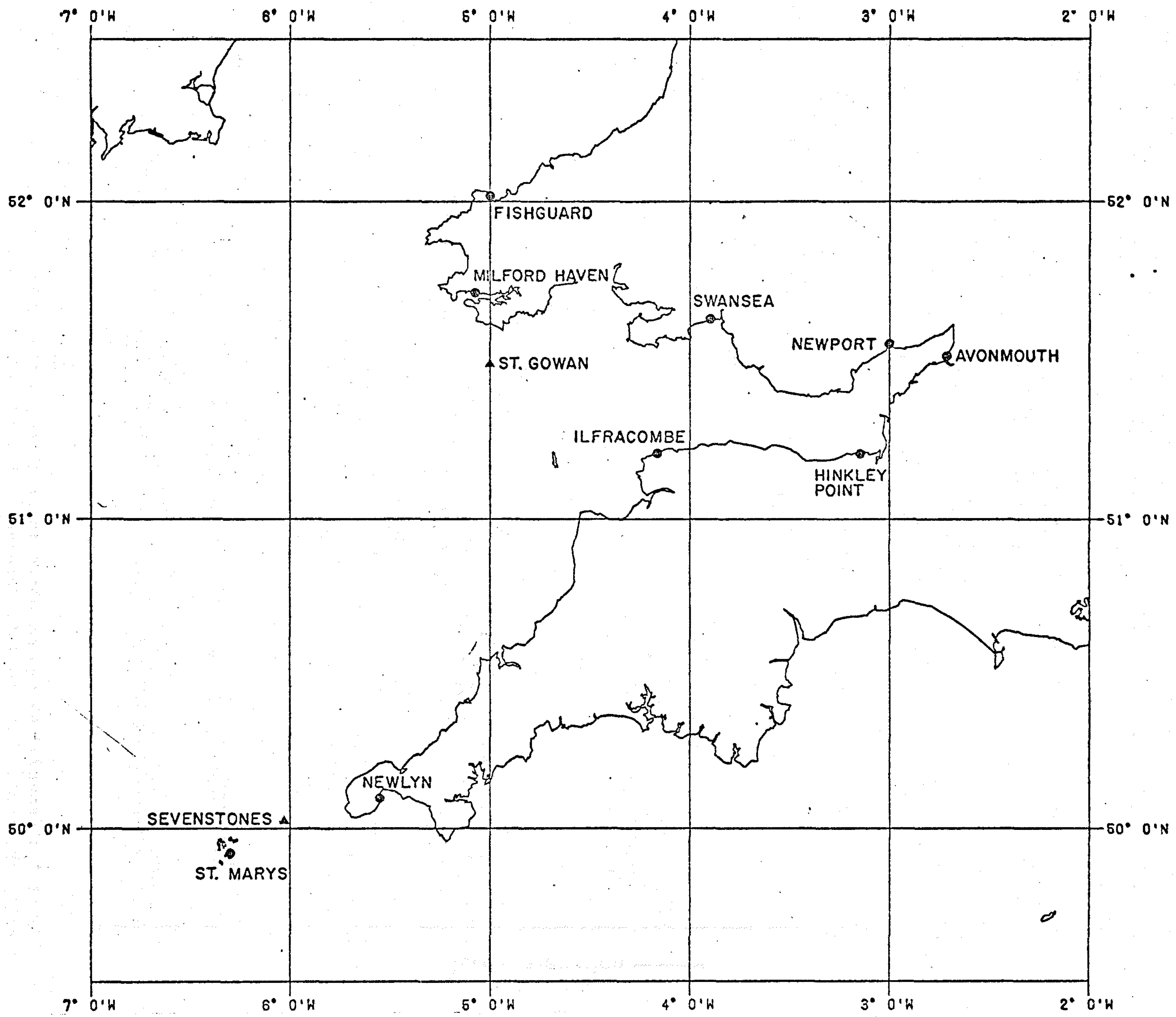


Figure 4 : Locations of tide gauges (⊛) and light vessels operating wave recorders (▲) referred to in the text.

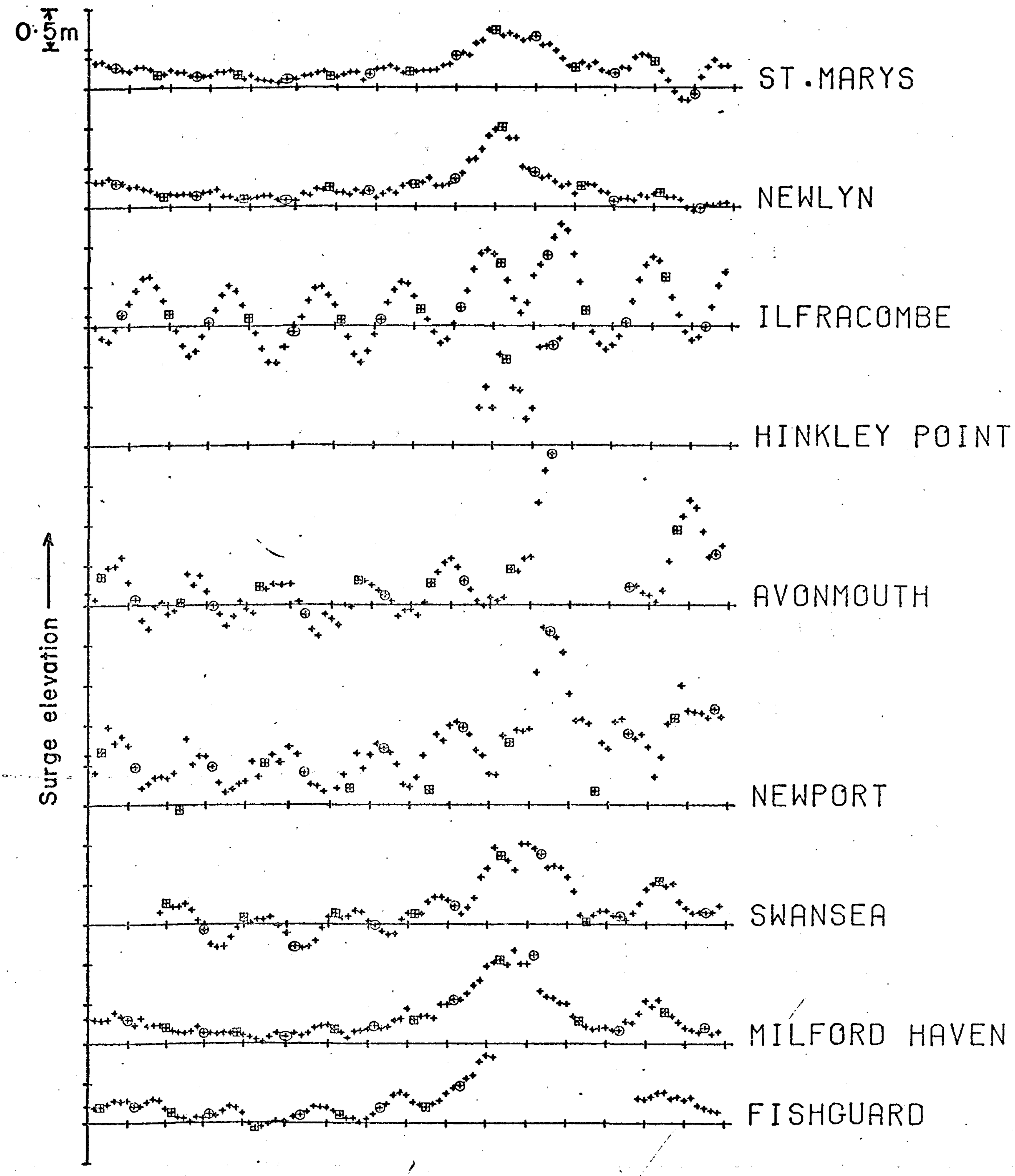


Figure 5 : Observed surges at ports in or close to the Bristol Channel during the period 11th to 14th December 1981. Residuals closest to times of high and low water are indicated by ⊕ and ⊞ , respectively.

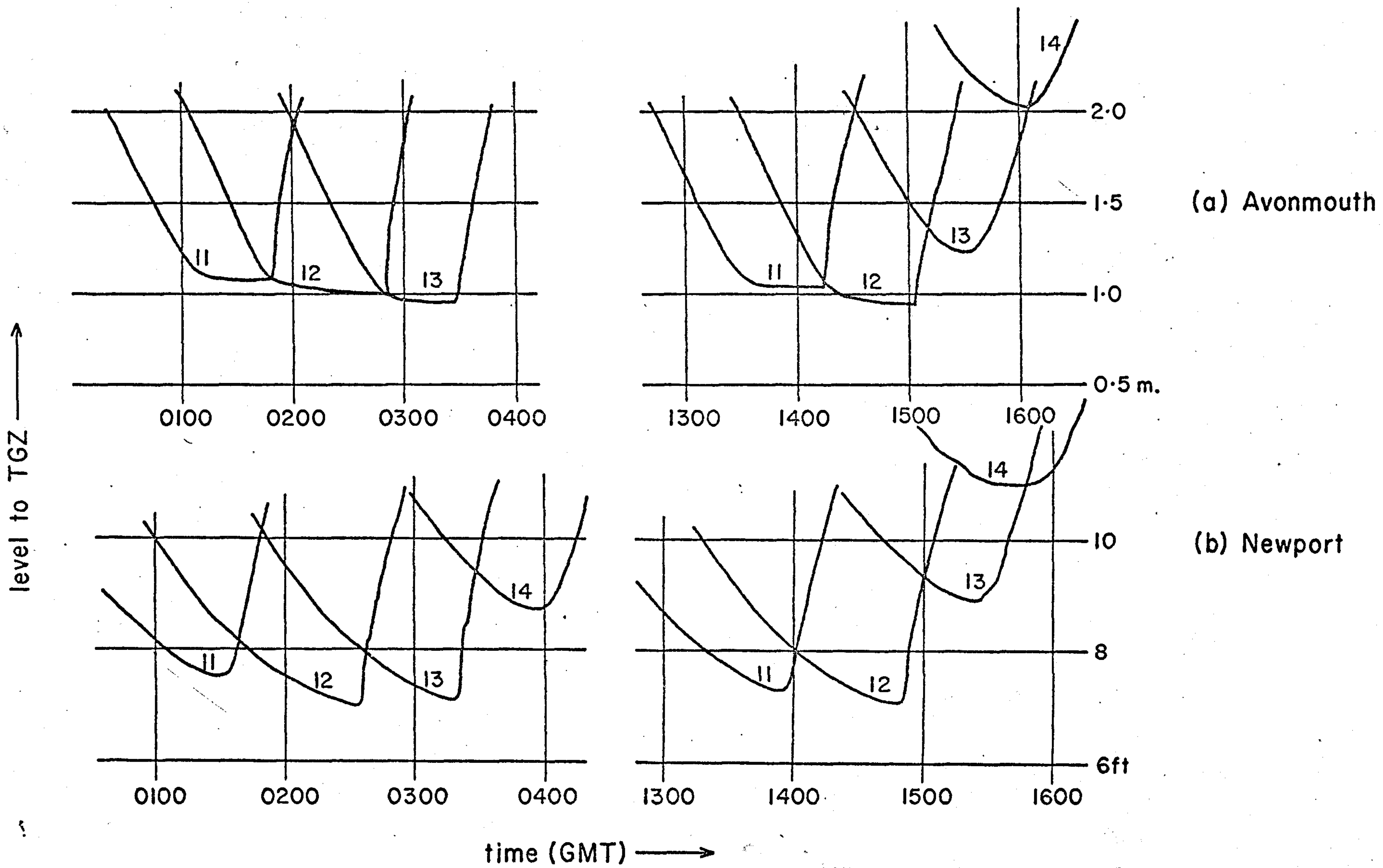


Figure 6 : Low waters recorded at Avonmouth and Newport on 11th - 14th December 1981.

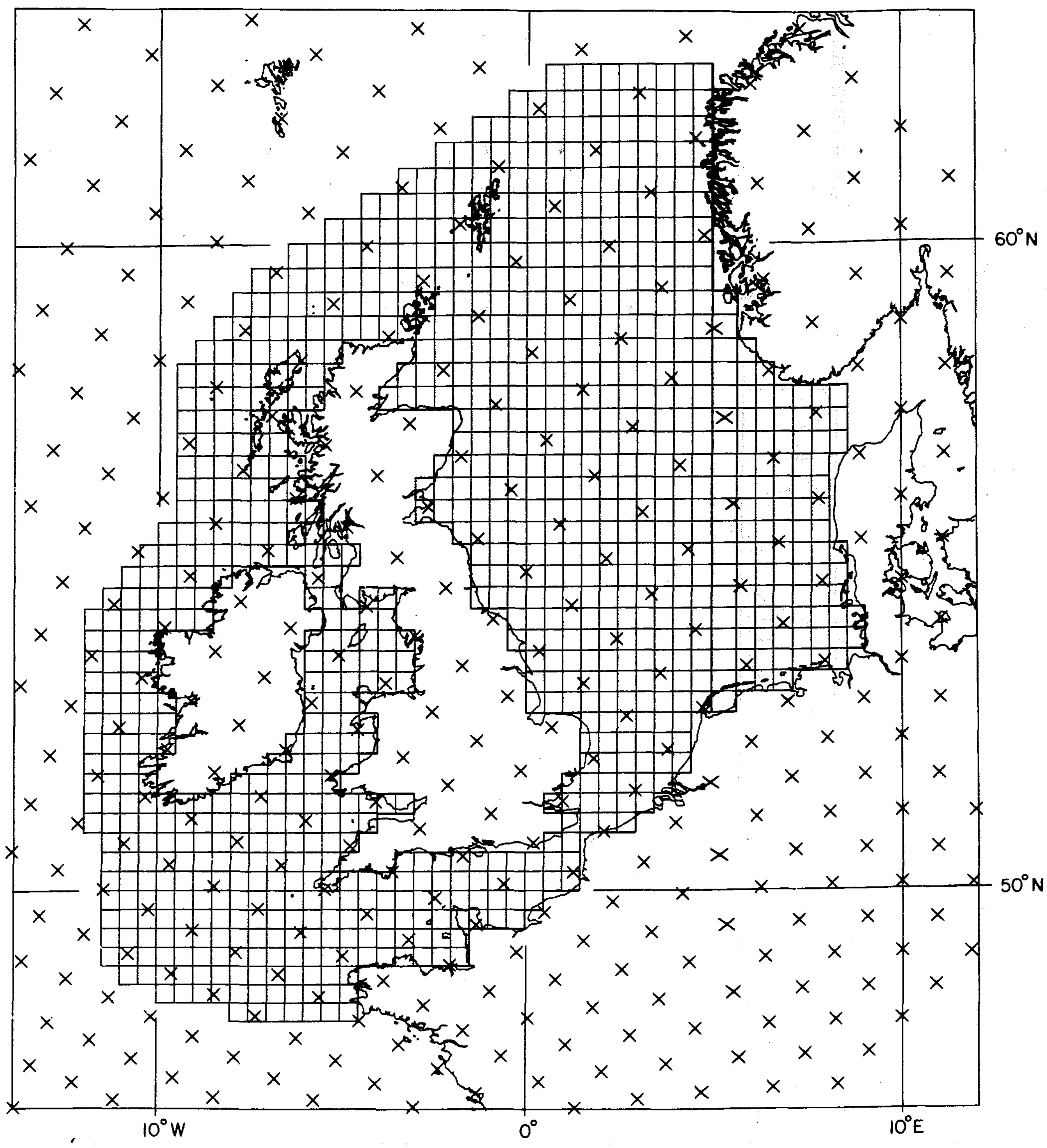


Figure 7 : Continental shelf sea model (CSM) used as the basis for surge forecasts with grid points (X) of the Meteorological Office's 10-level weather prediction model which supplies the required forecast winds and atmospheric pressures.

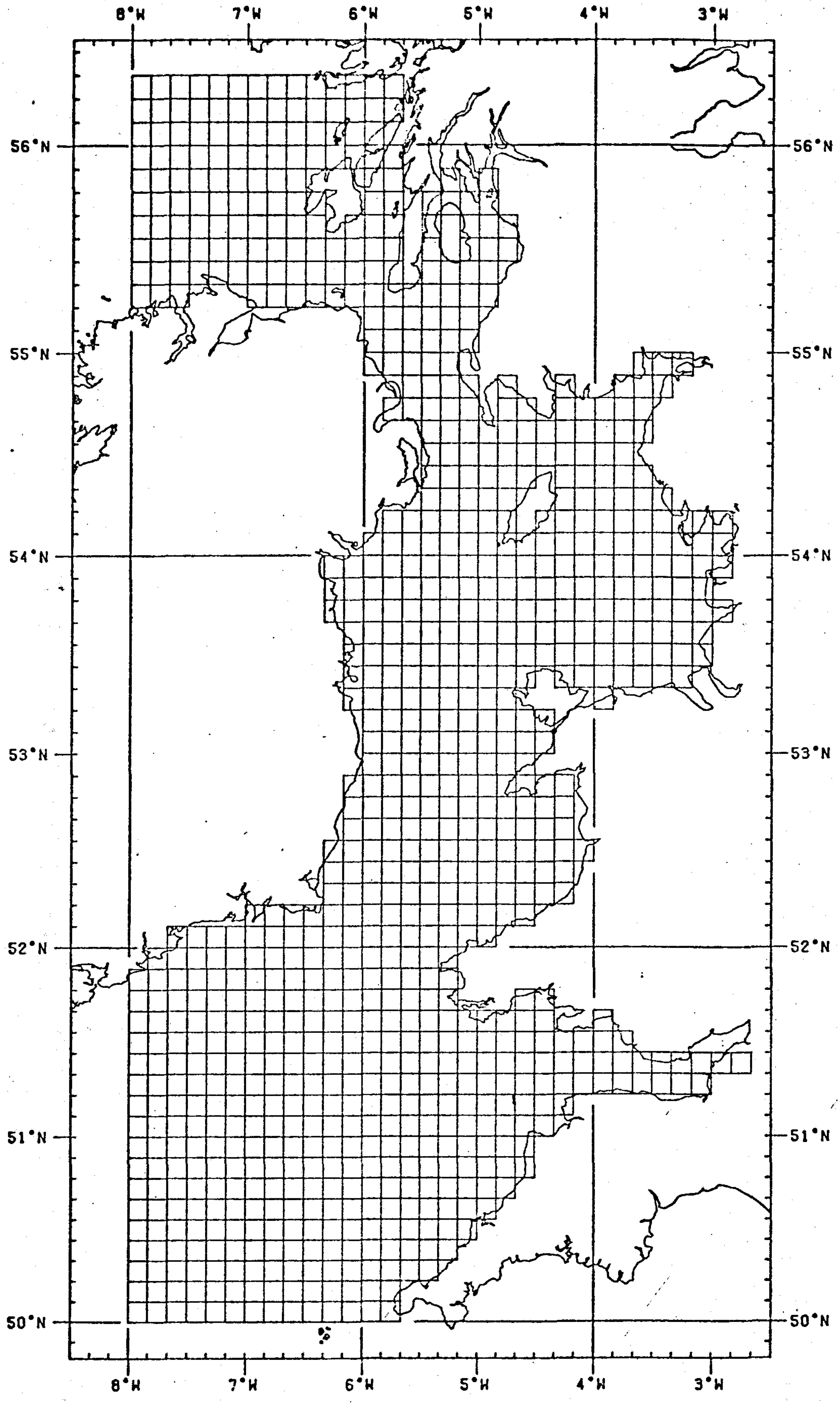


Figure 8 : The experimental West Coast Sea Model (WCM) under operational testing during the period December 1981 to March 1982.

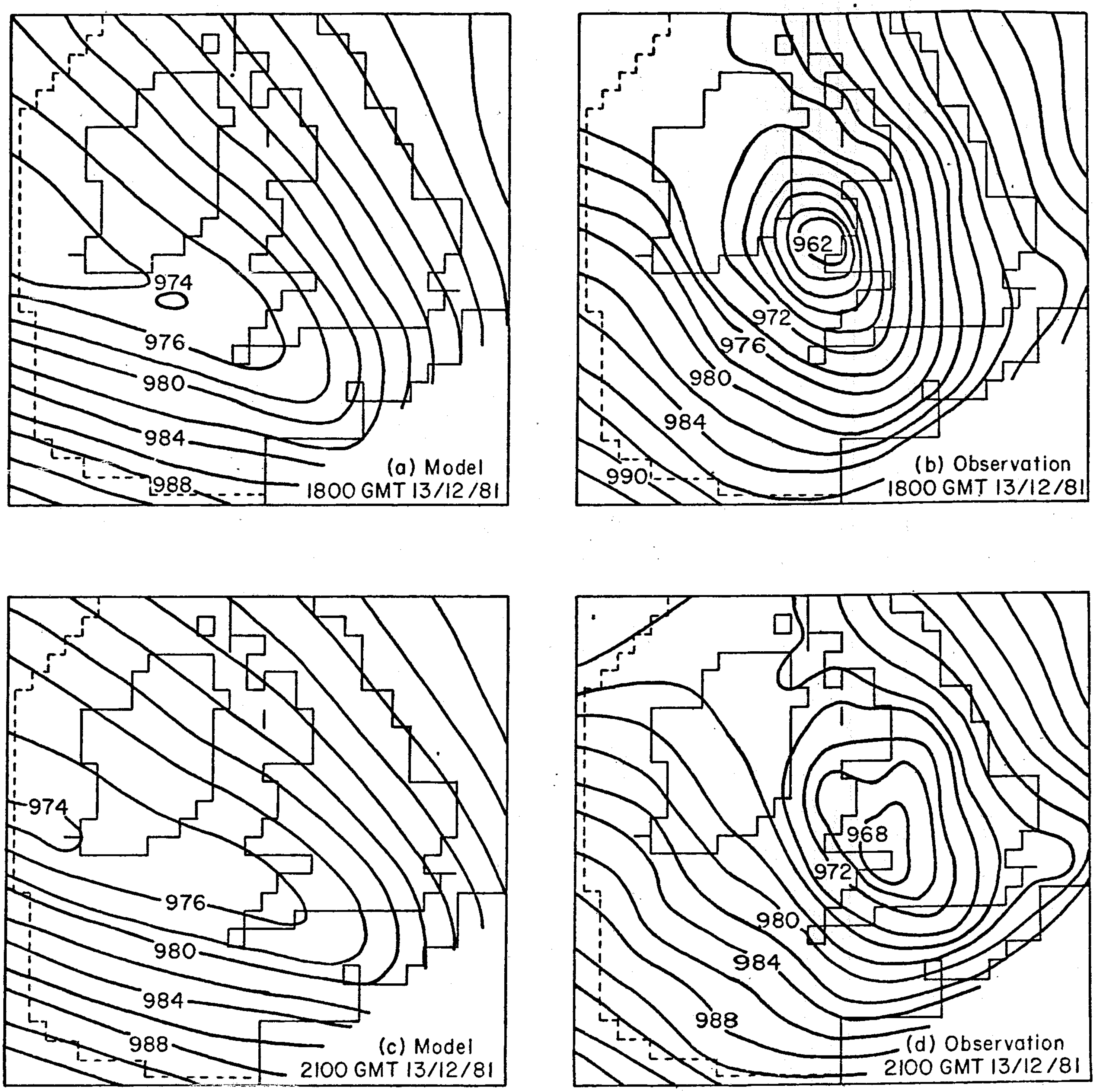


Figure 9 : Distributions of surface atmospheric pressure at 1800GMT and 2100GMT 13th December based on the atmospheric model forecast starting at 0000GMT on 13th (a) and c)) and on observations (b) and d)).

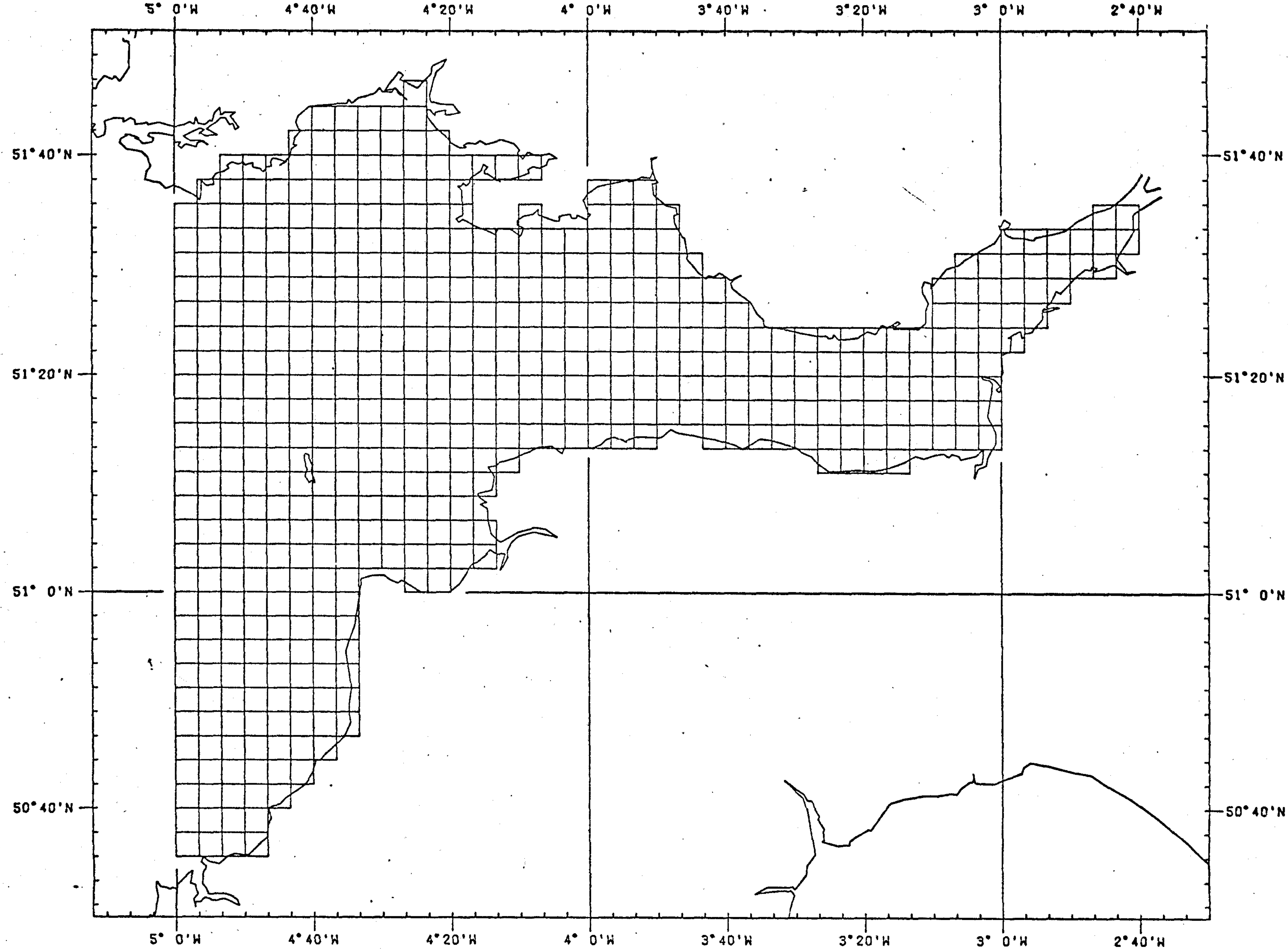


Figure 10 : Bristol Channel model (BCM)

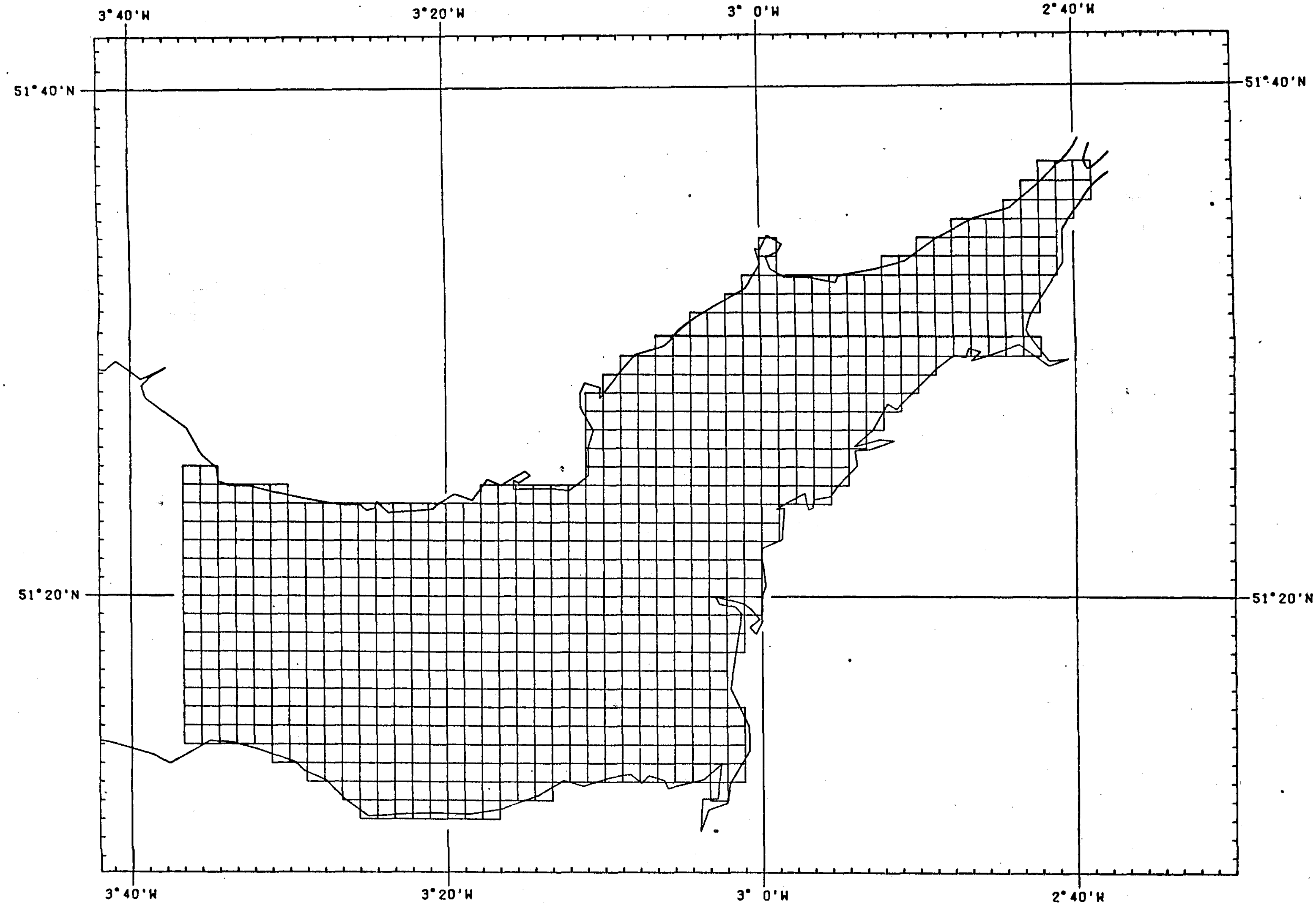


Figure 11 : Severn Estuary model (SEM)

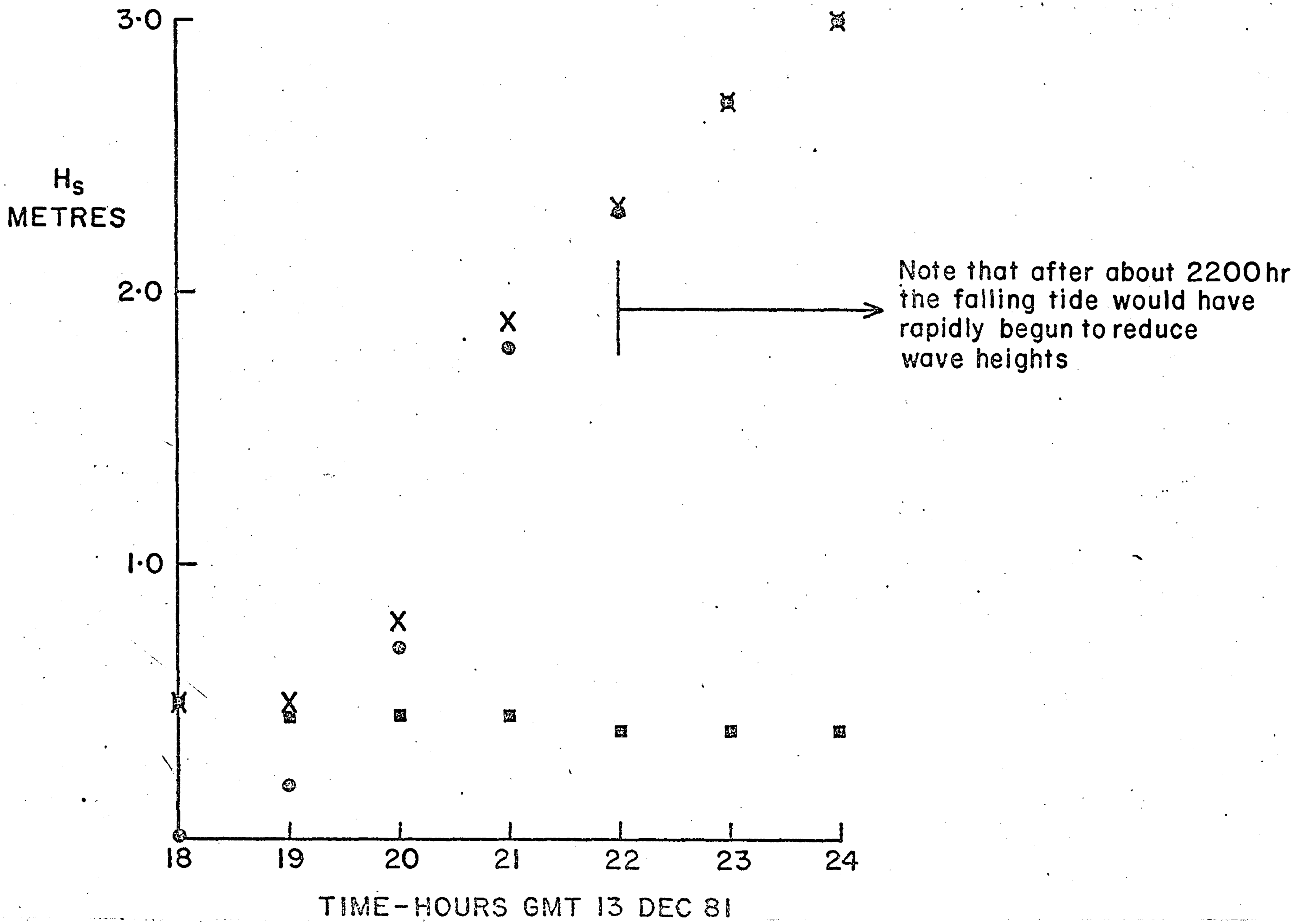
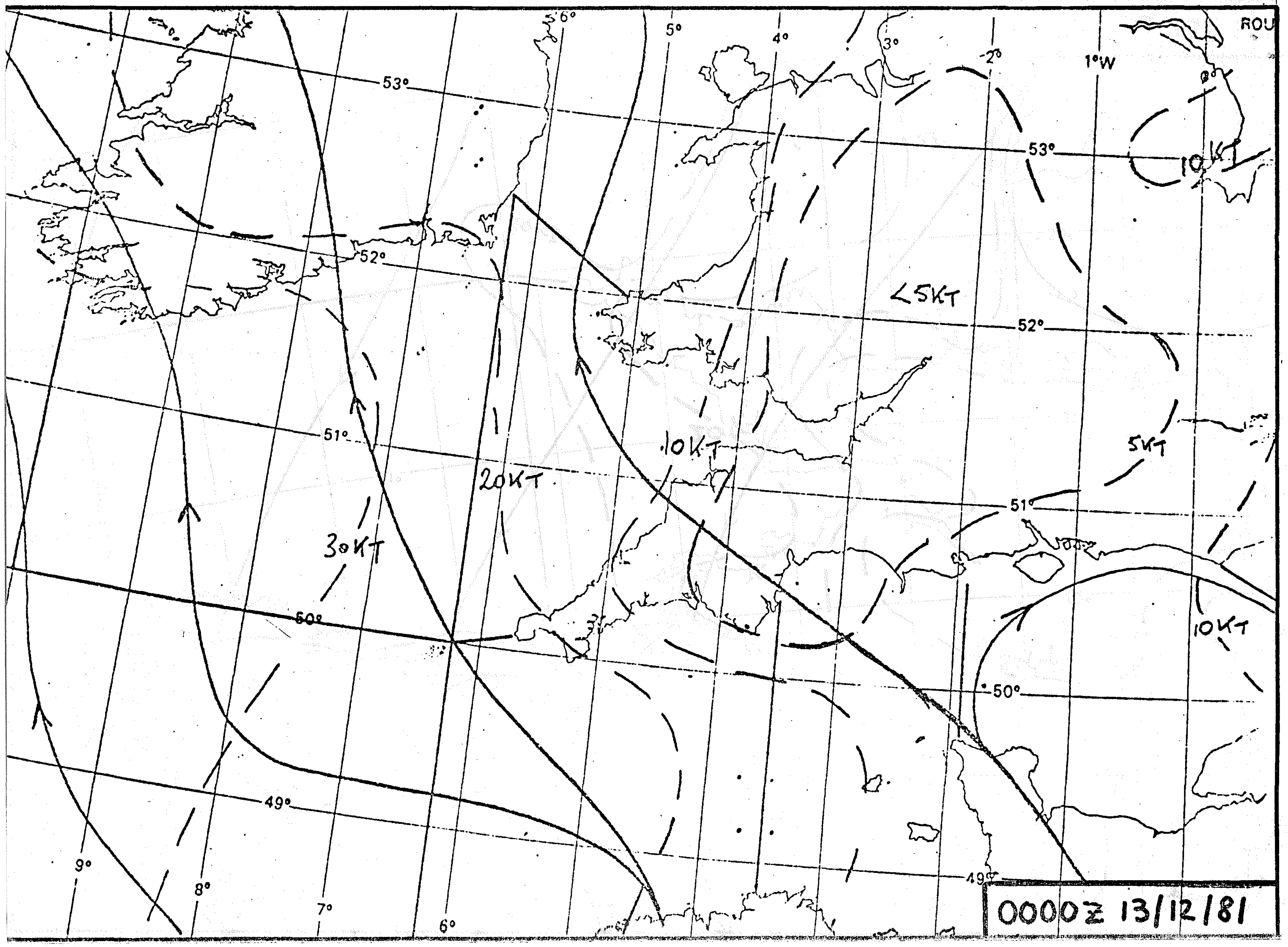


Figure 12 : Estimated wave conditions in the upper Bristol Channel on 13th December 1981.

swell; pure locally-generated waves; combined height

APPENDIX

Wind analyses prepared by the Marine Climatology Branch (Met. O.3c) of the Meteorological Office at the request of I.O.S.. Broken lines are contours of wind speed (knots), solid lines indicate wind directions.



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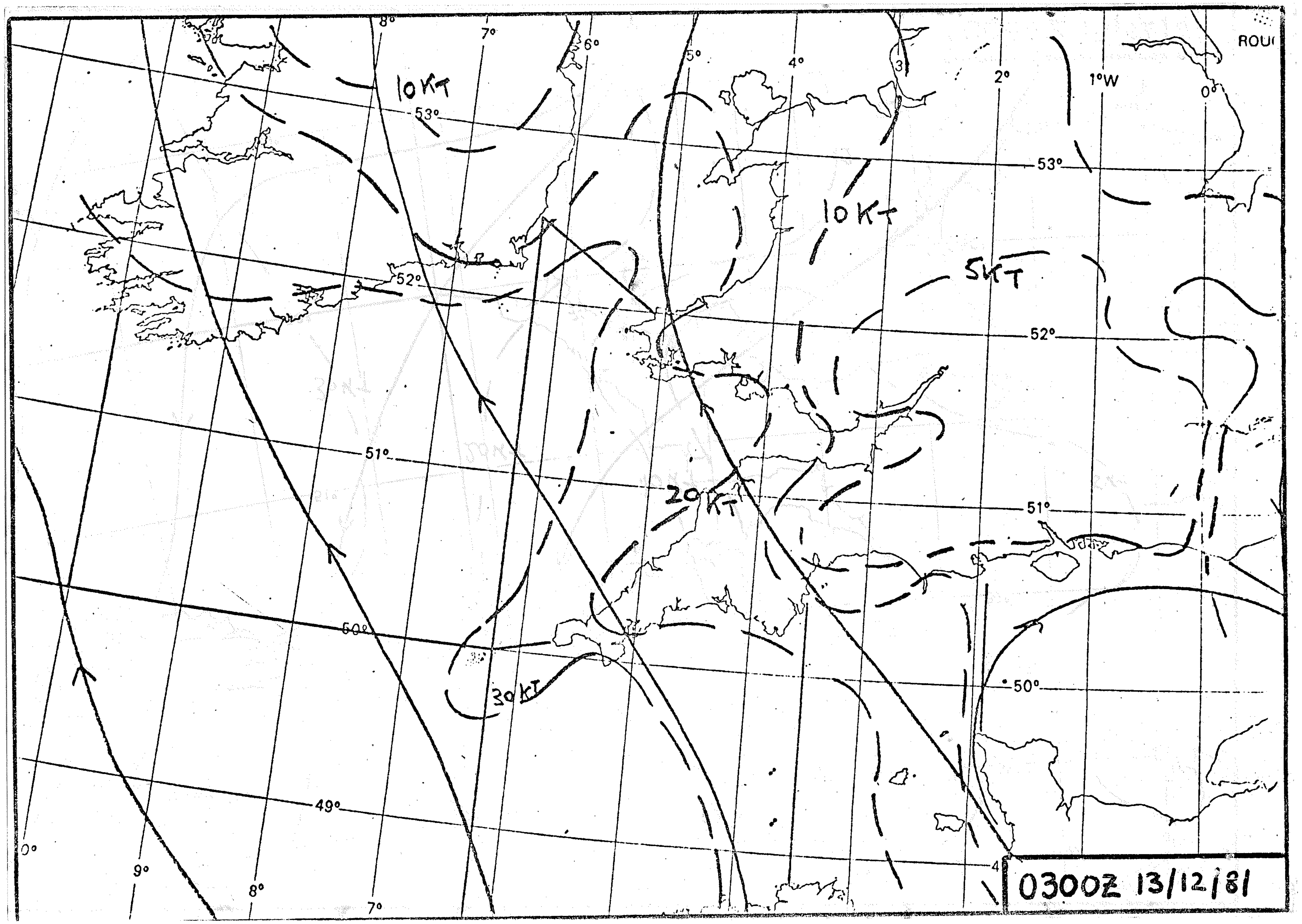
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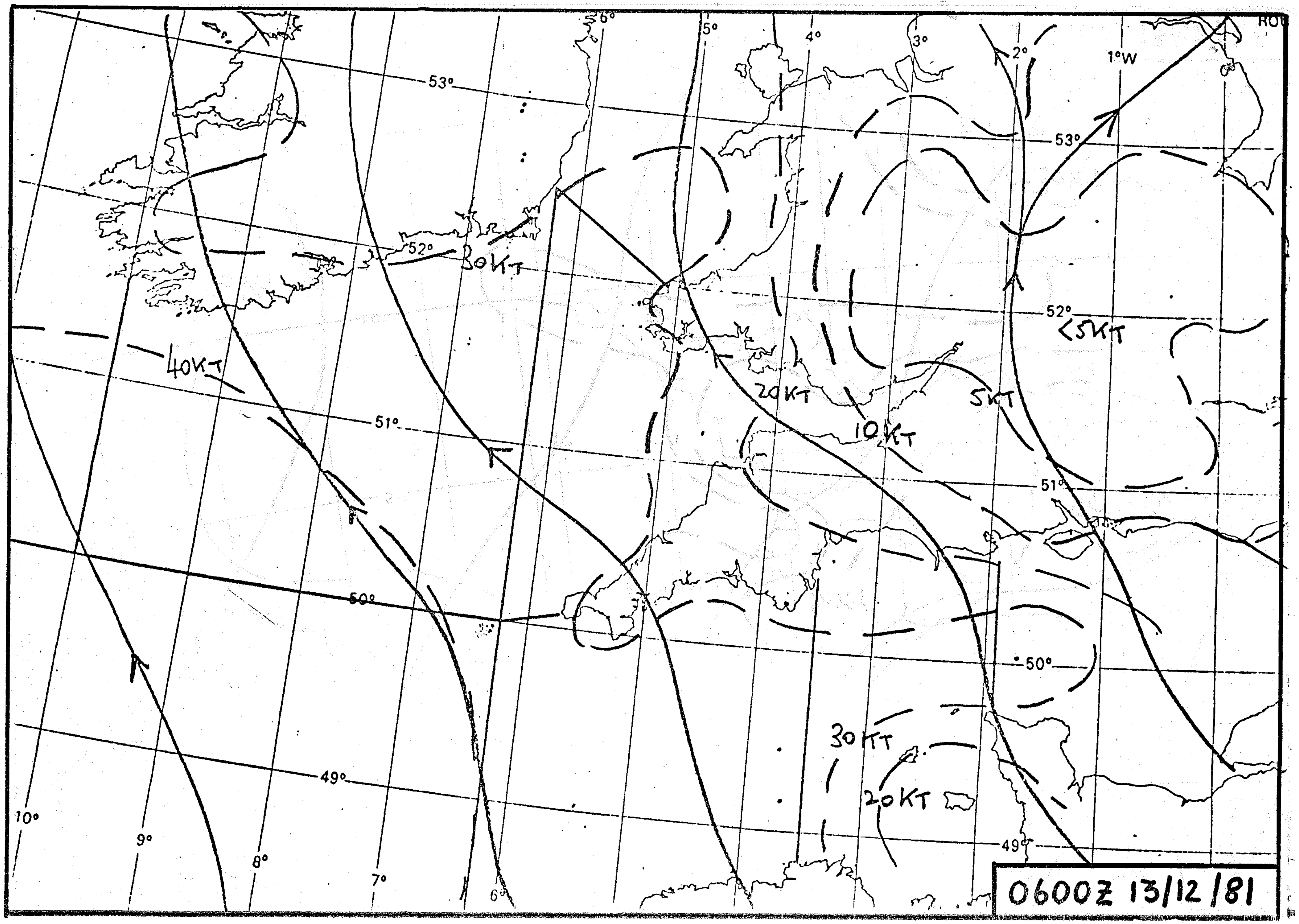

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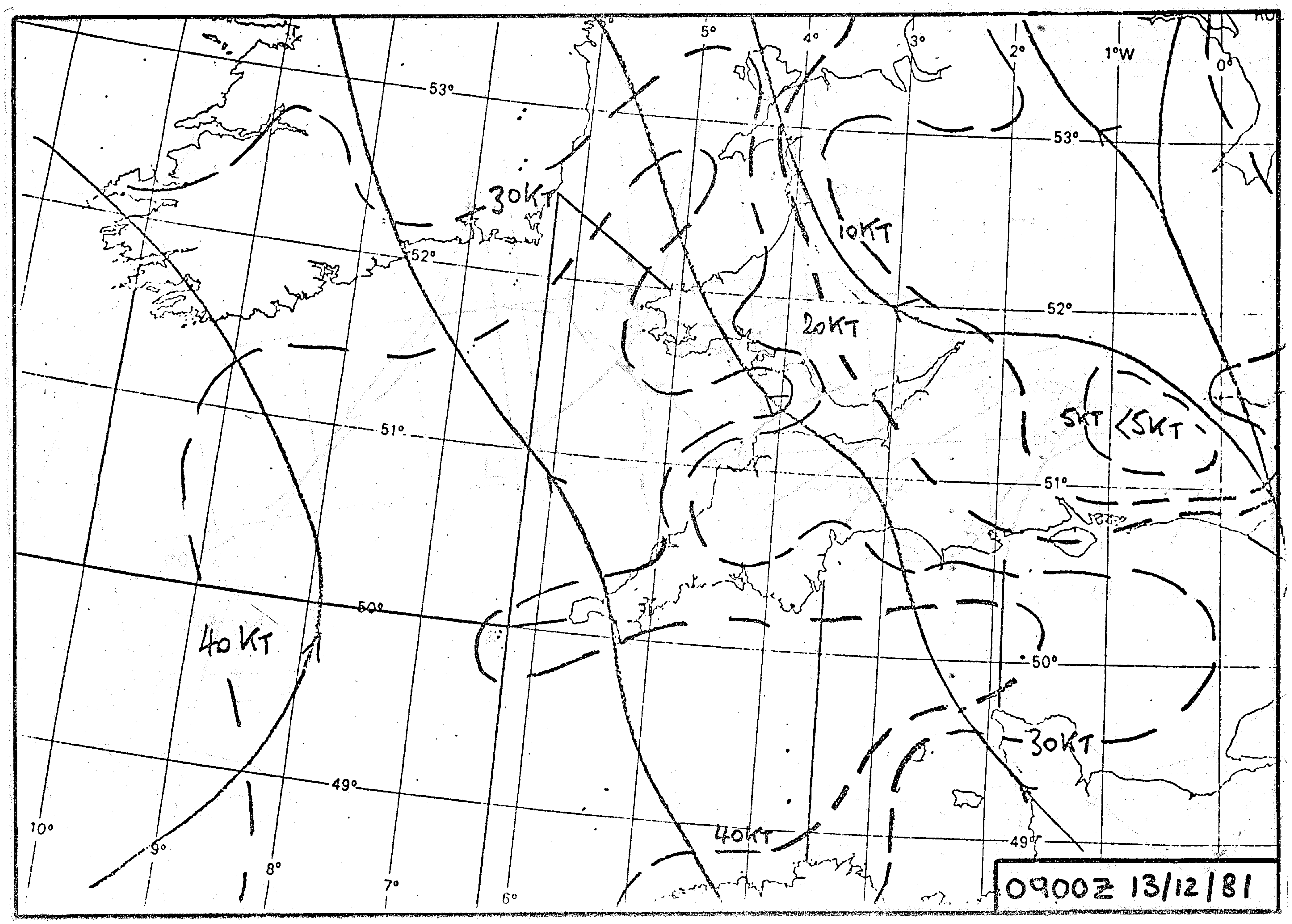

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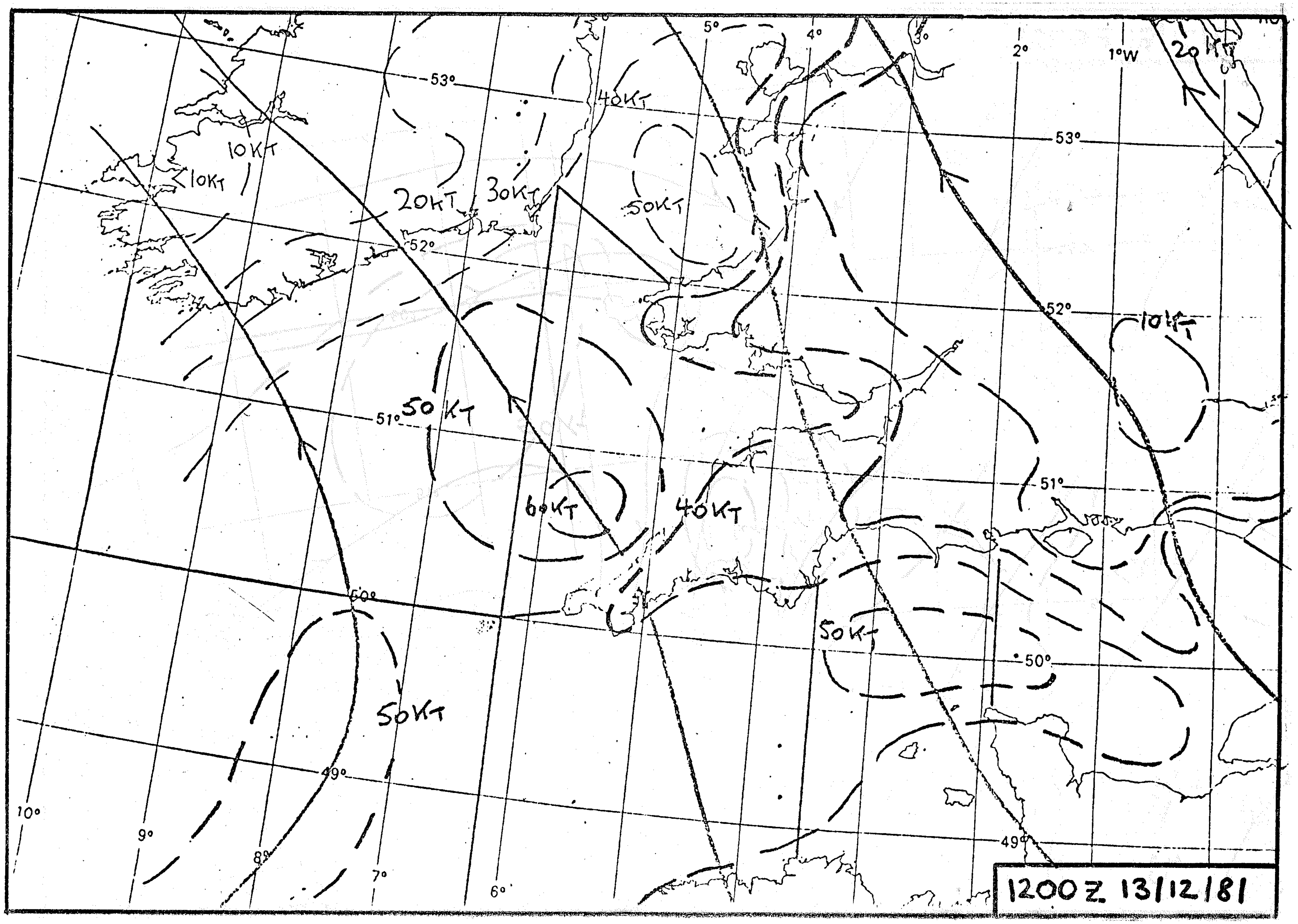
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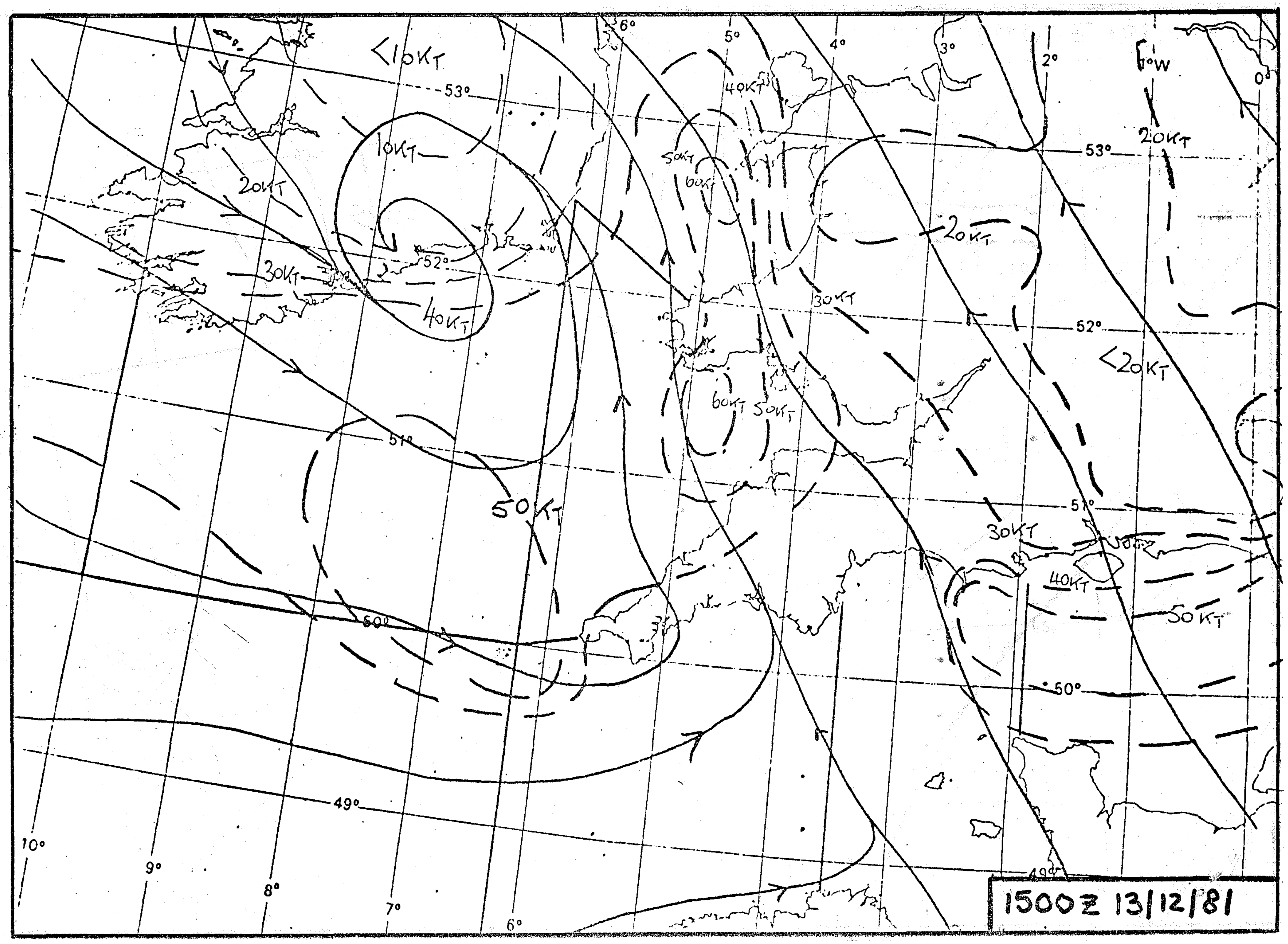

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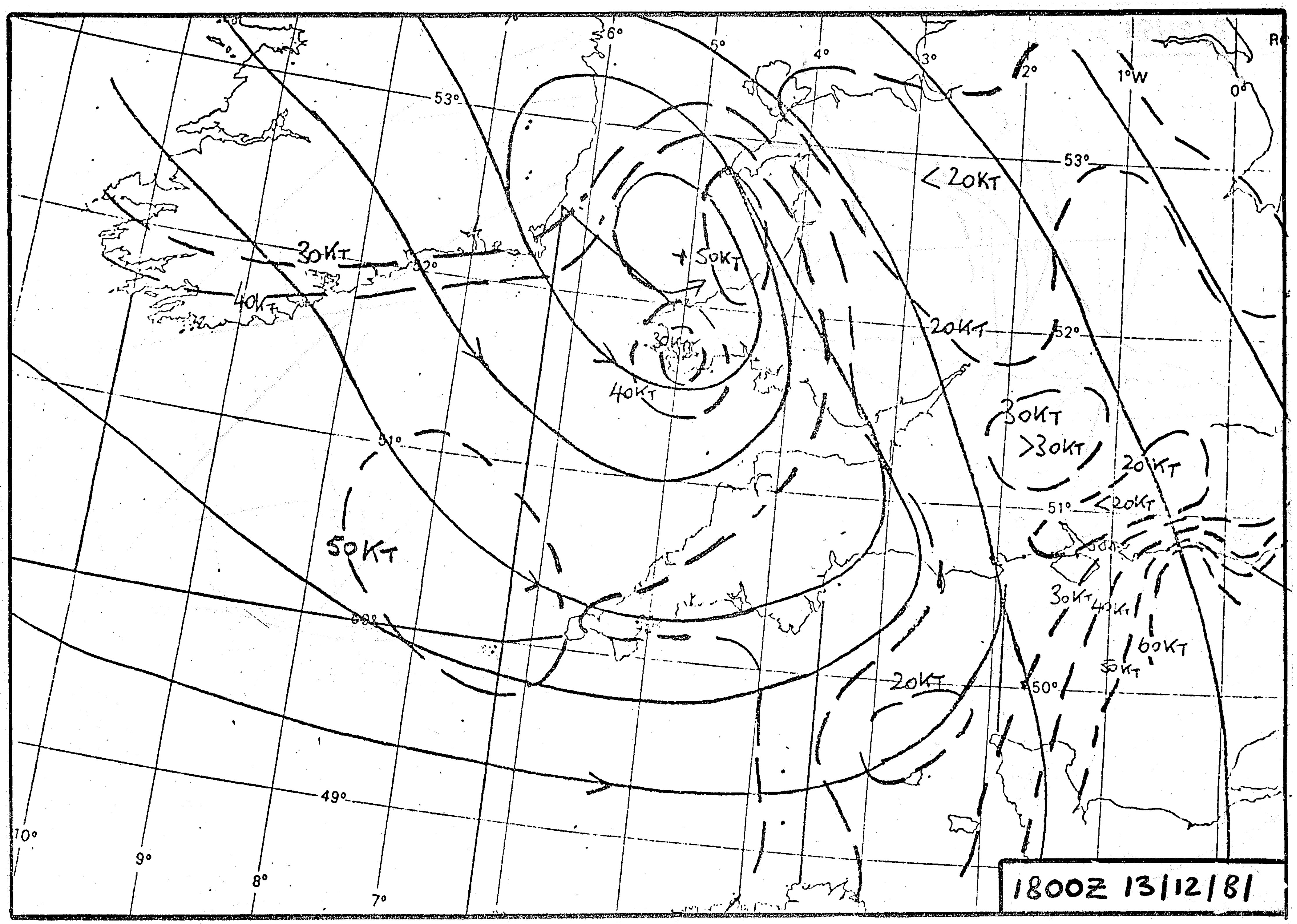

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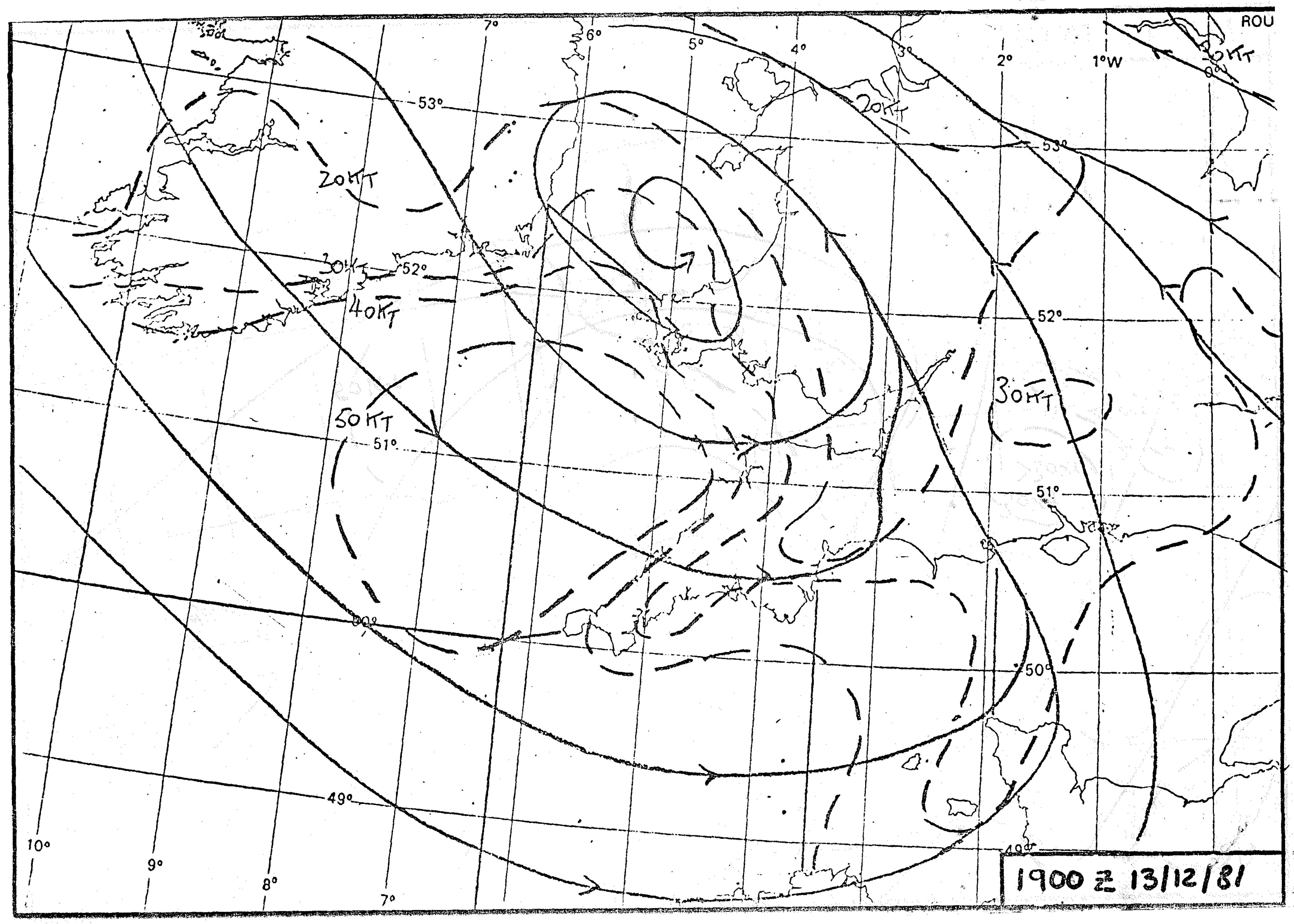
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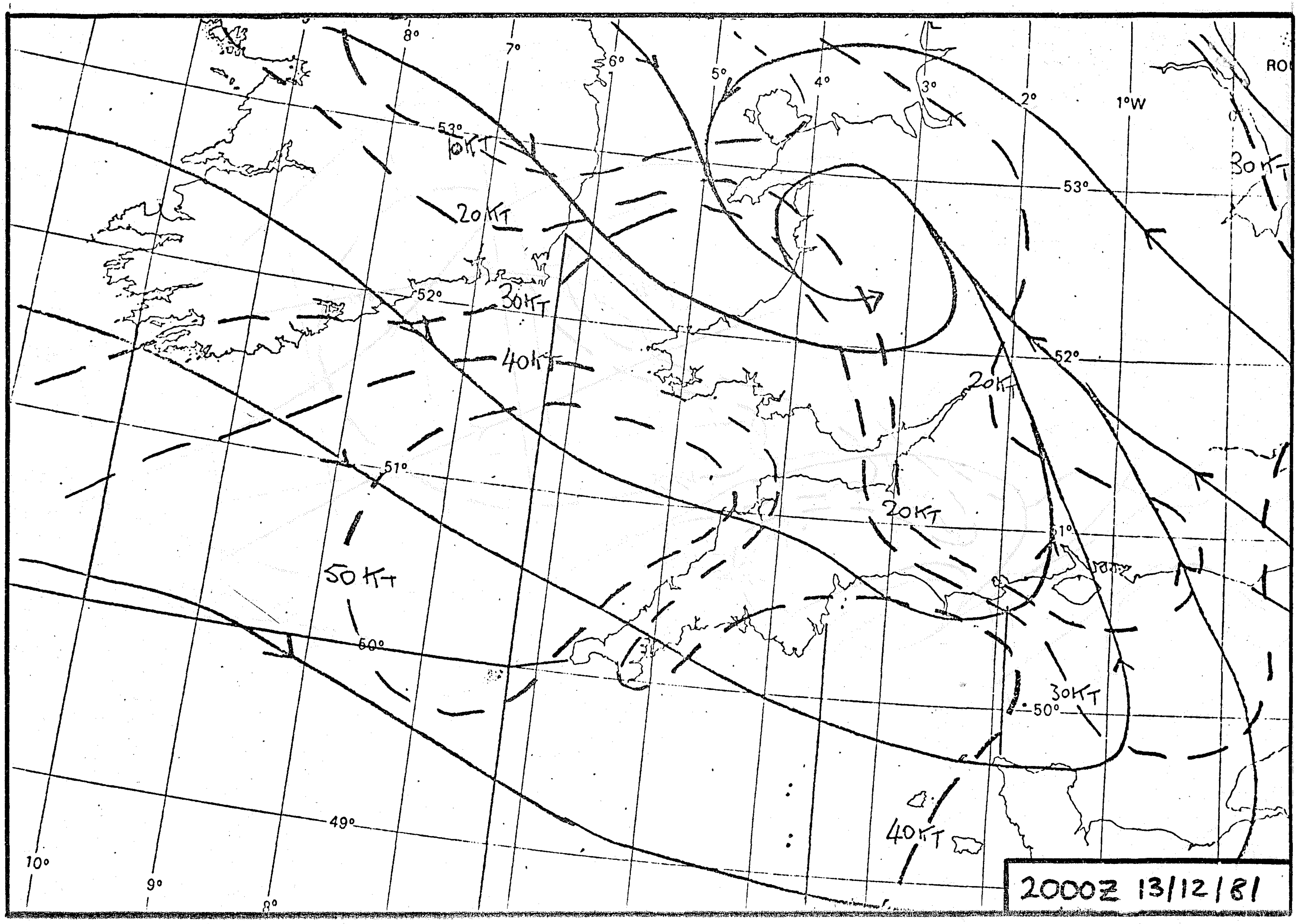

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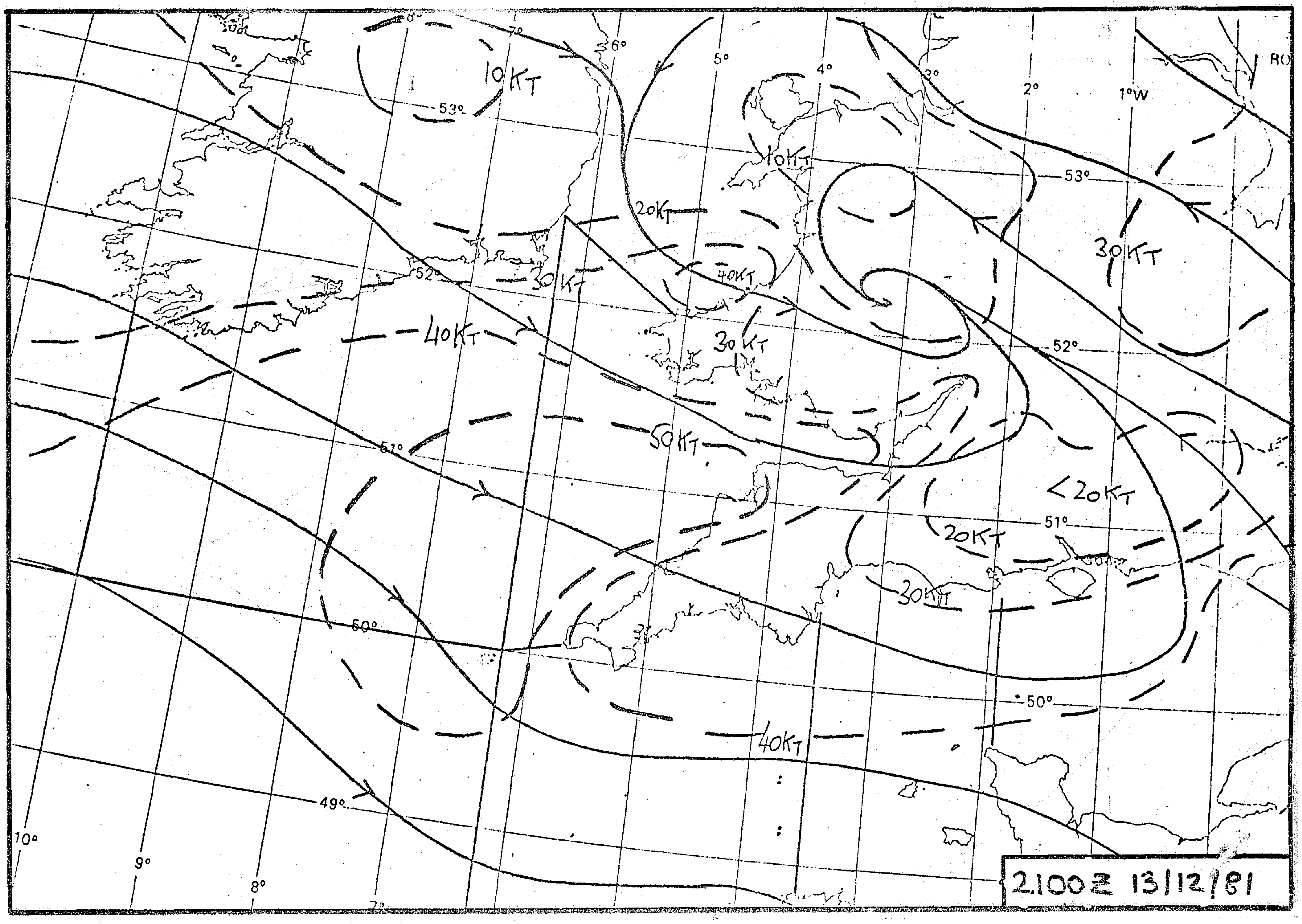
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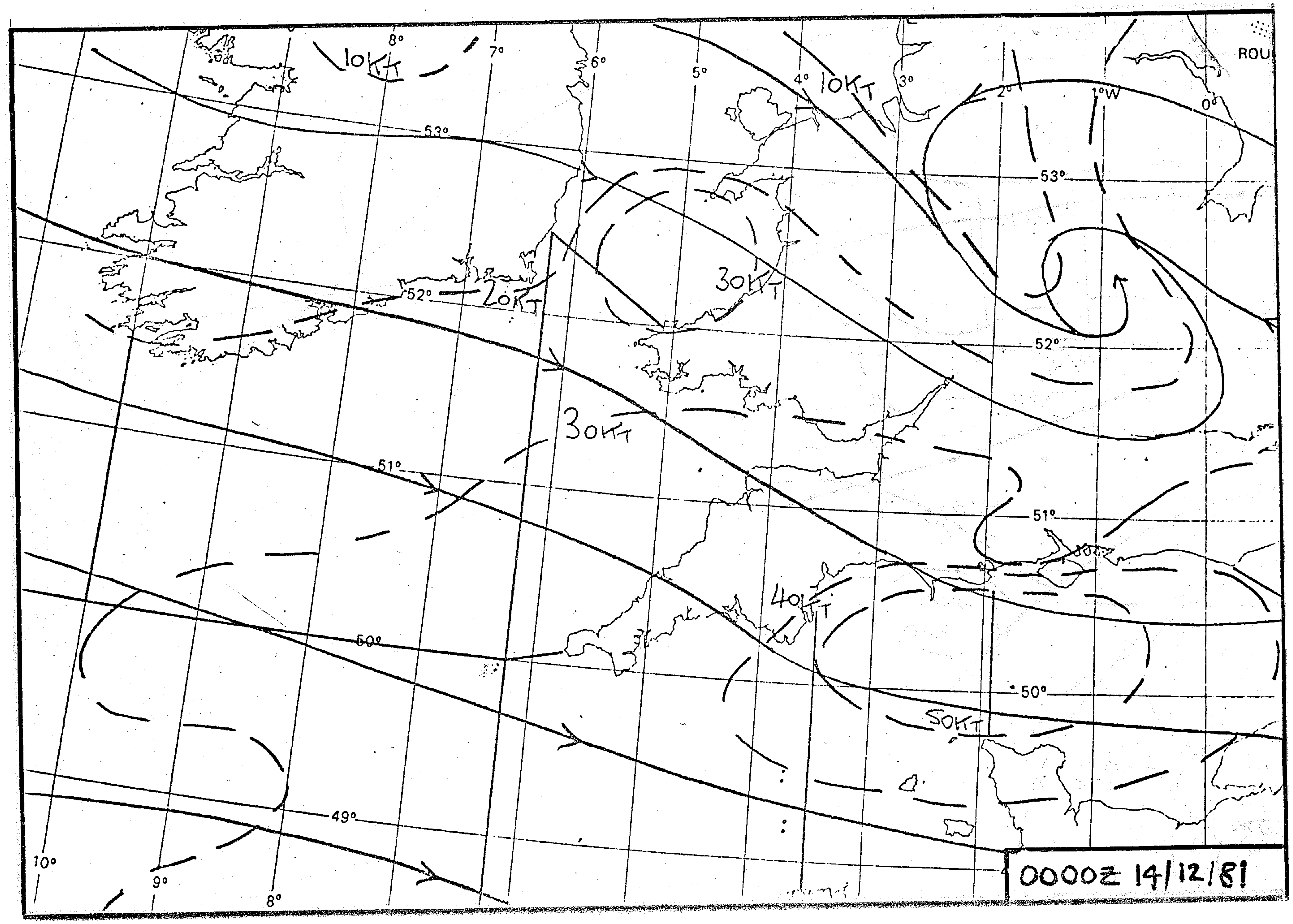
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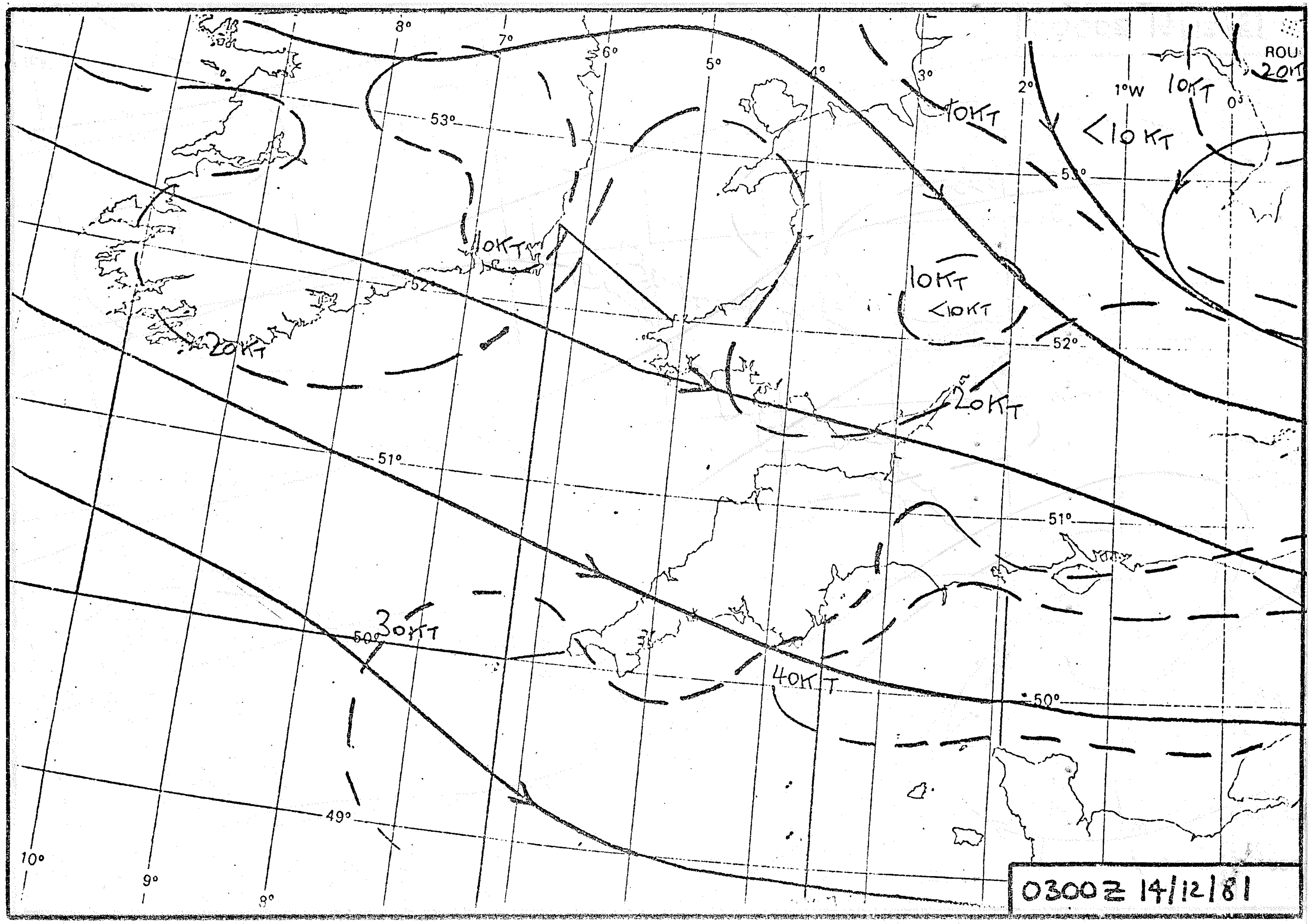
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