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Assessment of Wave Hindcast Methodologies in the Scotian Shelf, Grand Banks and Labrador Sea Areas

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by

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ABSTRACT

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Hindcast by the U.S. Army Engineer Waterways Experiment Station (WES) are reviewed, and recommendations for their use in Canadian portions of the Atlantic Ocean are made. Six storms typical of problems in those hindcasts are selected, and complete hindcast analyses are performed for each. Since the wind model and wave model used in these new hindcasts are identical to the WES models, conclusions regarding error sources can be formed from comparisons of the two sets of hindcasts. Sources of error detected here and methods of obtaining reliable hindcast wave heights are discussed.

RÉSUMÉ

Resio, Donald T. 1982. Assessment of wave hindcast methodologies in the Scotia Shelf, Grand Banks and Labrador Sea areas. Can. Contract. Rep. Hydrogr. Ocean. Sci. 4:128 p.

Ce rapport donne un compte rendu des prévisions à posteriori faites par le U.S. Army Engineer Waterways Experiment Station (WES) et formule des recommendations au sujet de leur utilsation dans les eaux canadiennes de l'océan Atlantique. On présente l'analyse complète des prévisions à posteriori faites pour six tempêtes, constituant des exemples typique des problèmes rencontrés dans les prévisions à posteriori. On peut tirer des conclusions au sujet des sources d'erreur en comparant les deux séries de prévisions à posteriori, parce que les modèles du vent et des vagues utilisés pour ces nouvelles prévisions à posteriori sont identiques aux modèles du WES. On examine les sources d'erreur relevées ici et les méthodes permettant d'obtenir des prévisions à posteriori sûres.

2. INTRODUCTION

In recent years there has been an increasing need for improved wave information for design of coastal and offshore structures in the Labrador Sea, Grand Banks and Nova Scotian shelf areas. Wave data needs for operations relating to these structures have likewise increased. Although wave measurements are available for intermittent periods of time over the last nine years or so in these waters, these measurements are available only at a few sites and do not cover sufficient time to be suitable for extrapolation to design conditions.

This situation is quite similar to that faced by most planners and designers of marine projects. Alternatives for solving this problem are to employ visual ships' observations which have been archived since the early 1900's or to reconstruct past wave conditions via numerical models. Unfortunately, past visual observations are sporadic in time and space; thus, it is difficult to determine their applicability to a problem involving extrapolation through time in order to obtain estimates of extremal return periods. Also, effects of individual observer biases as well as the overall tendency of ships to steer clear of severe storms are difficult to quantify. Consequently, most design conditions are obtained through a procedure of hindcasting a set of the largest past storms to obtain extrapolated estimates of return periods.

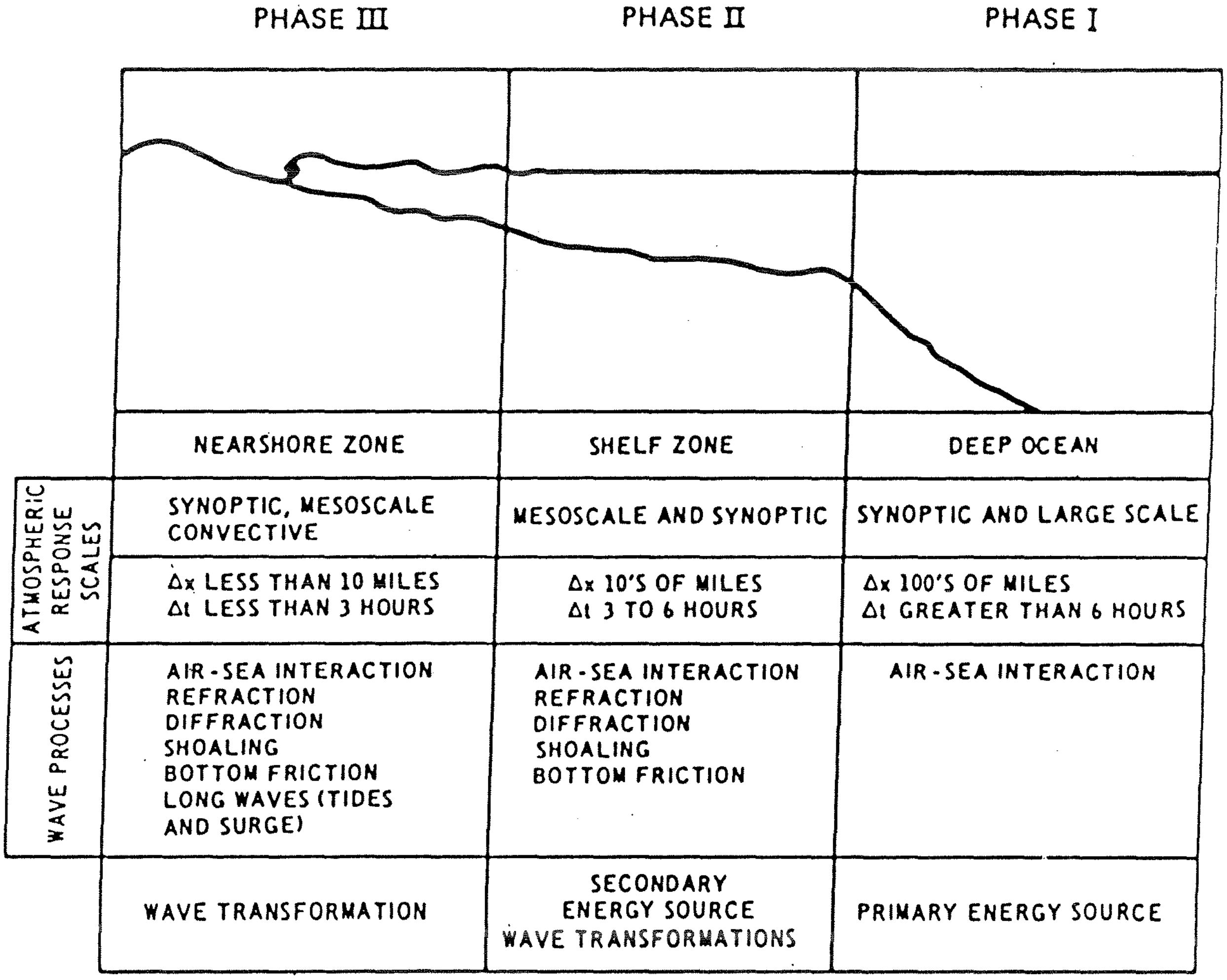
The U. S. Army Corps of Engineers, Waterways Experiment Station (WES) recently completed a 20 year hindcast of the Atlantic Ocean, including the area off of the Canadian East Coast. There are several questions regarding the application of data from this study to important design and planning decisions in Canadian waters, particularly in light of the fact that this previous effort did not concentrate much effort on predicting waves outside of the U. S. East Coast. The purpose of this report is to review the results of this previous effort as well as the methodology used in that study and where applicable, to make recommendations regarding possible significant improvements in this methodology specific to wave prediction in the Labrador Sea, Grand Banks and Nova Scotian shelf areas.

In making an evaluation of wave hindcasts, it is important to bear in mind the intended use of the calculated wave information. For some structural design work, a methodology that concentrates its effort on intense storms, while allowing significant errors in low wave conditions, might be optimal. For some applications involving structural fatigue, the probability distribution of wave heights and periods might be required; however the exact sequence of wave conditions might be relatively unimportant. For other wave data requirements, such as planning considerations in operating and servicing oil rigs, the duration of wave heights above some threshold can assume critical importance. Consequently, any conclusions drawn concerning the adequacy or inadequacy of hindcast wave data must be related to the intended application of the data.

Initially, there were to be two reports in this investigation. The first report was to be a concise review of the WES hindcast methodology. The second was to formulate a procedure for possible improvements, if required. However, after only a brief interval of work, it became apparent that the two reports were very much linked in their contents. In order to critique the WES hindcasts, new hindcasts were needed to explore the possible sources of error in this previous study. The selection and analysis of these hindcast procedures would be a good means of examining possible improvements to the WES methodology. Thus, the two reports have now become one.

3. EVALUATION PROCEDURE

There are several factors concerning the comparison of hindcast data to gage data which must be considered here. First, since the hindcast data were obtained under the assumption of deep water in the wave model, shallow water effects present in the measured data must not be construed as as problem in the deep-water hindcast methodology. To obtain wave information in shallow water via hindcasts, it is necessary to employ a sequence of models,each treating a set of appropriate processes at specific scales, as was done in the complete WES study for the U. S. East Coast (Figure 1). Second, it is also necessary to recognize the site specific nature of measured wave data. Whereas, numerical wave models typically ignore geographic features smaller than the scale of the spatial grid increments, wave gages respond to all geographic features, even the most local. A good example of this can be found in the systematic difference between wave conditions measured at site 90(4) and 91(5), located only 80 miles apart (Figure 2). As seen in Figure 3,during the periods in 1974 of March 5-6, April 1-2, April 5-8, April 10-12, and April 16-18, the gage at site 91(5) consistently reports larger wave conditions than the gage at site 90(4). Since both of these gages are being compared to the same hindcast location, it is obvious that the hindcast data cannot agree with both. Figures 4-7 show the weather maps at 12-hour intervals for the March 5-6 storm event. It is clear from these figures that there are no consistent features in the wind field which would produce higher waves at site 91(5). If anything, the increased fetch to site 90(4) might lead one to suspect that the waves would be higher there. Consequently, the difference can almost certainly be ascribed to local geographic features. In this case it appears that the presence of Sable Island to the southwest of site 90(4) serves to shelter this site from particular wave directions. Analogous to the shallow water situation, accurate predictions at a site such as 90(4) must be taken from a nested system of grids each resolving successively



	PHASE III	PHASE II	PHASE I
	NEARSHORE ZONE	SHELF ZONE	DEEP OCEAN
ATMOSPHERIC RESPONSE SCALES	SYNOPTIC, MESOSCALE CONVECTIVE	MESOSCALE AND SYNOPTIC	SYNOPTIC AND LARGE SCALE
	Δx LESS THAN 10 MILES Δt LESS THAN 3 HOURS	Δx 10'S OF MILES Δt 3 TO 6 HOURS	Δx 100'S OF MILES Δt GREATER THAN 6 HOURS
WAVE PROCESSES	AIR-SEA INTERACTION REFRACTION DIFFRACTION SHOALING BOTTOM FRICTION LONG WAVES (TIDES AND SURGE)	AIR-SEA INTERACTION REFRACTION DIFFRACTION SHOALING BOTTOM FRICTION	AIR-SEA INTERACTION
	WAVE TRANSFORMATION	SECONDARY ENERGY SOURCE WAVE TRANSFORMATIONS	PRIMARY ENERGY SOURCE

Figure 1. Conceptual diagram of the three phases of the wave information study (WIS) performed at the U. S. Army Engineer Waterways Experiment Station (WES) from: Corson et al (1981).

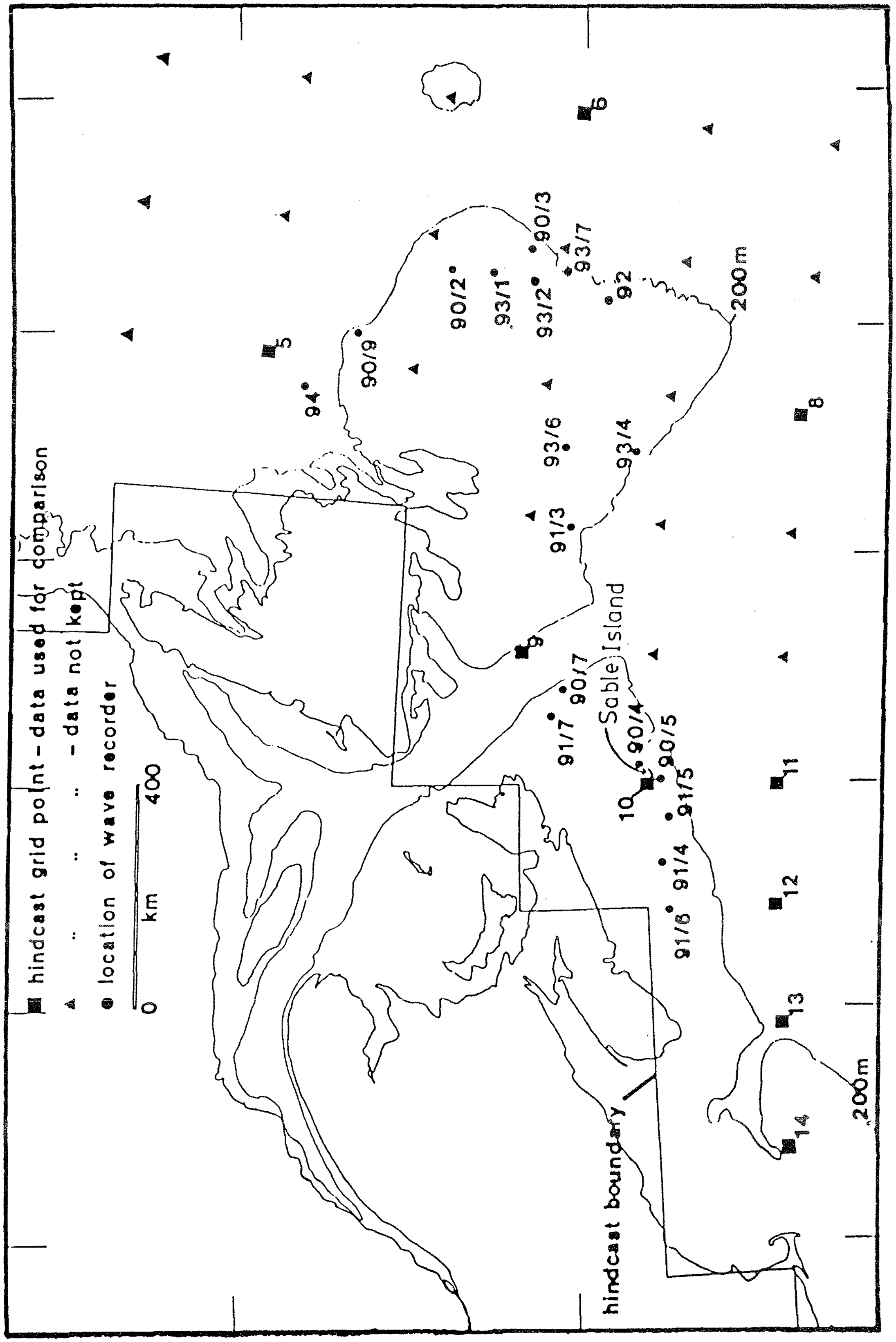


Figure 2. Location map for wave comparisons performed by Baird and Readshaw (1981).

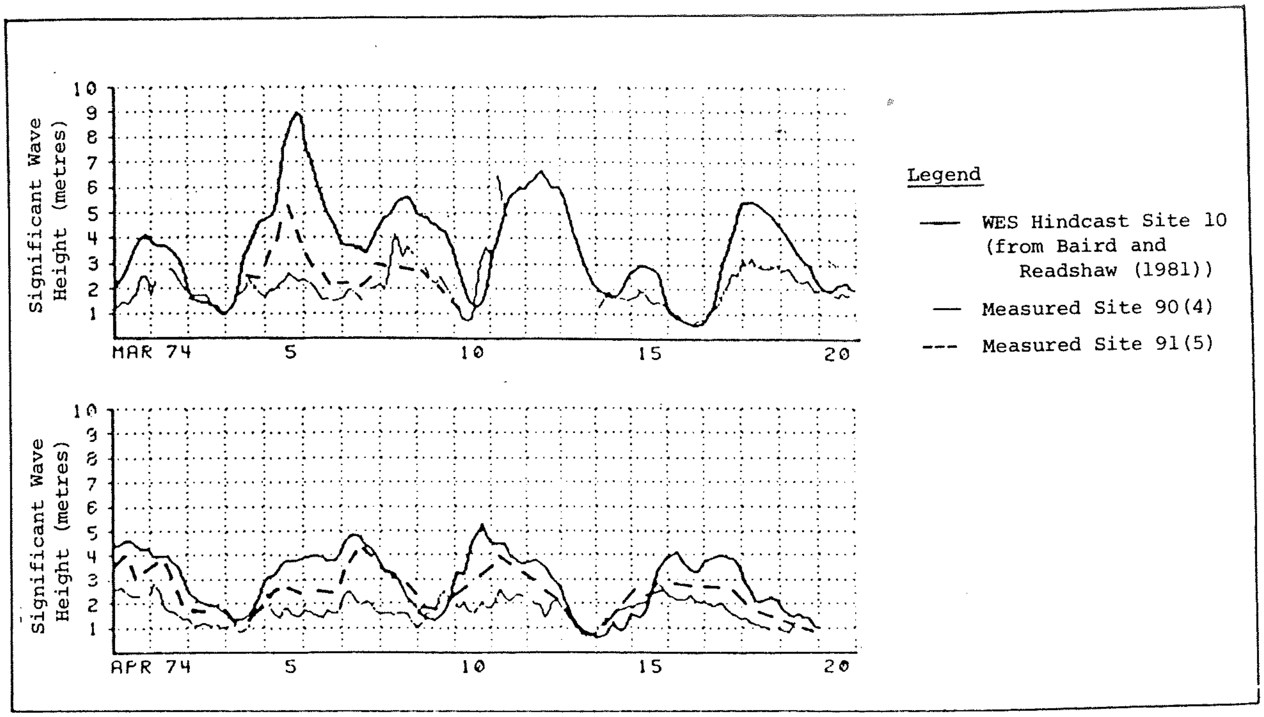


Figure 3. Comparison of hindcast waves from WES study (site 10) to measured waves at sites 90(4) and 91(5) from Baird and Readshaw (1981)

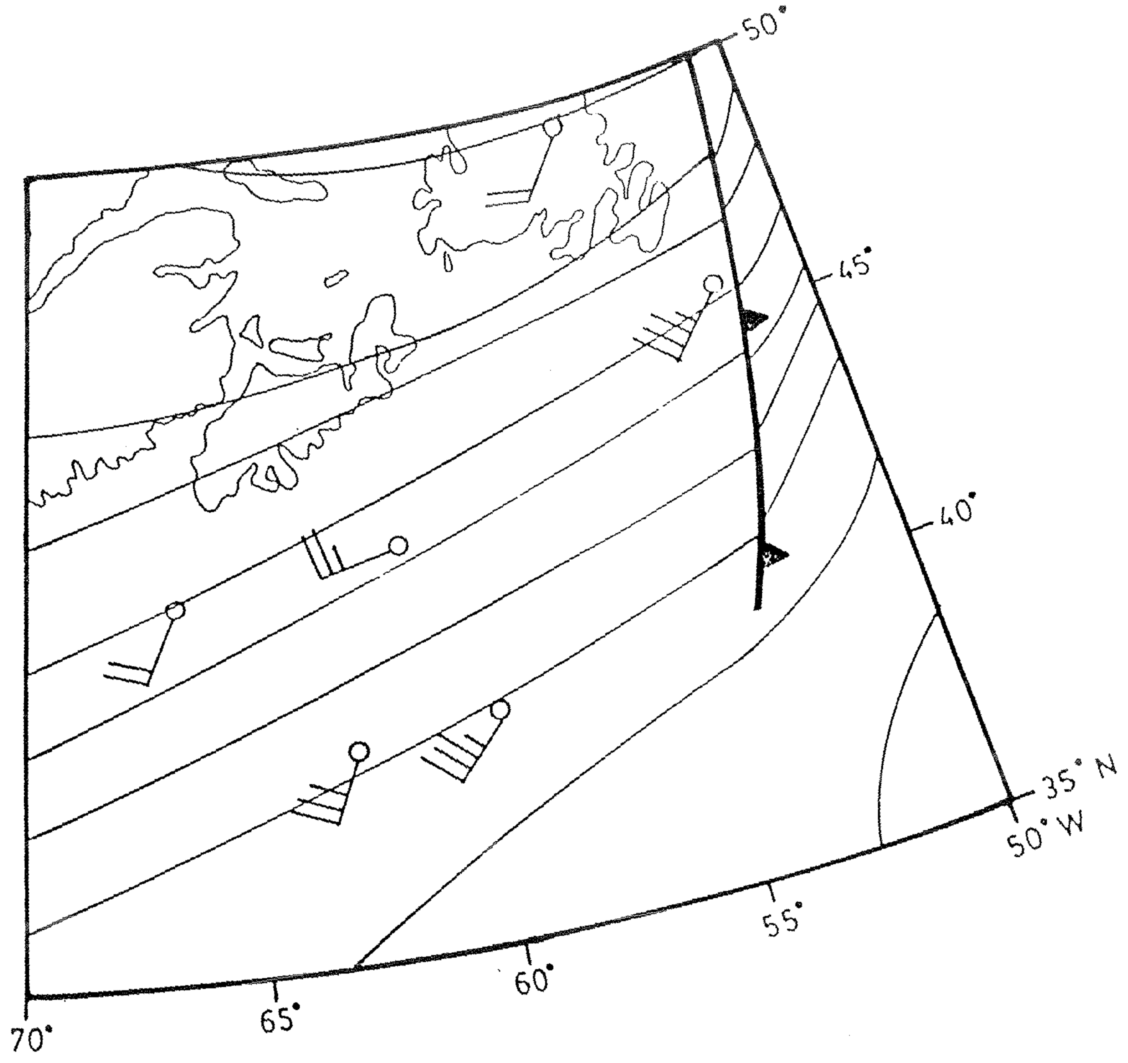


Figure 4. Synoptic weather map for Sable Island area 74030500

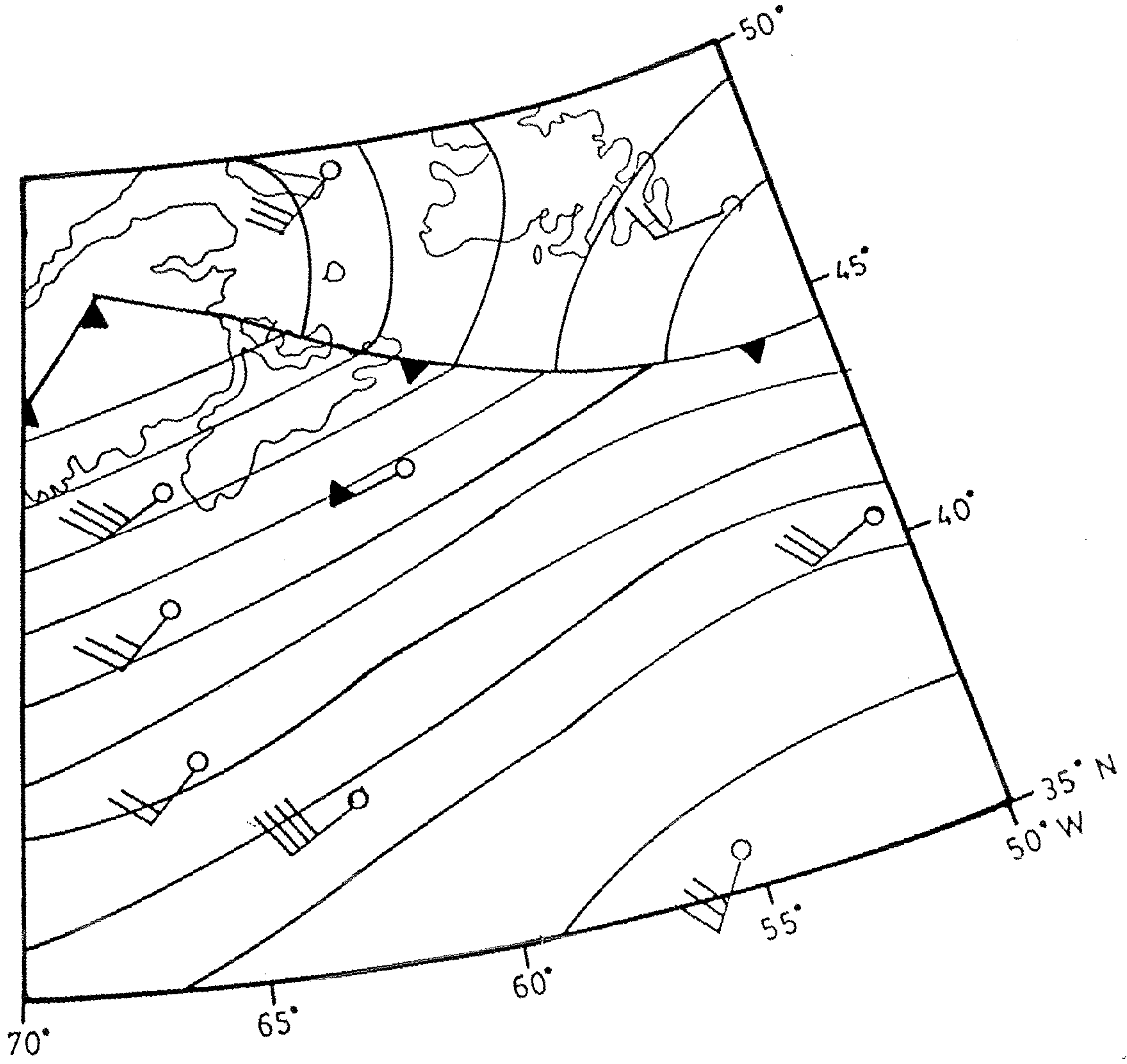


Figure 5. Synoptic weather map for Sable Island area 74030512

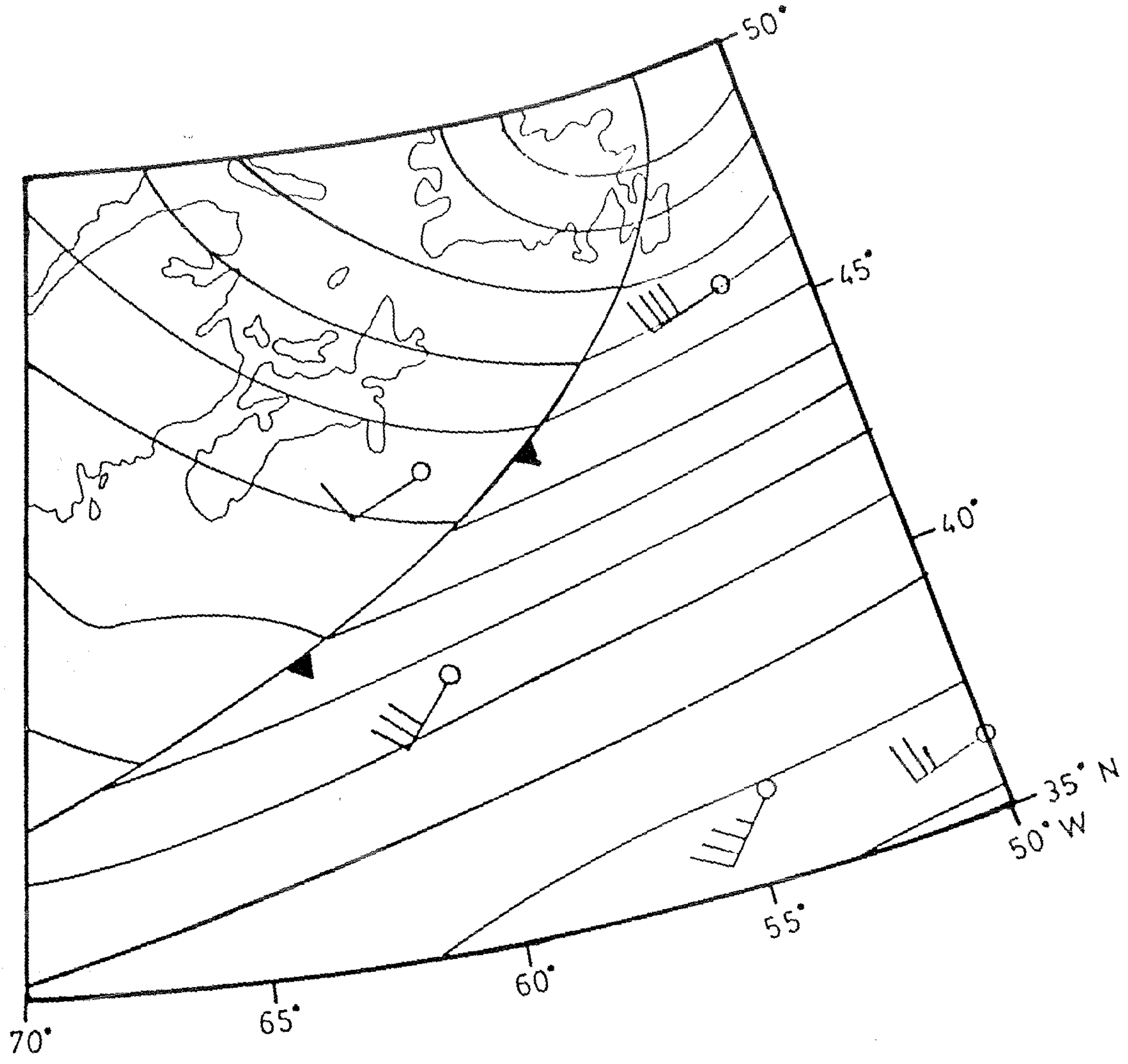


Figure 6. Synoptic weather map for Sable Island area
74030600

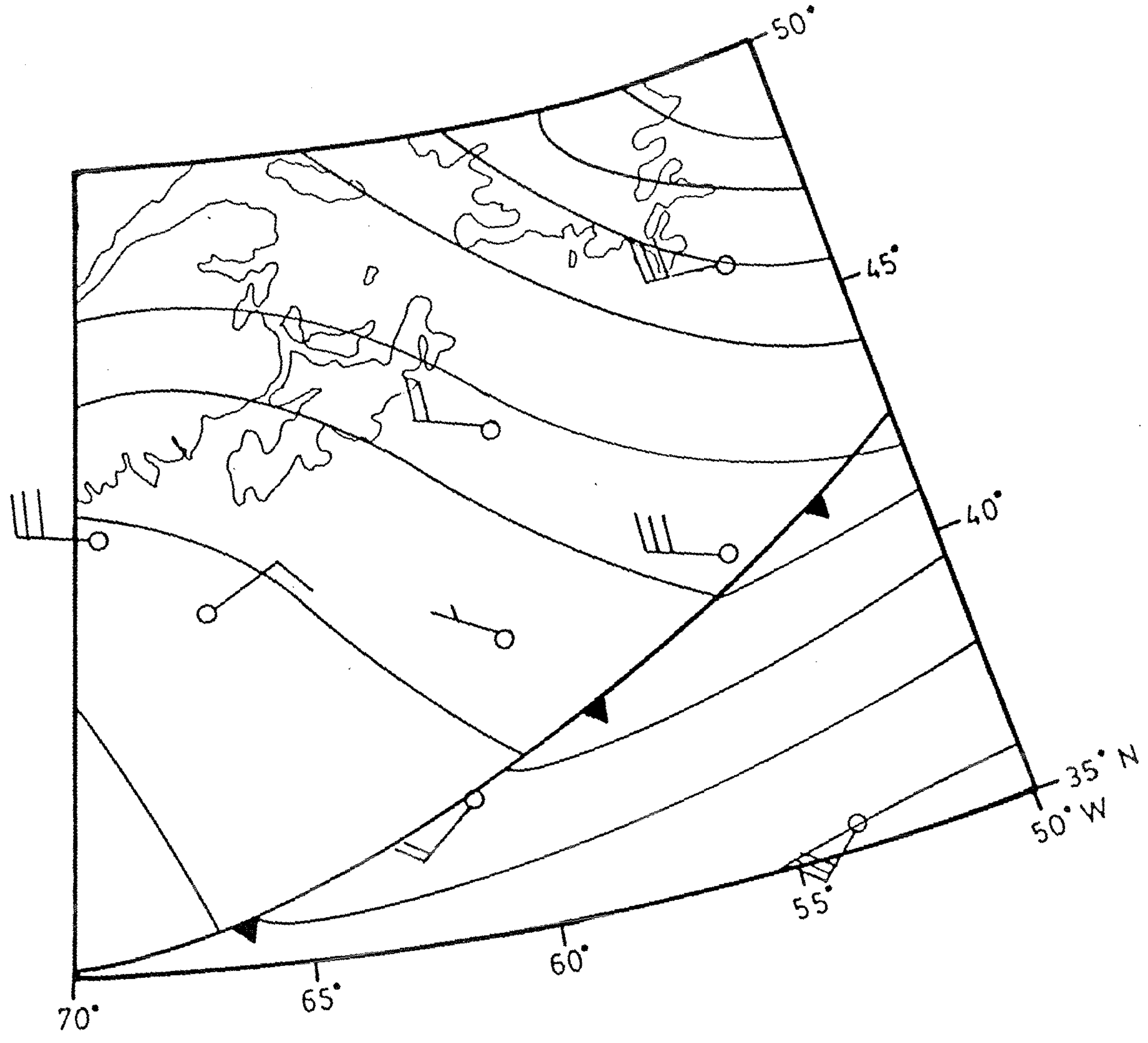


Figure 7. Synoptic weather map for Sable Island area
74030612

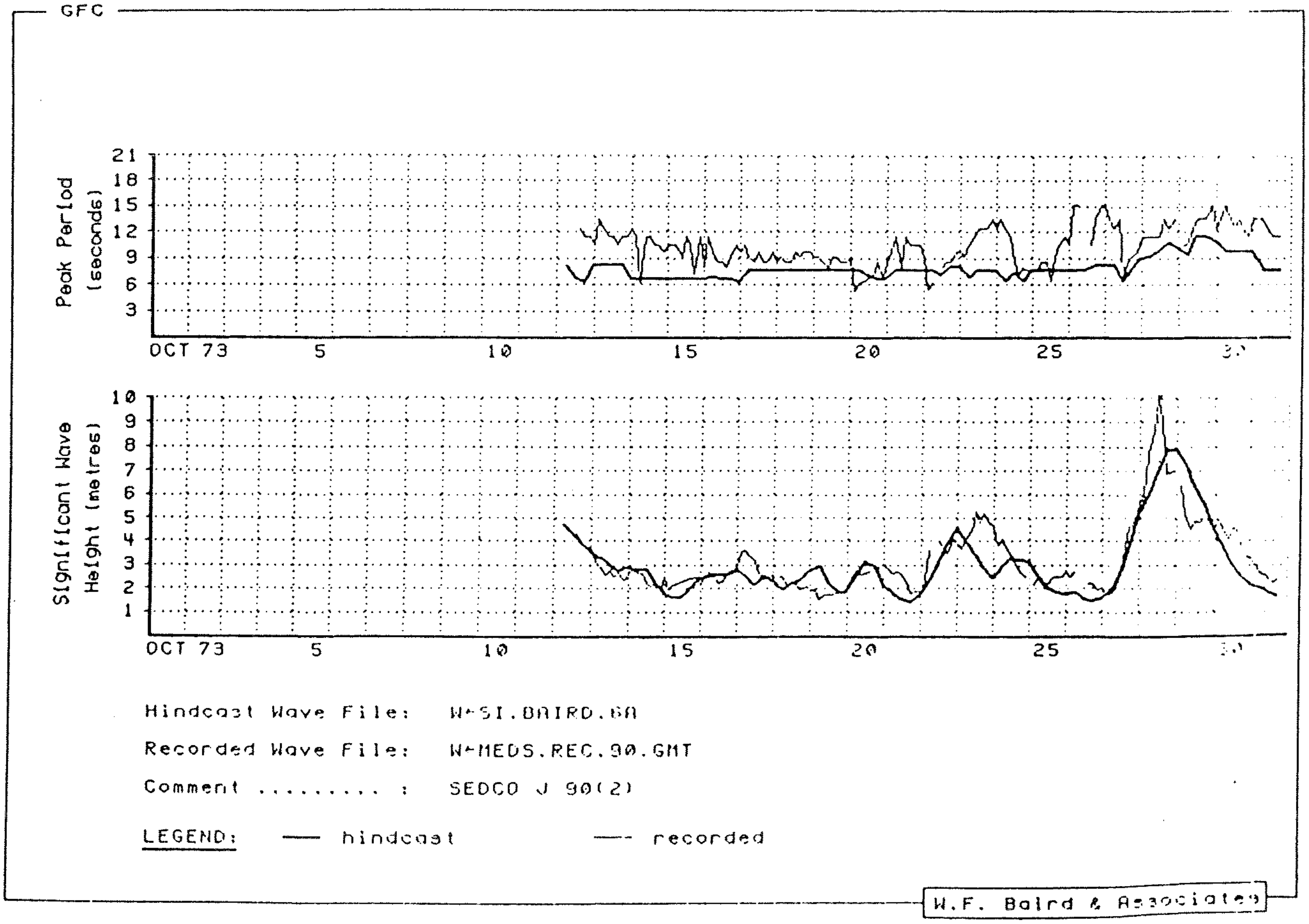
finer spatial scales until Sable Island is included in a reasonable form. Since such a treatment was not considered in the Canadian region of the Atlantic Ocean, site 90(4) will be disregarded in comparisons to hindcast data in this report.

Baird and Readshaw (1981) give comparisons of all available comparable gage and hindcast data sequences. The purpose of this report is not to repeat that study but to examine more closely the nature of specific, significant errors and to make recommendation on possible improvements which might avoid these errors in future hindcasts. In particular, deviations related to apparent problems in the wind field specification will be examined since this affects the value of available wind field data for future hindcasts. If errors in the hindcasts were primarily due to problems in the grid specifications and not the wind fields, it would be possible to interpolate the wind fields onto a different wave model grid. One could then re-hindcast the waves with no additional effort placed on wind field analyses. On the other hand, if the wind fields are suspect, then improved wind fields must be obtained before any additional hindcasts are performed.

Six wave generation events have been selected to attempt to isolate possible sources of hindcast errors. These include the wave generation events listed below:

1. October 26-30, 1973 (site 90(2))
2. November 11-15, 1973 (site 90(2))
3. December 21-25, 1973 (site (91(3))
4. January 8-11, 1974 (site 91(3))
5. March 4-8, 1974 (site 91(5))
6. April 2-11, 1974 (site 91(5))

Figures 8-13 show the comparisons by Baird and Readshaw of the WES hindcasts to gage data for these events. In the WES study, the entire procedure used

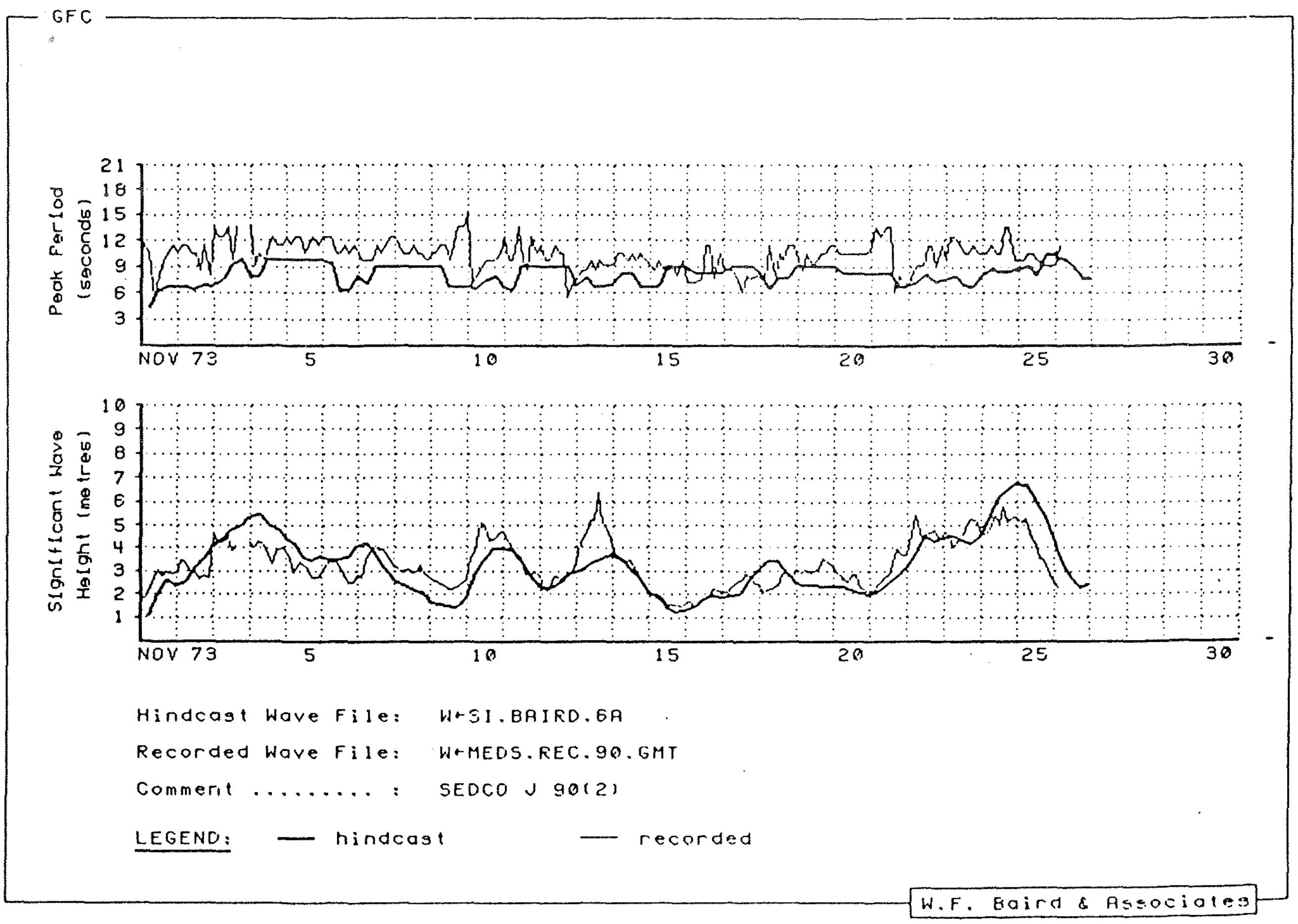


Hindcast Wave File: W*SI.BAIRD.6A

Recorded Wave File: W*MEDS.REC.90.GMT

Comment .... : SEDCO J 90(2)

Figure 8. Comparison of WES hindcast to measured waves from Baird and Readshaw 1981 for October 1973 (site 90 (2)).



Hindcast Wave File: W+SI.BAIRD.6A

Recorded Wave File: W+MEDS.REC.90.GMT

Comment .... : SEDCO J 90(2)

Figure 9. Comparison of WES hindcast to measured waves from Baird and Readshaw (1981) for November 1973 (site 90(2)).

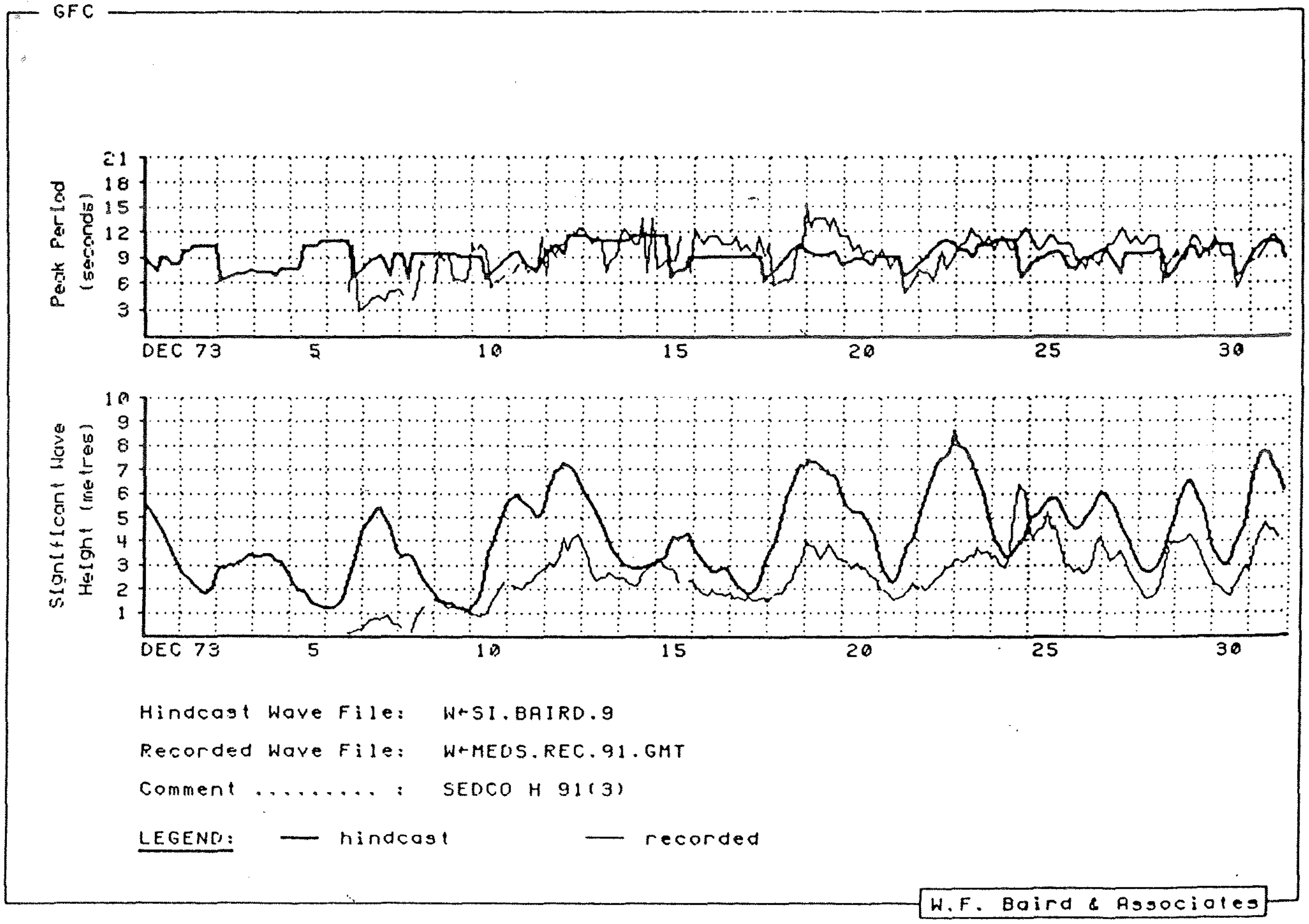


Figure 10. Comparison of WES hindcast to measured waves from Baird and Readshaw (1981) for December 1973 at (sites (91(3) and 90(3)).

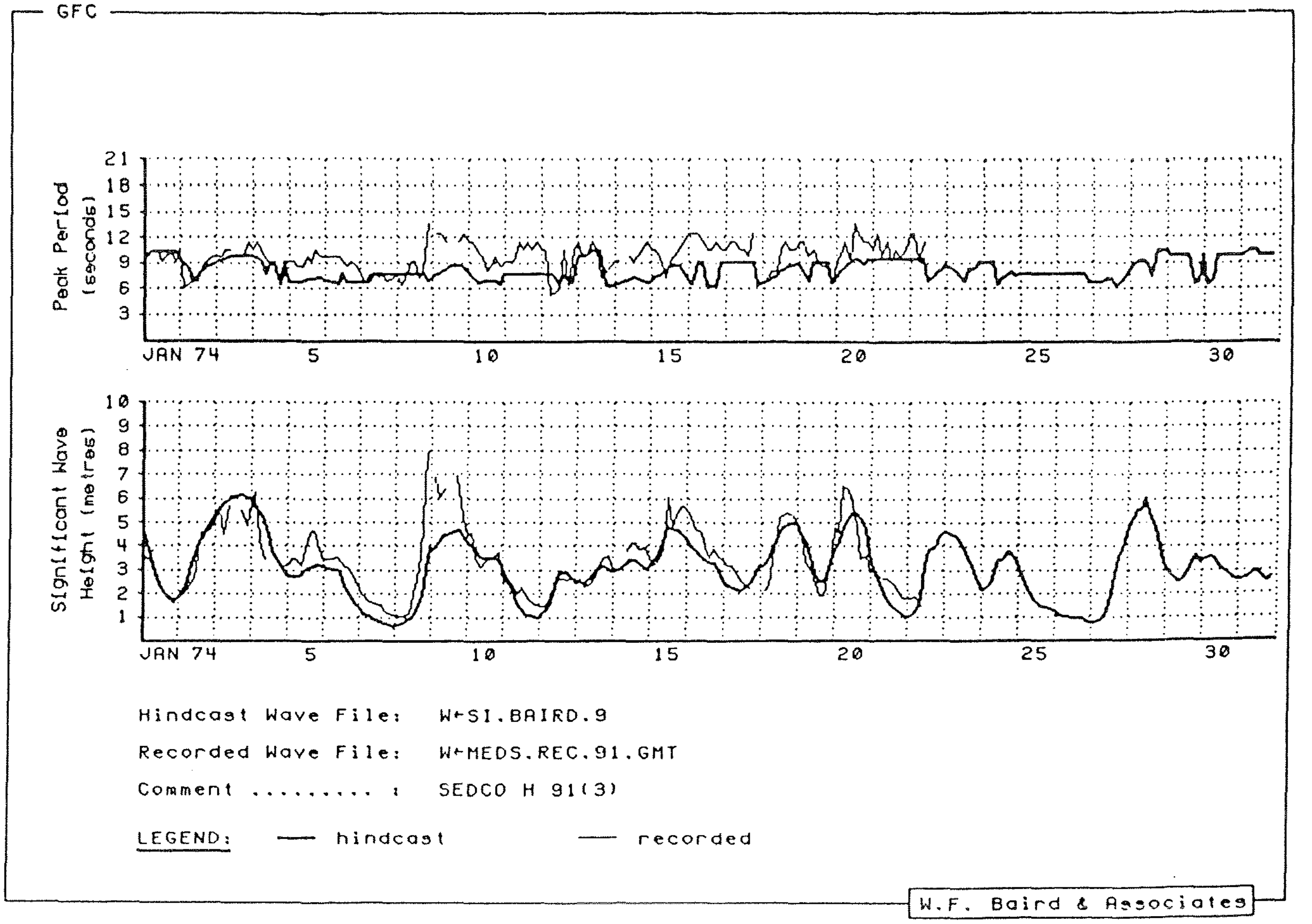


Figure 11. Comparison of WES hindcast to measured waves from Baird and Readshaw (1981) for January 1974 at (site 91(3)).

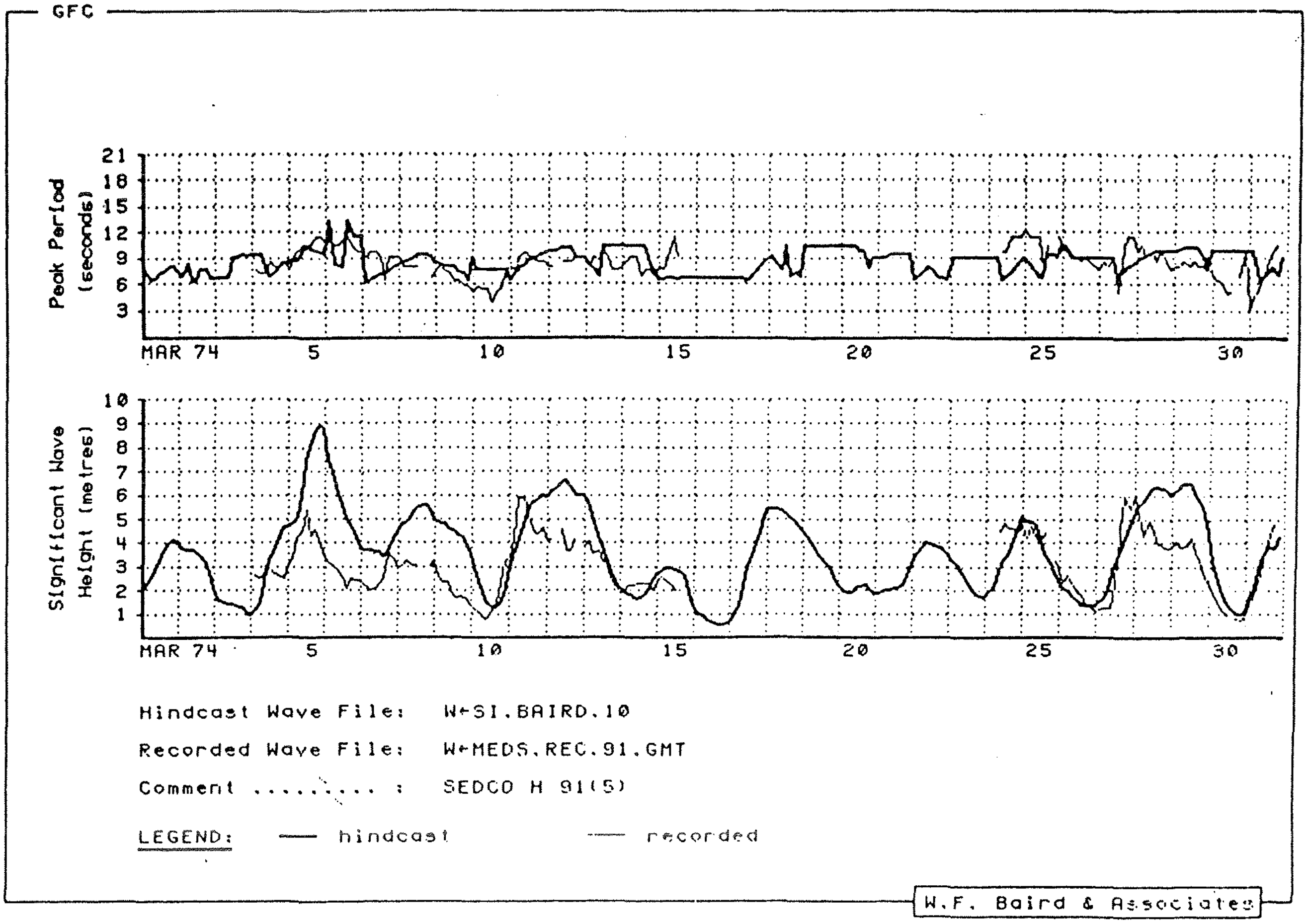
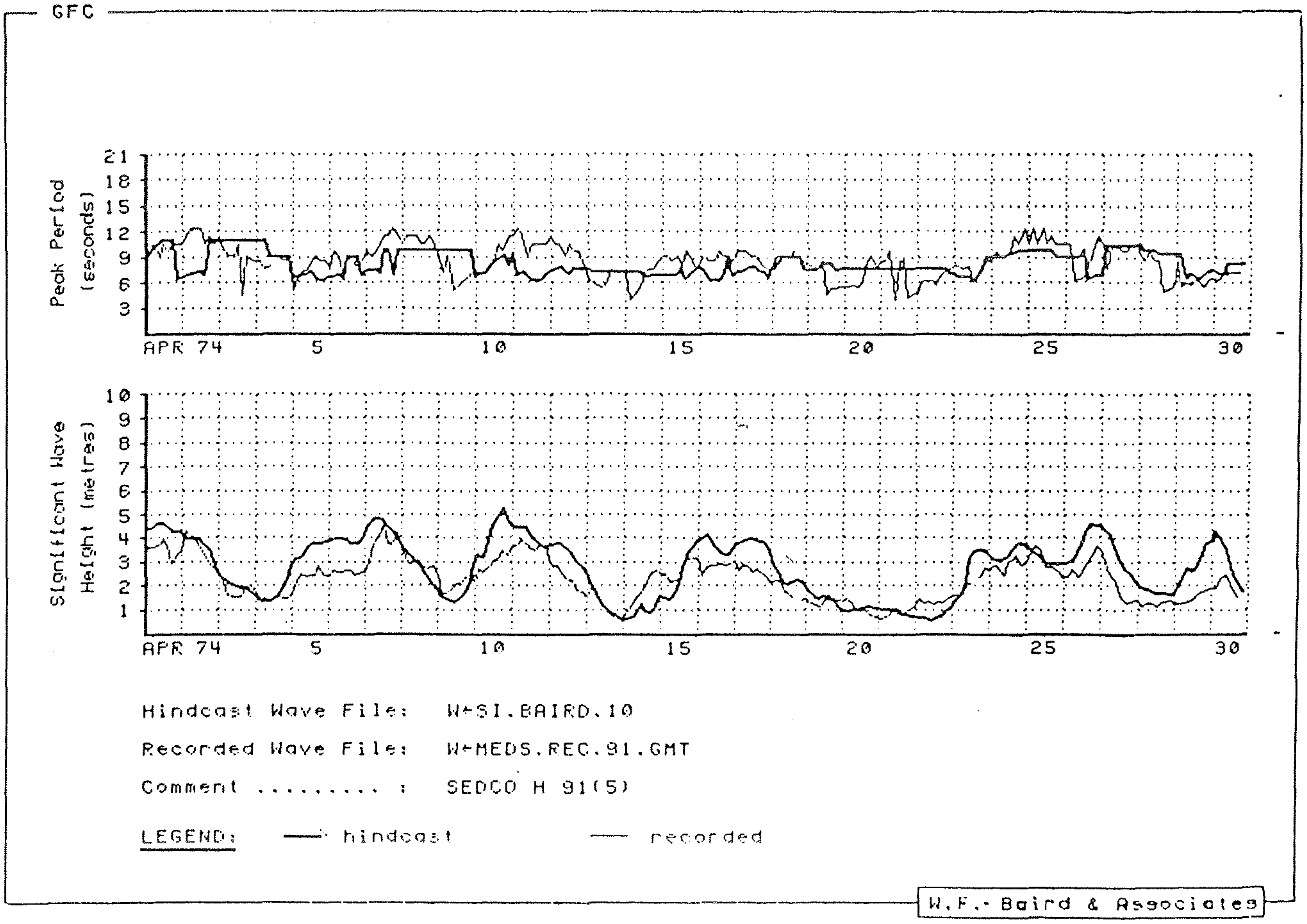


Figure 12. Comparison of WES hindcast to measured waves from Baird and Readshaw 1981 for March 1974 at (site 91(5)).



Hindcast Wave File: W*SI.BAIRD.10

Recorded Wave File: W*MEDS.REC.91.GMT

Comment .... : SEDCO H 91(5)

LEGEND: —— hindcast —— recorded

Figure 13. Comparison of WES hindcast to measured waves from Baird and Readshaw 1981 for April 1974 at (site 91(51).

in the preparation of wind fields was performed via computer. The pressure fields were machine-processed, the estimation of the wind at the geostrophic level, the boundary-layer transformation, and all edit procedures were automated. Even the incorporation of ships' wind observations into the final wind fields was done by computer. Such a "machine-only" approach to the winds must rely heavily on the set of assumptions inherent in the theoretical foundations of the numerical models. Probably the most significant of those assumptions is that of a "quasi-equilibrium" among the various forces acting on the winds at the geostrophic level. In the western Atlantic Ocean, rapid cyclogenesis and storm movement can create large departures from geostrophic flow conditions; consequently, the theoretical basis adopted in these models might fail on such occasions. This raises a question regarding what improvement might be attainable through the use of a man-machine mix, since, in weather prediction schemes such an approach has often proved quite fruitful.

Appendix A gives a brief description of the type of information on wind fields that an analyst can obtain from a sequence of weather maps. Such an analysis is referred to as a kinematic analysis. The human ability to integrate individual elements (in this case wind vectors) into a coherent pattern is the basis of this type of analysis. Using concepts of continuity of the flow field in both space and time, an analyst prepares streamlines which originate in high pressure areas and extent toward centers of low pressure areas. Once the streamlines are constructed, isotachs are added to complete the analysis. In cases where one weather map might lack information in critical areas, information can be interpolated from prior and subsequent weather maps. In general, where the density of wind observation is good, excellent estimates of wind fields can be obtained through this procedure.

In this study, the machine-only and man-machine mix will both be used obtain wind fields for hindcasts using the Resio (1981) wave model. Since the wind model used here is the same as that used by the WES study, difference between the WES hindcasts and the machine-only hindcasts produced here must lie in the input pressure fields. Based on experience with the WES hindcasts, it is suggested that, during most broad-scale well-defined synoptic weather situations, the machine-only approach produces reasonable agreement between hindcast and measured waves. Consequently, kinematic analyses will be made only for selected weather maps. These selected times typically include the period of most intense wave generation during the peak of a storm. Although it might seem advisable simply to overlay the machine-only winds with the hand-analyzed winds in the area of interest, a more stable estimate is obtained from a weighted average of the two independent estimates of the wind. In the comparisons presented here, result from the machine-only wind fields are referred to as Method I. Results from a man-machine mix, using a .8 weighting on the kinematic analysis and a .2 weighting on the machine calculated winds, are referred to as Method II.

Figure 14 shows a map with the locations of the wave model grid points from the hindcasts tests conducted in this study. The model used here is a similar projection to that used in the WES study; however a 277 km spacing was adopted rather than the 222 km spacing of the WES study. Rather than try to ascertain a priori some optimal spacing of the grid points, the spacing here will be used unless it is found insufficient. Some discussion of consequences of the grid size selection as found in this study will be presented in later sections.

Since all of the storms hindcast were treated as discrete events, there is usually a period near the beginning of each hindcast in which the hindcast wave conditions are substantially lower than the measured

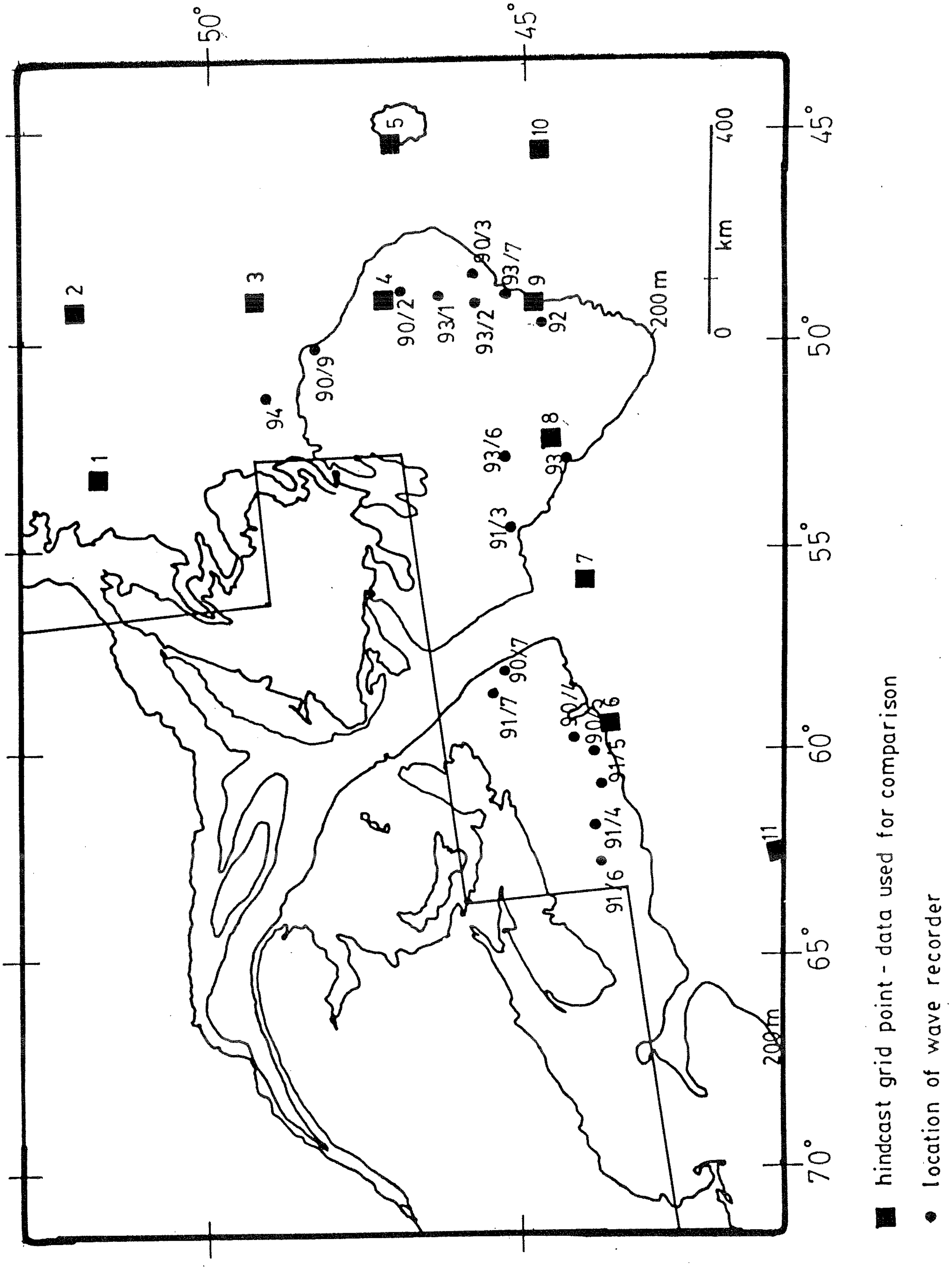


Figure 14. Map with the location of the wave model grid points used in hindcast of 6 events analyzed in this study.

conditions. This is due to the persistence of wave energy in nature which was generated before the start of the model run. This energy is not present in the wave model, since it initialized with zero-energy conditions. The interval during which the model comes into agreement with all wave energy is often termed the model "warm-up" period.

In Appendix B, weather map information at 12-hour intervals is presented for the six selected events to be examined in this study. This appendix can be consulted when specific patterns of winds, pressure, or storm movements are referenced.

3.1 Description of October 26-30, 1973 Period and Hindcast.

This wave-generation event represents one of the most important storms along the Atlantic Coast of Canada in terms of design wave conditions during the 1973-1974 period of measurements. As can be seen in Figure 8, the Army hindcasts did reasonably well on this storm although the peak wave height was underpredicted by about 2 metres.

At 0000 Ƶ on the 26th, tropical storm Gilda is centered at approximately 34° N, 70° W with its winds extending as far north as 42° N. The local winds at site 90(2) are low at 5 to 10 knots out of the northwest. During the next 36 hours, this storm moves along a northeasterly course and, by 1200 Ƶ on the 27th winds from this storm have moved into the area of site 90(2). The rapid growth in wave heights measured by the gage at this site during the 24 hours is probably due both to local wave generation and to a lesser extent to traveling inside the storm reaching the site. During this 24 hour period, the storm intensifies from 30-40 knot peak winds to 50-60 knot peak winds. Consequently, it affords an excellent test of duration-limited wave growth in the wave model. After 1200 Ƶ on the 28th, the storm center moves progressively away from site 90(2). The primary wave train shifts from a dominant southwesterly approach direction to a northwesterly approach direction after the center has passed the site, and there is gradual decay in the wave heights, down to under 4 metres by 1800 hrs. Z on the 30th.

Figure 15 gives a comparison of the new hindcasts using methodologies I and II. Viewing both Figures 8 and 15 shows that the WES hindcast for this storm and the machine-only hindcast performed here give comparable results. Although phasing is shifted between these two hindcasts, they both give maximum significant wave heights of about 8 metres, which is over 2 metres less than the measured maximum of 10.2 metres. With the inclusion of kinematic analyses for an interval near the storm peak, the maximum wave height hindcast is increased to 9.3 metres. Since the storm generating these waves is a large one, it is not surprising that the machine-only analyses do a reasonable job of reproducing observed wave conditions. Hindcast growth rates and decay rates from this method for most of the storm are quite compatible with those observed. It is only the twelve-hour period during the peak of the storm that is missed in this analysis. The reason for this can be found by comparing peak winds produced by Methods I and II. In the case of the machine-only winds, there is a broad period of 40-knot winds in the vicinity of site 90(2), but the highest wind speed is only 44 knots. In the case of the winds obtained by kinematic analysis, the peak wind speed is 52 knots. With the blending algorithm used here, the actual peak windspeed at the this site input to the wave model was 48 knots.

After about a 30-hour "warm-up" period, the general agreement between predicted and measured wave growth and decay rates is quite good. The 0.9 metre underprediction during the storm peak is probably attributable to a commeasurate underestimate of the input wind speed. If there were a large difference between wave model growth rates and actual growth rates, it should have shown up well before -hours prior to the storm peak.

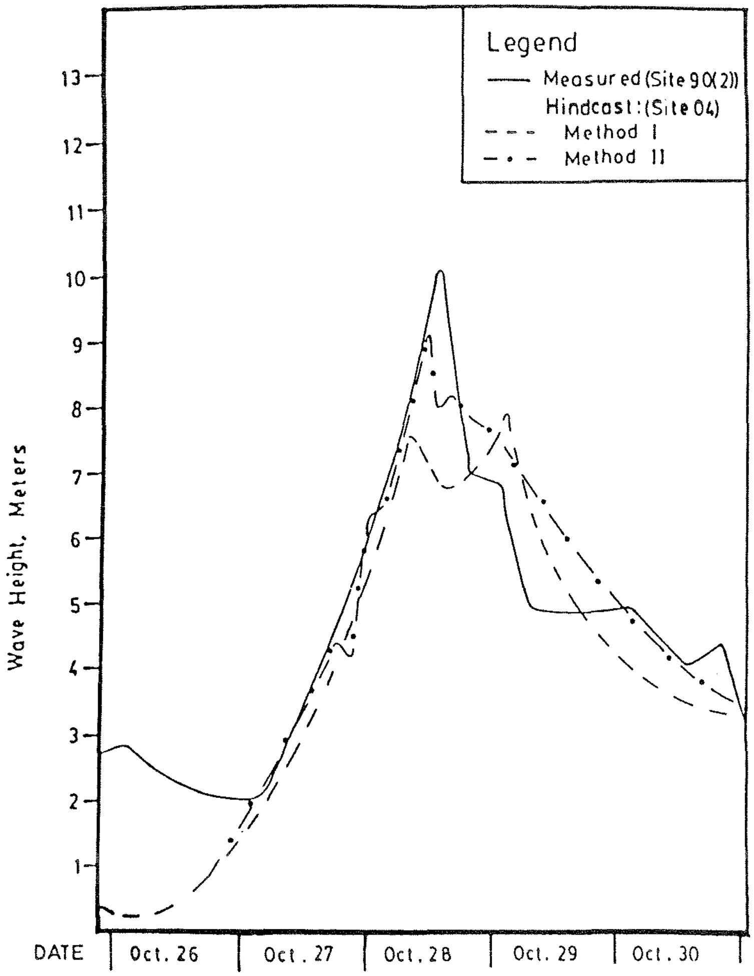


Figure 15. Comparison of hindcast waves using machine-only (method I) and "blended" (method II) winds to measured waves for October 26-30, 1973 (site 90(21)).

The disagreement in the "blended" wind speeds at the peak is, to a large part, attributable to the underprediction of the "machine-only" winds at the time of the storm peak, as evidenced by the trough in the machine-only wave heights during the peak of the storm.

3.2 Description of November 11-15, 1973 Period and Hindcast.

The major wave generation event during this period comes from a small low passing about 200 km southeast off the coast of Newfoundland. The WES hindcasts (Figure 9) apparently do not resolve this storm sufficiently and underpredict the peak waves by about 2.5 metres.

During the period 0000 Z on the 11th until 1200 Z on the 12th, winds in the vicinity of site 90(2) are moderate (10-35 knots). At 1800 Z on the 12th, a small extratropical cyclone is located at 40° N, 53° W with an associated pattern of isobars extending up to site 90(2). Although this storm is small, ships' reports indicate winds of 40-50 knots. By 1800 Z on the 13th, the storm center has just passed southeast of site 90(2). Winds in the wave-generation area for this site are approximately 35-40 knots out of the northeast. After this time, storm movement toward the northeast takes the high winds out of the wave generation area for site 90(2) and subsequently the storm joins into a trough and decays.

Whereas, the WES hindcast appears to miss the November 13th storm entirely, the machine-only hindcasts (I) performed in this study seem to compare reasonably to the observed waves (Figure 16). The only marked deviation comes, as in the case of the October storm, during the peak of the storm. The hindcasts from the kinematic winds (II) again appear to reduce this underprediction. In this case from about 1.2 metres to less than .5 metres. The significant deviation between the WES hindcasts and the machine-only hindcasts from this study indicate that there is a difference in the pressure fields used in these two studies. This storm was

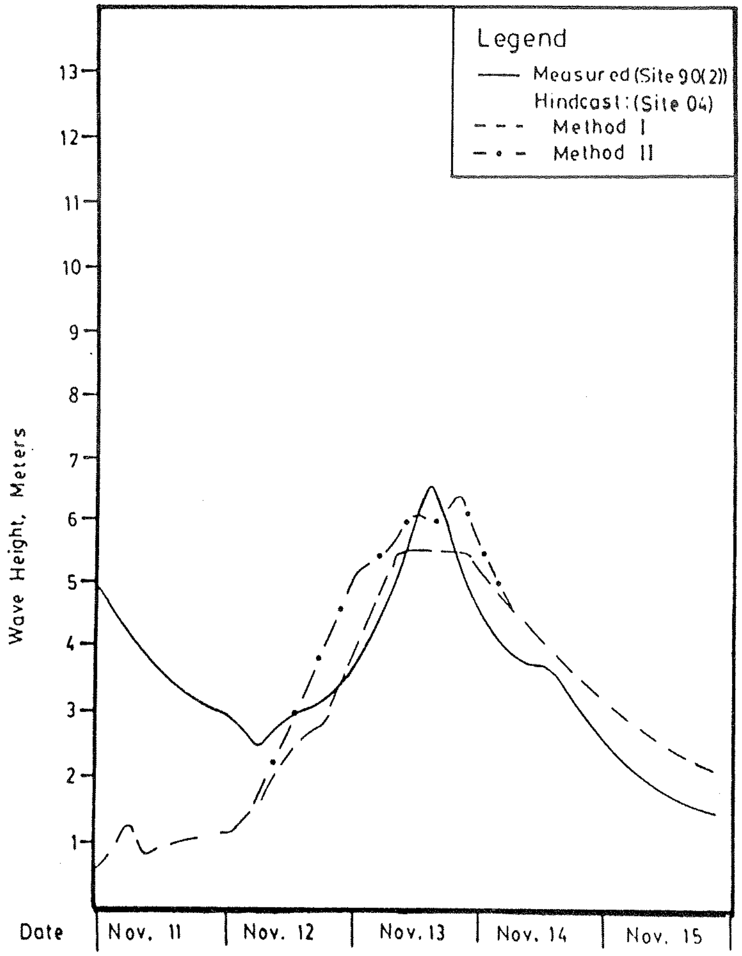


Figure 16. Comparison of hindcast waves using machine-only (method I) and "blended" (method II) winds to measured waves for November 11-15, 1973 (site 90(2)).

small and seems to have been missed by the previous study. There was no emphasis in the WES study placed on obtaining pressure fields in this region, since that study was intended to supply information primarily to the U. S. East Coast. Hence, it is not surprising that this omission occurred.

3.3 Description of December 21-25, 1973 Period and Hindcast.

This time interval represents one in which the WES hindcasts first include a substantial overprediction of wave heights by about 5 metres and then slight underprediction by about a metre. The first wave generation event appears to be associated with a low centered northwest of site 91(3). The second seems to come from a very small low passing just west of site 90(2).

During the 21st through the 23rd a low forms along the Virginia-North Carolina border in the U. S. and then moves toward the north-northeast maintaining its center always landward of the coast. During this interval, the winds are never very high over the wave generation area of site 91(3). By 1800 Z on the 23rd, this low has moved far to the north of site 91(3) and no longer has winds extending into this site. At 0000 Z on the 24th, a small low begins to form along the Nova Scotian coast. By 1800 Z on the 24th, this low has intensified to include 3 closed isobars in a very small area and 50 knot winds speeds are reported in the wave generation area for site 91(3) at 0000 Z on the 25th. Subsequent to this, the storm moves in a northeasterly direction carrying the high winds out of the vicinity of site 91(3).

The substantial overprediction in the WES hindcasts during December 22-23 is not duplicated by the machine-only hindcasts here (Figure 17); however, the underprediction of the December 24-25 event is. As in the two previous comparisons, the hindcasts from the "blended" (II) winds appear to produce peak wave heights comparable to those observed, al-

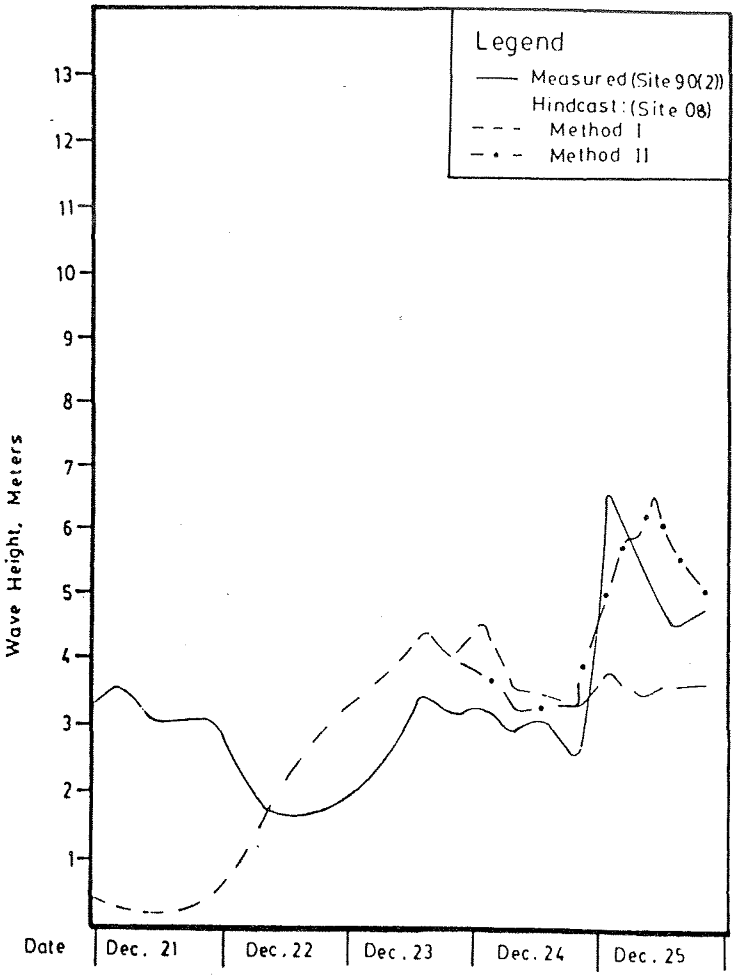


Figure 17. Comparison of hindcast waves using machine-only (method I) and "blended" (method II) winds to measured waves for December 21-25, 1973 (site (91(3)).

though there is about a 9-hour phase lag in the hindcast peak. The over prediction in the WES hindcasts by over 5 metres is apparently due to some data error in the input pressure fields. In this case, it is possible that the method of overlaying one pressure field with another (Corson and Resio, 1981) created artificially high gradients in this area since this is close to the boundary of the overlaid region.

3.4 Description of January 8-11, 1974 Period and Hindcast.

The major wave generation event during this period comes from a small low which forms within a trough of a large low-pressure system located over Iceland. The small low merges with the larger system and very high winds out of the northwest result. This particular wind direction is such that waves generated in the Gulf of St. Lawrence can propagate through Cabot Strait and on toward site 91(3). This storm thus provides at least a partial check on the grid resolution in this area.

The critical portion of this wave generation sequence which produces significant wave heights of 8 metres begins with a small depression forming over Newfoundland at 1200 Z on the 8th. Only six hours later wind speeds are already up to 40 knots in the vicinity of site 91(3) as this small low begins to merge with the larger low to the northeast. By 0000 Z on the 9th, wind speeds of 50 knots are reported in the generation area for site 91(3). Because of the perturbation in the flow field created by the small, secondary low, the wind directions are out of the west-southwest at this time. By 0600 Z, the wind direction has shifted to out of the northwest. There is no evidence suggesting a lessening of wind speeds at this time; hence the reduction in measured wave heights must relate to a reduction in the fetch length for wave generation This suggests that the Gulf of St. Lawrence is not an important contributor to wave energy at site 91(3), even when the wind directions are favorable for propagation through Cabot Strait.

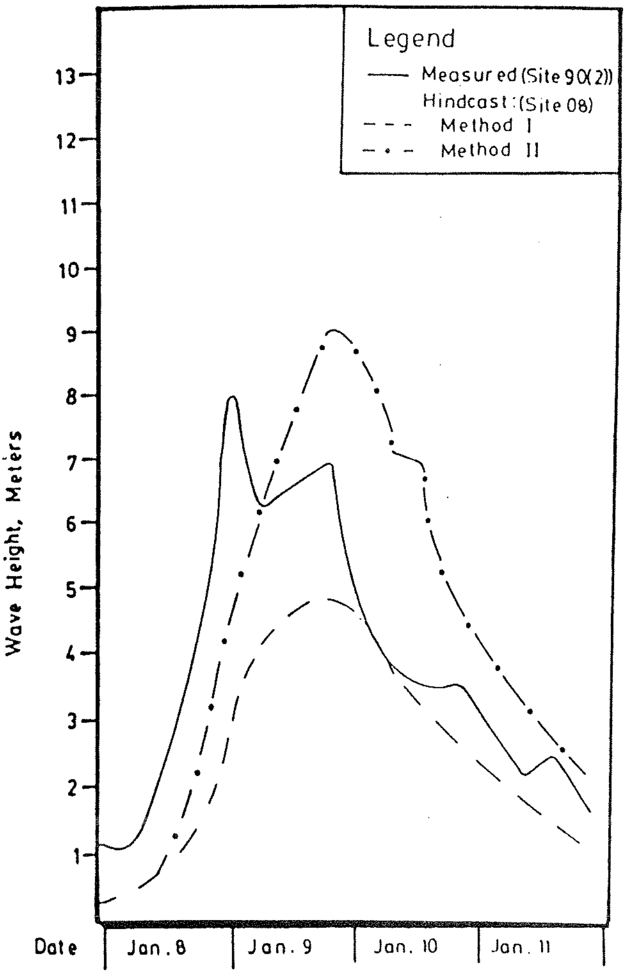


Figure 18. Comparison of hindcast waves using machine-only (method I) and "blended" (method II) winds to measured waves for January 8-11, 1974 (site 91(3)).

This conclusion almost certainly would be reversed for points closer to the mouth of Cabot Strait. A shift in wind direction back toward a more westerly direction at 1200 Z and 1800 Z is probably responsible for the brief resurgence of wave heights during this interval. After 1800 Z on the 9th, the storm wind fields move progressively out of the wave generation area for site 91(3) and there is a commeasurate drop in wave heights.

This January storm provides the largest difference between the machine-only approach and the kinematic analysis method. As seen in Figure 11 and 18 both the WES and the machine-only hindcasts produce peaks of 4-5 metres. Measured wave heights peak at 8 metres. At this time, the winds are coming from off the coast; thus the waves are fetch limited. Since the hindcast site is farther offshore, the predicted waves should be higher than measured waves. In the hindcasts from the man-machine mix (II), the peak hindcast waves are slightly over 9 metres. The difference in the hindcasts I and II in this case exceed 4 metres. The reason for the underprediction in the machine-only winds is not clear. Two possibilities are that there is a very strong consistent ageostrophic component to the winds or that the pressure field is analyzed incorrectly on the weather maps.

3.5 Description of March 4-8, 1974 Period and Hindcast.

The WES hindcasts for this storm shown in Figure 12 show an overprediction of peak wave heights by about 4 metres. The storm type responsible for the wave generation is similar to that of December 22-23 which was also overpredicted in that study.

Starting at 1200 Z on the 4th, the isobaric pattern of a low centered at 57° N, 77° W extends itself over site 91(5). Winds are reported in the

20-40 knot range in the wave generation area for 91(5). This alongshore pattern of winds remains until the storm system begins to dissipate and shift at 1200 Z on the 6th. Thus, the wind direction during this entire interval of wave generation is quite constant.

The over 3-metre overprediction in the WES hindcast is not duplicated by the machine-only hindcasts performed in the present study (Figure 19). As noted previously, this suggests that there is a large difference in the input pressure fields. Since this storm moves along a track similar to the December storm, this tends to support the contention that there is a problem with the overlaid boundary in the pressure fields in this area. The slight underprediction of the machine-only hindcasts (I) appear to be alleviated in the kinematically obtained winds.

3.6 Description of April 2-11, 1974 Period and Hindcast.

This period represents a period in which the WES hindcasts seem to reproduce the measured waves at site 91(5) reasonably well for two separate storms. These storms are of a similar type, having rather broad, well-defined isobaric patterns in the area of wave generation for site 91(5).

The first storm begins with winds out of the southwest at 0000 Z on the 5th. Winds in the range of 20-30 knots continue from this direction over the next 48 hours until a front moves across the wave generation area on 0000 Z and 0600 Z on the 7th. The second storm begins as a low in the Eastern U. S. and moves offshore at about 37° N. Since this storm is not joined to another low farther north, the isobaric patterns are more closed than those of the first storm. Consequently, the wind directions are initially out of the southeast at 1800 Z on the 9th. By 0600 Z on the 10th

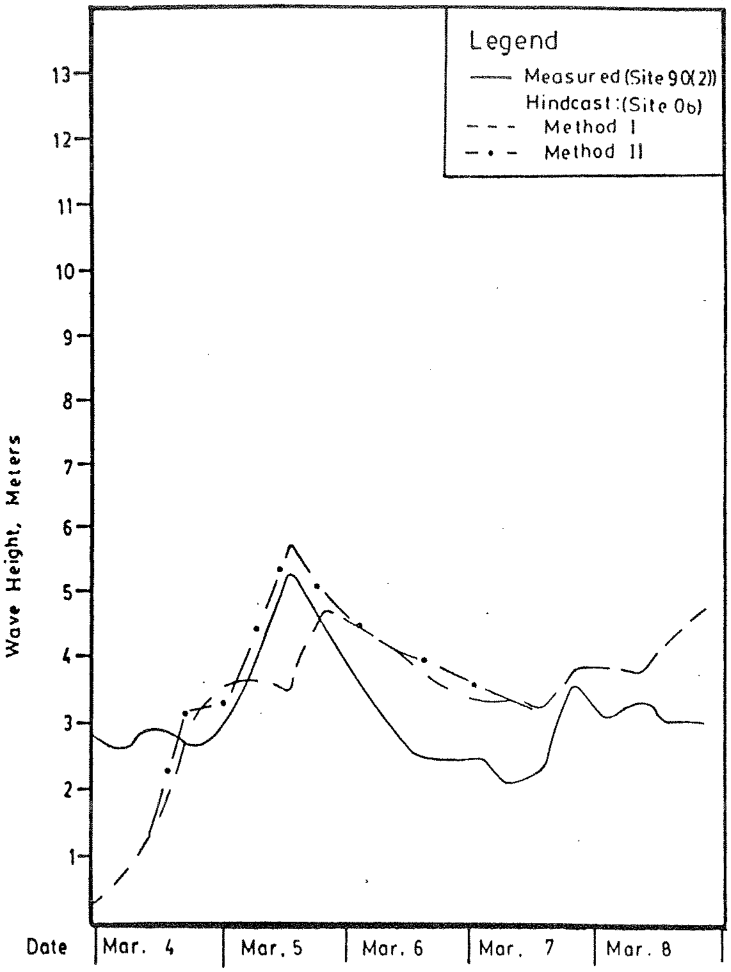


Figure 19. Comparison of hindcast waves using machine-only (method I) and "blended" (method II) winds to measured waves for October 26-30, 1973 (site 90(21)).

the wind direction has shifted to out of the southwest with windspeeds of 25-30 knots; and by 1800 Z on the 11th, the storm center has moved up to 51° N, 57° W with wind directions out of the northwest at site 91(5).

As can be seen in Figure 13 and 20, this period in April is one in which three hindcasts produce comparable results which agree well with the observed waves. This is expected since the storms in this sequence are slowly-varying with rather simple isobaric pattern. Thus, the winds at the geostrophic level should maintain themselves close to geostrophic equilibrium values.

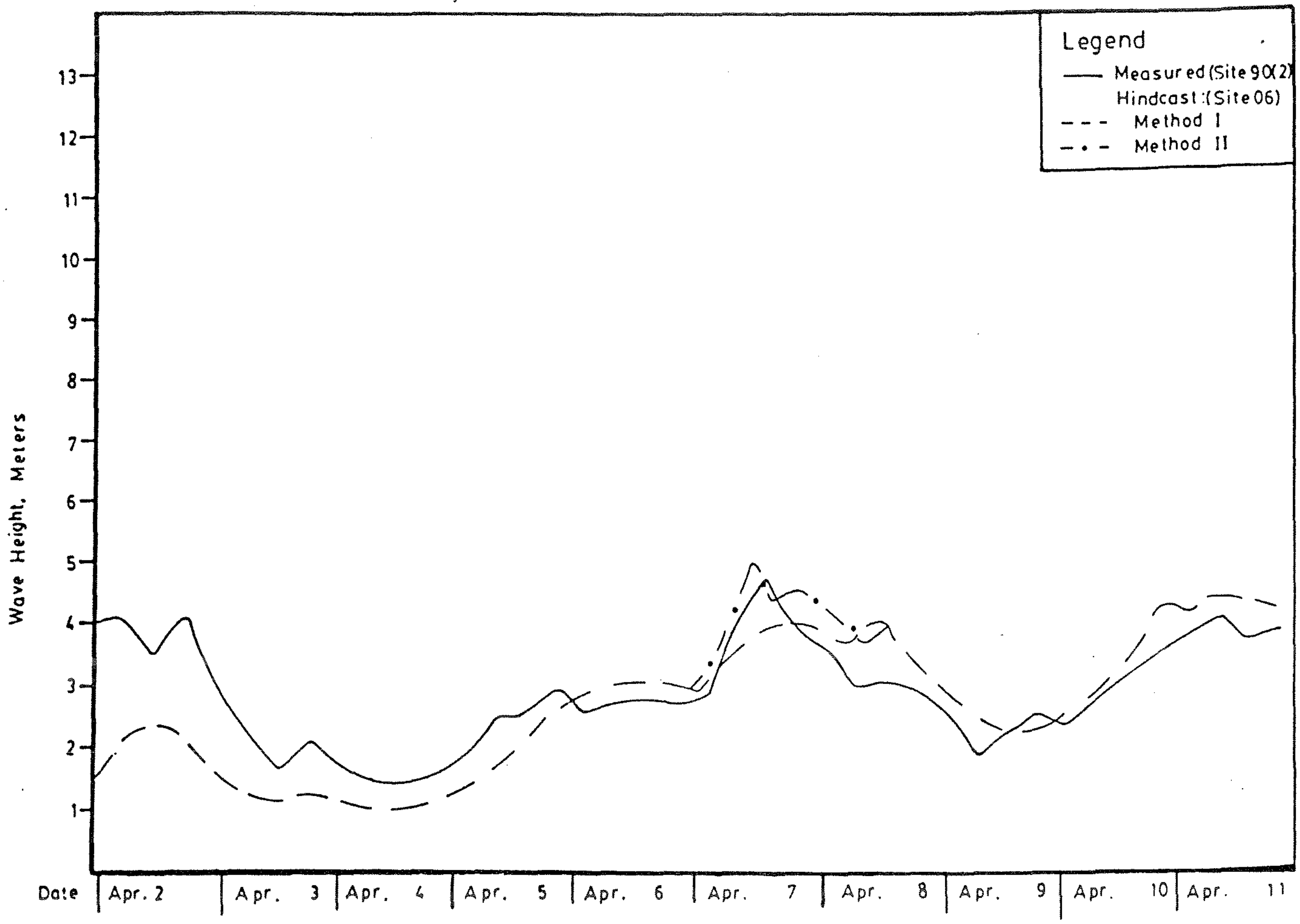


Figure 20. Comparison of hindcast waves using machine only (method I) and "blended" (method II) winds to measured waves for April 2-11, 1974 (site 91(5)).

4. DISCUSSION OF RESULTS

It should be noted at the onset of this section that all but one of the time intervals selected for analysis were chosen on the basis of discrepencies in the WES hindcasts. Thus, they represent a set of the worst comparisons between measured waves and these hindcasts; and it should not be construed that the remainder of the WES hindcasts contain this magnitude of discrepency. Also, it must be recalled that the WES effort, including most of its editing and quality control, was concentrated along the U. S. East Coast. Hence, the magnitude of discrepencies noted in the Canadian area should not be interpreted as errors characteristic of the U. S. East Coast area. Since the WES hindcasts represent a particular type of "machine-only" approach to the preparation of wind fields, these time intervals are also those most likely to present problems to the "machine-only" methodology in the present study.

4.1 Analysis of Wind Field Methodologies

In the comparisons shown in Figure 15-20, the combined machine and kinematically analyzed winds consistently provide the best estimate of wave heights near the peak of each storm. In each case, the combined winds produce a higher peak value of significant wave height, which suggest that there is some smoothing of peak winds taking place in the machine only approach. Since storms in this area tend to be rapidly changing, it is also possible that the ageostrophic terms contribute somewhat to increased wind speeds near the center of these storms. In the January 1974 comparisons, both the WES hindcasts and the machine-only hindcasts performed during this investigation appear to miss a large high wind area of a major storm. In this case the kinematic analysis provides a much better representation of the storm wind field through a two-day period of the storm.

In the broad-scale portions of these storms, the machine hindcasts performed here provide reasonable comparisons to recorded wave heights. The large overpredictions in the December 1973 and March 1974 WES hindcasts are most likely associated with problems in the pressure-field specification which are localized near the Scotian Shelf areas. In no situations did such overpredictions seem to occur in comparisons in the Grand Banks area. As seen in Figure 21, the boundary of the area into which a detailed pressure field was overlaid onto a broad-scale pressure field coincides with the tracks of the two storms which gave problems in hindcasts on the Scotian Shelf. The machine-only wind fields obtained in this investigation were derived through the same wind model as that of the WES study. Only the input pressure fields were changed. Since hindcasts using these winds do not reproduce the large overpredictions, this suggests that there was a problem with the pressure fields in the WES study in the Scotian Shelf area and not with the wind model.

Figure 22 shows a comparison of hindcast and measured peak significant wave heights from the six intervals hindcast. The improvement due to the kinematic analysis is clearly demonstrated here. Whereas the machine-only hindcasts performed show individual errors in excess of 3 metres, the combined approach gives results consistently within 1 metre. Also, the tendency toward a low bias in the machine-only hindcasts appears to be corrected with this methodology. Figure 23 presents a comparison of the WES hindcasts and the machine-only hindcasts performed in the study along with a separate comparison of the machine-only and kinematic analysis hindcasts. Results of comparisons shown in Figure 23 are consistent with the following interpretation. The two machine-only methodologies agree quite well on the three large, well-defined storms (October 1973, January 1974 and April 1974). Since the methodologies used in obtaining wind fields from pressure fields were quite similar, this suggests that the input pressure fields were almost identical in these three storms. The November 1973 storm was a small localized storm.

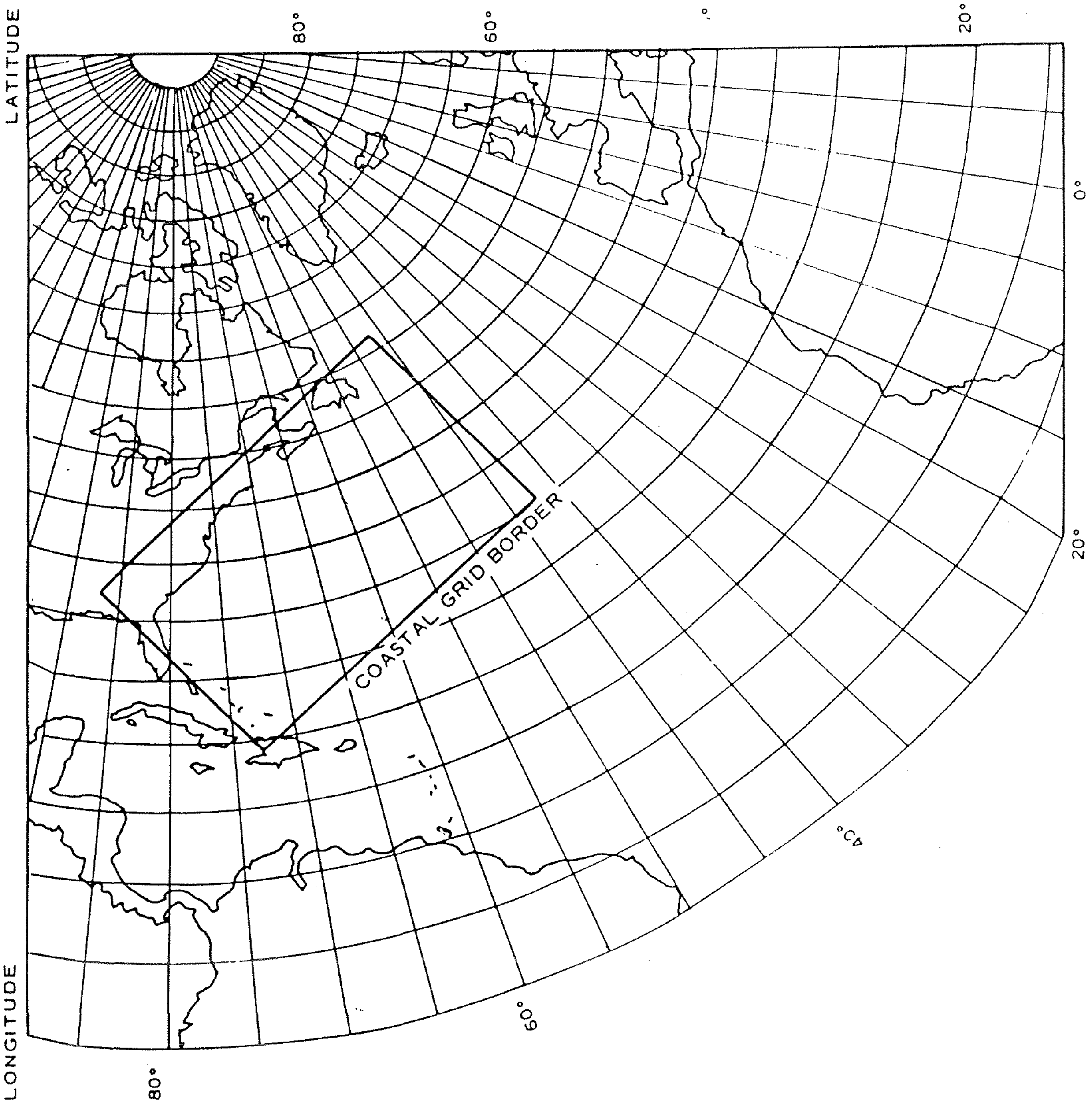


Figure 21. Outline of the coastal grid area into which a detailed pressure field was overlaid onto a broad-scale pressure field in the WES study. (after Corson et al (1981)).

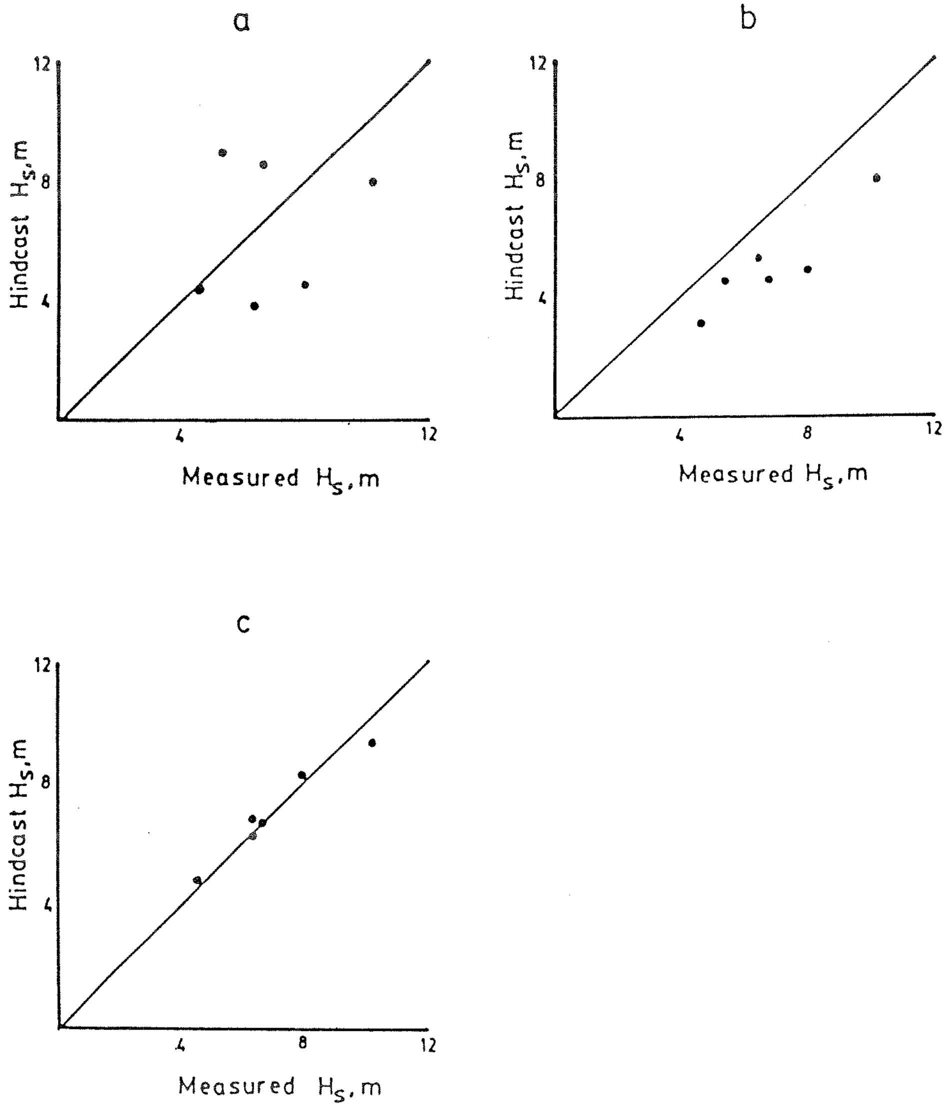


Figure 22. Comparison of hindcast peak significant wave heights from 6 events analyzed in this study to measured peak significant wave heights from the same events for a) WES hindcasts, b) method I hindcasts and c) method II hindcasts.

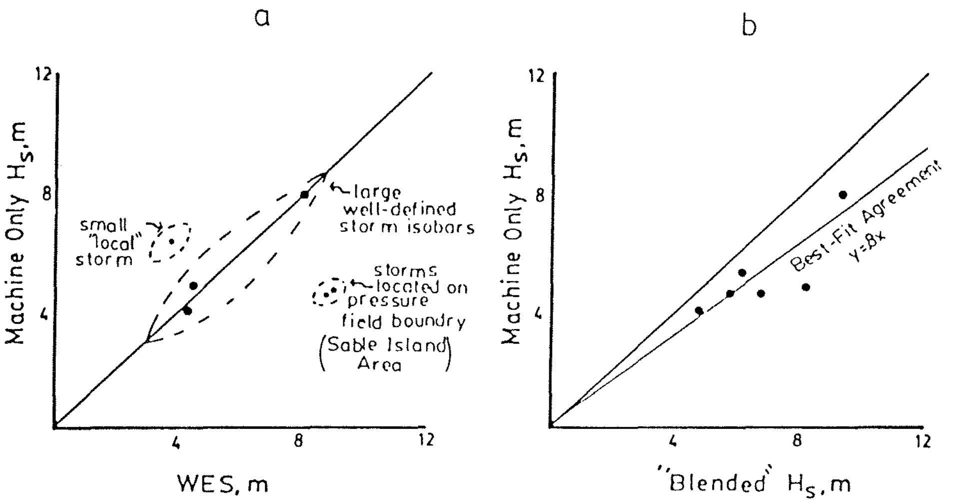


Figure 23. Comparison of peak significant wave heights hindcast by a) WES and machine only method employed in this study and b) machine only and blended approach used in this study.

Pressure fields obtained in the present study apparently were able to resolve pressure gradients in more detail; consequently, the machine-only hindcasts from this study predicted higher waves than the WES study by almost a factor of two. It should be recalled that hindcasts still underpredicted the measured peak wave conditions so there is a strong implication that the WES hindcasts missed some significant features in the pressure fields during this storm. The storms during December 1973 and March 1974 both were significantly overpredicted in the WES hindcasts. This overprediction was not duplicated in the present study; therefore, it is not believed that the overprediction is a property of the pressure-to-wind conversion procedure. Since both of these storms followed similar tracks, it would appear that the method of overlaying two independent pressure fields used in the WES study is capable of creating artificially high pressure gradients in the vicinity of the border of the overlaid region.

Figure 23 shows a clear, consistent tendency for machine-only hindcasts to be lower than those based on kinematically analyzed winds. Several factors such as meso-scale enhancement of winds near fronts, confluence of winds spiraling toward a low-pressure center, and inertial forces probably contribute to this apparent underprediction of winds near the peak of a storm. It is also possible that, since there are typically few observations in the immediate vicinity of the storm center during an intense storm, there can be some inherent underestimation of the storm development in this area. From the regression line in Figure 23 and the knowledge that wave height is approximately linear with respect to wind speed during intervals of active growth, it could be hypothesized that the non-equilibrium contributions to the peak winds amount to about 20% of the total wind speed.

During the course of this investigation several approaches were employed to obtain machine-only wind fields. First, a neutral baratropic wind model was considered and run for all six selected time intervals.

Next, a diabatic barotropic model was run, and finally, a diabatic baroclinic model was run for all cases. Information on the air-sea temperature difference and horizontal temperature gradients were taken from available ships' observations. In all of these storms, the winds did not vary by over 20% due to the inclusion of the baroclinicity term. Typically, this variation was restricted to a region near the fronts within the storms. Since these frontal areas also tend to be areas in which the "quasi-equilibrium" assumption of the wind model is most often violated, it is not clear that any real additonal accuracy is gained in incorporating baroclinicity into the model. If input temperature fields are available and one is confident that the information is accurate then, for completeness, baroclinicity should be included into the wind model; however, this information is typically quite difficult to obtain in a hindcast mode. Since the emphasis in the hindcast mode is moving more toward a kinematic analysis in complex meteorological situations, it is probably better to concentrate this effort on the kinematic analysis rather than into reconstructions of past temperature fields. In the forecast mode, the temperature fields are a normal part of the forecast information. In this case, since a kinematic analysis is impossible in a forecast mode, baroclinicity should be included for its additional information content pertaining to the winds.

The inclusion of stability effects through consideration of air-sea temperature differences can make a large difference in estimated wind speeds over substantial portions of the total hindcast area. In particular, the change in estimated surface winds under the assumption of neutral stability and under slight unstable conditions can be quite striking. It is very import to distinguish between stable and unstable conditions. It is less import to specify the exact magnitude of the stability terms. In the machine-only hindcasts shown in Figures 15-20, a standard value of -2.0°C for the air-sea temperature difference was used. This does not seem to have had too adverse of an effect on the hindcast results. Moreover, it is improbable that changing the air-sea temperature difference by even 2 or 3 degrees would make that much additional difference. As can be seen in Figure 24, most of the adjustment of the surface wind speed to air-sea temperature difference occurs in the ±2° band around neutral stability. Only in a two or three month period during the summer will stable conditions be important during major storms. Consequently, there is little to be gained by extensive analyses of air-sea temperature difference; particularly if kinematic analyses are used to supplement the machine-only analyses. However, if such information is readily available, such is the case of winds prepared in the forecast mode, then it should be included in the treatment of the winds.

4.2 Comments on the Wave Model

The six events hindcast in this study present complex sequences of time varying spatial patterns of wind speeds and directions. The waves modeled here include generation in frontal areas with extreme wind shifts as well as those generated in fetch-limited and duration-limited conditions. They also include periods of wave decay after peak storm conditions have passed. Consequently, it is believed that these test hindcasts represent an excellent series of real-world comparisons of this wave model. From the overall comparisons and, in particular the comparisons involving peak wave heights, it can be concluded that, when accurate wind fields are input into the wave model used here, reliable wave heights can be obtained for design applications.

One possible inconsistency between hindcast and measured wave heights was detected in this study. In almost all cases, there is a tendency for the hindcast waves to be higher than the measured wave heights during the period following the storm peak. The slopes of wave height decay through time for the hindcast waves are similar to

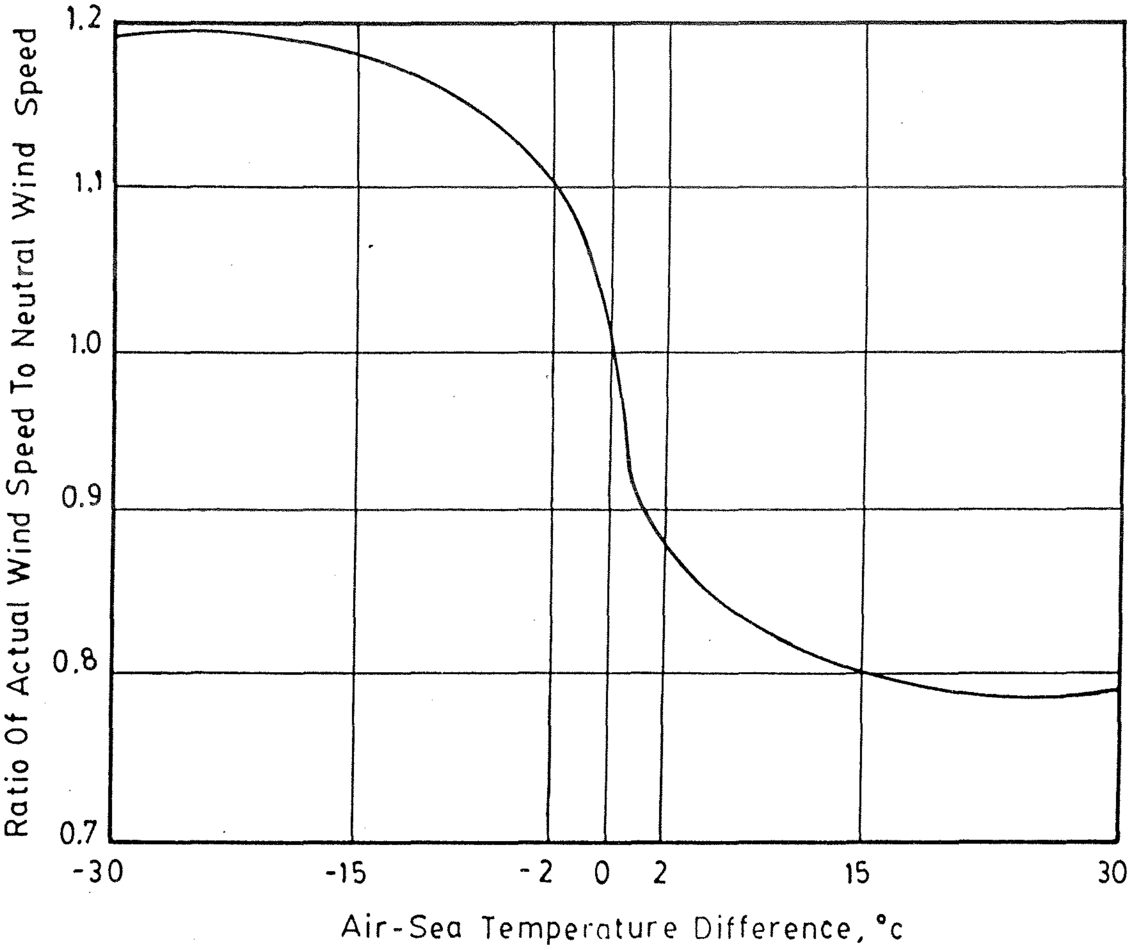


Figure 24. Behavior of the ratio of surface wind speed predicted from a diabatic PBL model to a neutral PBL model and a function of air-sea temperature difference.

those measured; however, there appears to be a consistent lag in the hindcast waves. This suggest that there is possibly insufficient decay in the period immediately following the peak wave height and then later the decay rate is adequate. Since wave decay involves both local decay mechanisms as well as propagation out of an area, it is difficult to isolate a single factor which is implicated by this interpretation.

4.3 Wave Model Grid Considerations

One of the more important questions to be answered in this investigation concerns the ability of the wave model grid to resolve important features in the wave field. Two factors must be considered in answering this question. First, what scale is necessary to resolve features in the wind fields appropriate for wave generation? Second, what scale is necessary to resolve the fetch-limiting and sheltering effects of land masses? In answering the first question it must be noted that the resolution of synoptic-scale wind motions is somewhat restricted by the scale of observations stations in marine areas. From viewing the weather maps included in Appendix B and the corresponding wave measurements in Figure 8-13, it can be ascertained that most of the important wind field features can be resolved on a spacing of 2° to 2½° latitude (approximately 222 to 277 km). The 2½° spacing was used in the model runs shown in Figure 15-20 and there does not seem to have been any significant degradation in the results. On the other hand, the resolution of coastal features becomes increasingly important as one moves progressively closer to the coast. Rather than bias the entire hindcast area (which may cover most of the Atlantic Ocean) toward resolving coastal gradients, it may be more appropriate to adopt a multiple-phase approach as was done in the complete WES study. Each phase can then be specifically tailored toward resolving its own significant scales. As an interim measure, points inside of the first water grid point can be taken as equal to the grid point values for waves not fetch-limited and as an interpolated function of the grid point value for fetch limited wave conditions.

Because of the avoidance of serious ice conditions, there is a dearth of good wave observations which can be analyzed for effects of the moving ice limit on wave generation. However, it is quite certain that there are some important effects in the area north of 55° N latitude. The changing fetches throughout the seasons most likely play an inportant role in modifying the wave heights accordingly. The role of ice drifts in filtering wave energy and in reducing the total momentum transferred from the wind into the wave field should probably be considered in a fashion which considers factors such as percentage ice cover, rather than the procedure adopted here which treats the ice cover as either total or zero. This may not be important to more southerly sites, but could become quite important in areas near the ice edge.

4.4 Consideration of Shallow Water Effects

As a final comment on the treatment of wave generation in the Scotian Shelf, Labrador Sea and Grand Banks areas, it needs to be mentioned that shallow-water effects may be important near some sites, particularly those in the Grand Banks Area. Recent research and field experiments have suggested that there can be a significant reduction in wave heights from deep-water values even in intermediate depths. Many of these findings have not at all been consistent with the use of a fixed bottom friction coefficient to model energy losses in shallow water. Additional research will be needed to verify the magnitudes of this energy loss and to establish the exact physical mechanisms responsible for the energy loss. However, at some stage it will be advisable to include their effects into the hindcasts. Since there were no shallow-water effects included in this study and yet the overall comparisons appear quite good, the areas considered here do not seem to be affected much by shallow-water effects.

5. CONCLUSIONS AND RECOMMENDATIONS

Recommendations here will address the two separate aspects of this investigation, a critique of the applicability of the WES hindcasts and an analysis of potentials methods of alleviating any problems, which were found in the WES hindcasts, in future hindcasts.

5.1 Recommendations Concerning the WES Hindcasts.

As discussed previously the "machine-only" approach produces results which compare very well to measured waves except possibly during the peaks of the storm; consequently, the operational wave climate from the WES study is probably adequate for most purposes.

In terms of the extreme waves in the WES hindcasts, results for the Scotian Shelf area should probably not be used due to the possibility of problems introduced by the pressure grid specification in that study. In other areas, the WES hindcasts seem to avoid major discrepencies with the measured waves. It is recommended, therefore, that the WES hindcasts be accepted as a reasonable first approximation to the the extreme wave climate in these areas. However, since design waves specifications can have enormous economic consequences, it is also recommended that a set of 20 to 30 of the largest storms be selected and have the wind fields re-analyzed using the method employed in this study. These storms should then be hindcast and the new results should form the basis of the design wave information for all Canadian Atlantic areas. It should be noted that this procedure is the same as that followed in the extremes analysis for waves along the U. S. East Coast in the WES hindcast study. In that study a set of the largest storms were re-analyzed and re-hindcast to obtain better extremal estimates.

5.2 Recommendations Concerning Future Hindcasts

From comparisons between the hindcast wave heights and using the man-machine mix and measured wave heights, it seems that, given good wind field information, reliable estimates of wave conditions can be obtained via the wave model described by Resio (1981). Since the storms modeled in this report cover a wide range of wave generation scales in time and space and include naturally occurring situations of strong wind shear near fronts, this indicates that the physics of the wave model and the numerical techniques used in solving the governing equations are capable of resolving the wave generation problem for most relevant synoptic-scale wind systems. Consequently; it is recommended that this wave model and combined method of obtaining wind fields be used in future hindcasts in regions of the Canadian Atlantic. The following additional recommendations are based on the findings of this study:

- Due to the strong possibility that there may be errors in the WES pressure fields it is not recommended that the winds or pressure fields from that study be used in future Canadian hindcasts.

- For hindcasts, a -2°C air-sea temperature difference used in the PBL model suffices to provide adequate winds from the machine-only portion of wind field reconstruction, provided that it is supplemented by winds obtained via kinematic analysis. In the forecast mode, since no kinematic analyses are possible, stability effects should be incorporated into the wind modeling.

- It is recommended that a 2½° (277 km) spacing be adopted for the deep-water hindcasts. Any near-coast effects can be factored into the waves during a post analysis or a multi-phase approach could be followed.

- A moving ice limit adaptation to the wave model should be incorporated into the present model. This is not difficult but should provide better wave estimates north of 55° N latitude at sites near the edge of the ice cover.
- Additional research should be considered in anticipation of shallow-water improvements to the wave model. In particular, design wave heights in some areas of the Grand Banks area might be significantly affected by depth effect.

6. REFERENCES

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APPENDIX A

A BRIEF DESCRIPTION OF KINEMATIC ANALYSIS

A BRIEF DESCRIPTION OF KINEMATIC ANALYSIS

This type of analysis is used to estimate surface wind flow patterns from available observations. Past studies have shown that certain flow patterns are expected for specific synoptic conditions. In general, these patterns depend on the location and interaction of cyclones and anticyclones, coupled with the orientation and gradient of the isobars in these systems. Typically divergence in the surface layers near the center of lows along with the frictional drag between moving air and the sea surface causes the wind to cross the isobars at an angle, spiraling into the low pressure areas and out of the high pressure areas in the surface layer of the winds. Thus, in almost all cases streamlines originate in the center of an anticyclone and follow curved paths toward the center of a cyclone.

The basic concept in performing a kinematic analysis is to fit the set of observations on a particular weather map into a preconceived flow pattern, according to fundamental meteorological principles. Continuity of flow in time and space, patterns of confluence and difluence, veering near fronts and flow patterns associated with cyclogenesis and storm movement are all integrated conceptually into a picture of estimated flow patterns from one weather map to the next. A sequence of maps then represents the evolution of a meteorological system, not just isolated sets of measurements. Consequently, additional information can be inferred on certain maps where data are sparse by time-wise interpolation. Also the development of consistent flow patterns can be recognized.

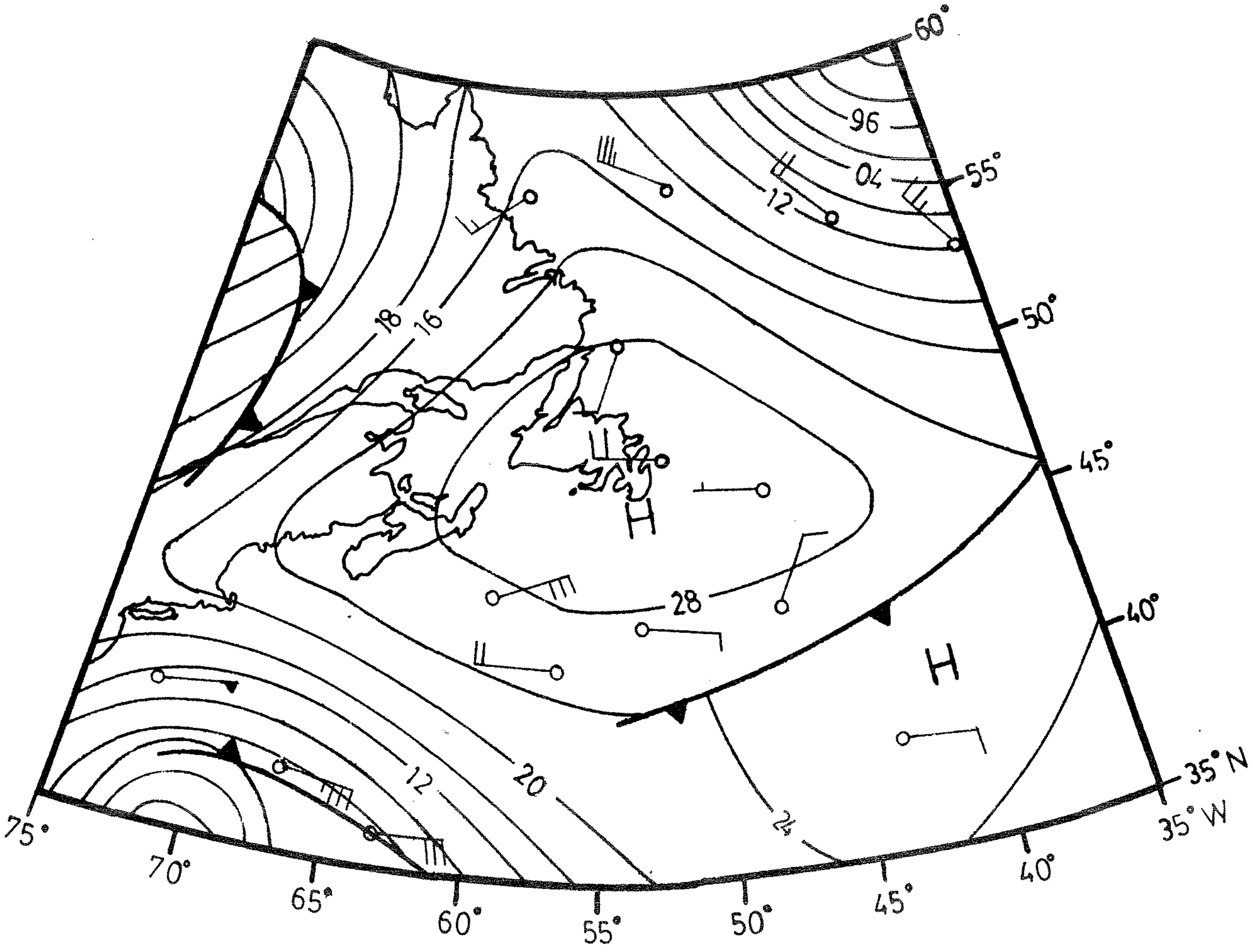
The basic techniques used in kinematic analysis rely on the construction of streamlines and isotachs to represent the wind field. First, streamlines are constructed from directional patterns of wind observations the isotachs are constructed in a manner consistent with the flow patterns resolved in the streamline analysis. The development of organized high-wind regions with storms can be reconstructed quite accurately using these tools along with the aforementioned meteorological principles. Thus, this overall method of analyzing wind fields is not at all equivalent to simply averaging wind observations into a theoretically derived wind field at spot locations.

APPENDIX B

WEATHER MAPS FOR 6 HINDCAST EVENTS

OCTOBER 26-30,1973
NOVEMBER 11-15,1973
DECEMBER 21-25, 1973
JANUARY 8-11,1974
MARCH 4-8,1974
APRIL 2-11,1974

OCTOBER 26-30, 1973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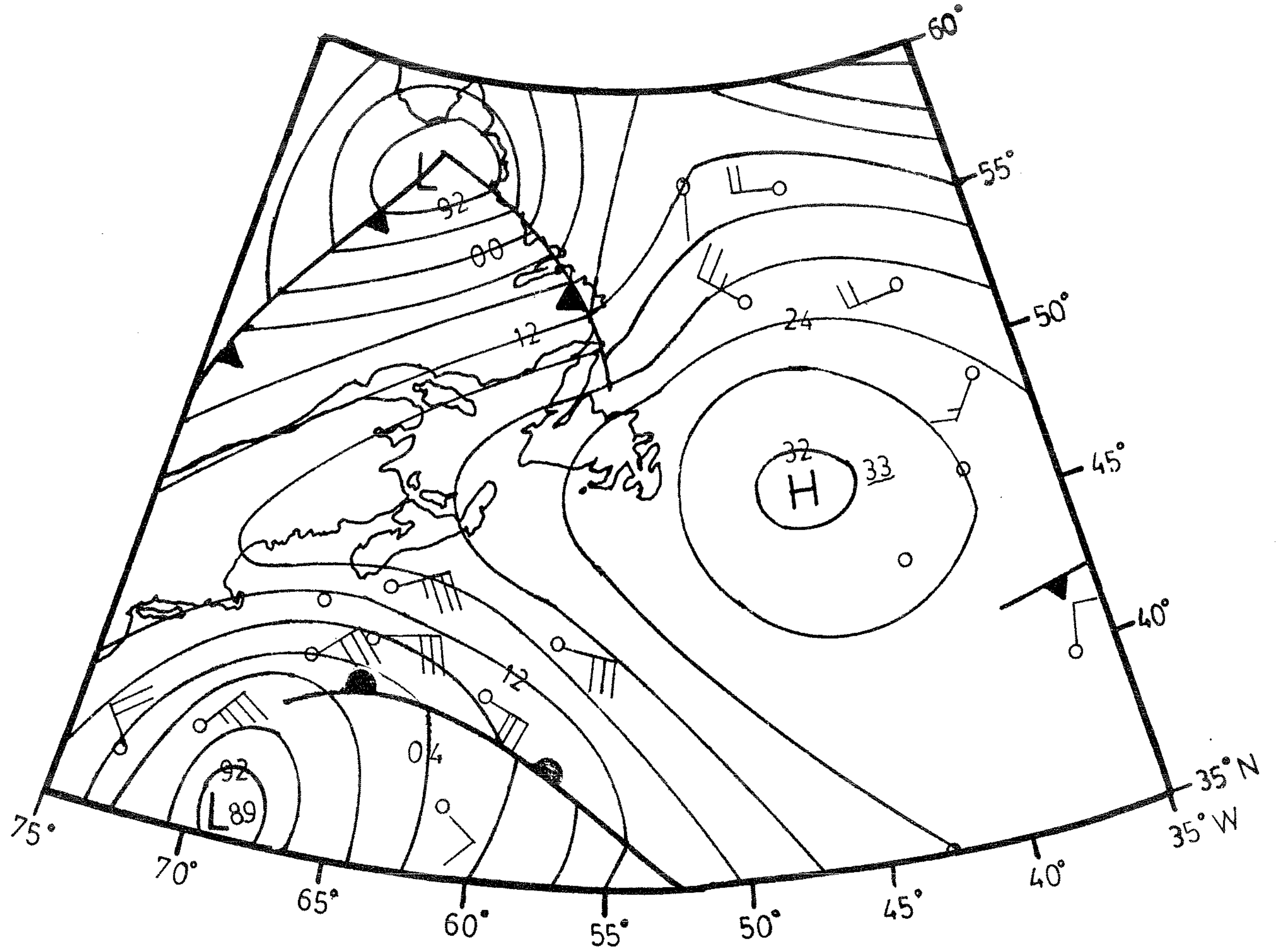

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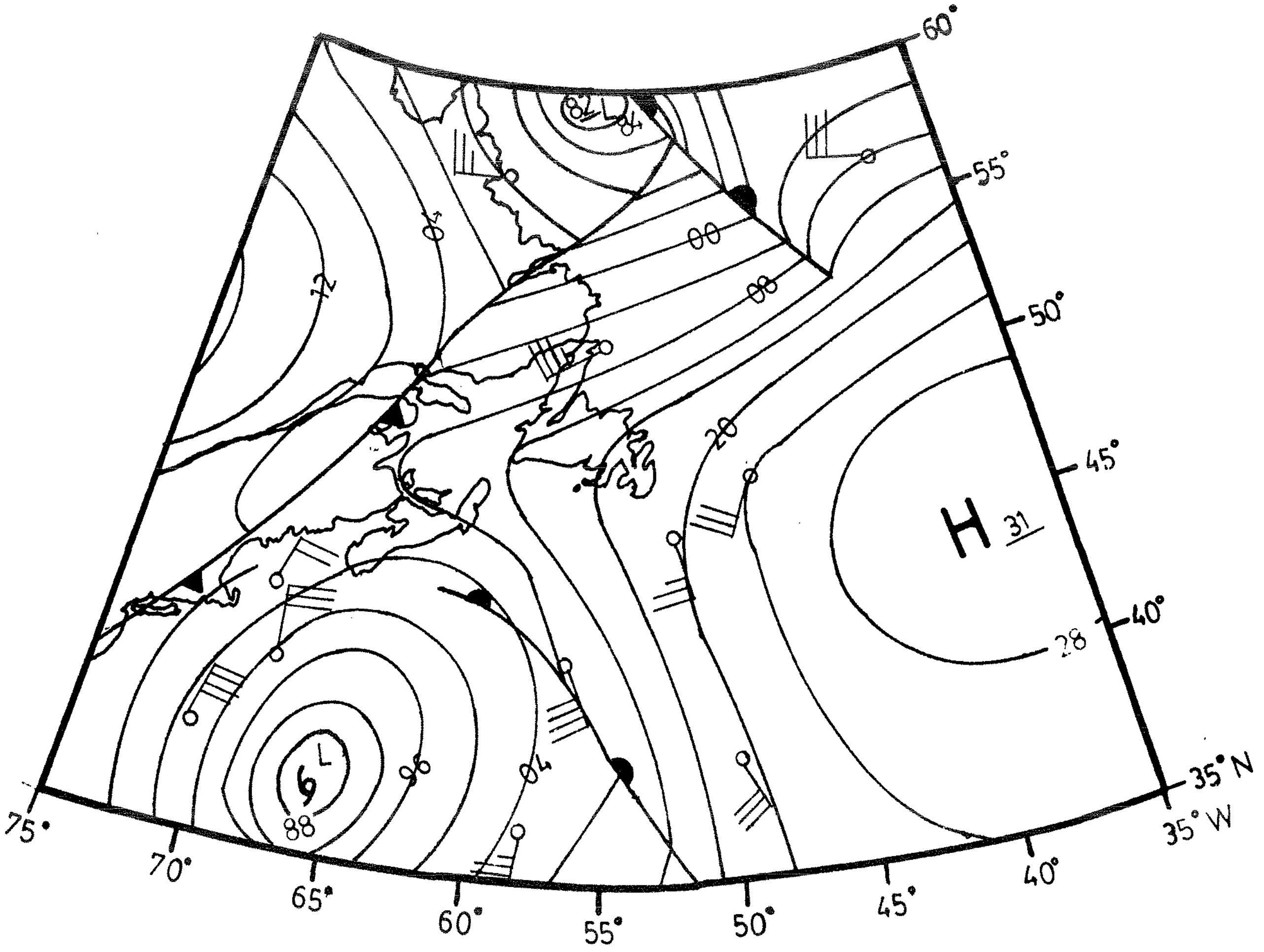

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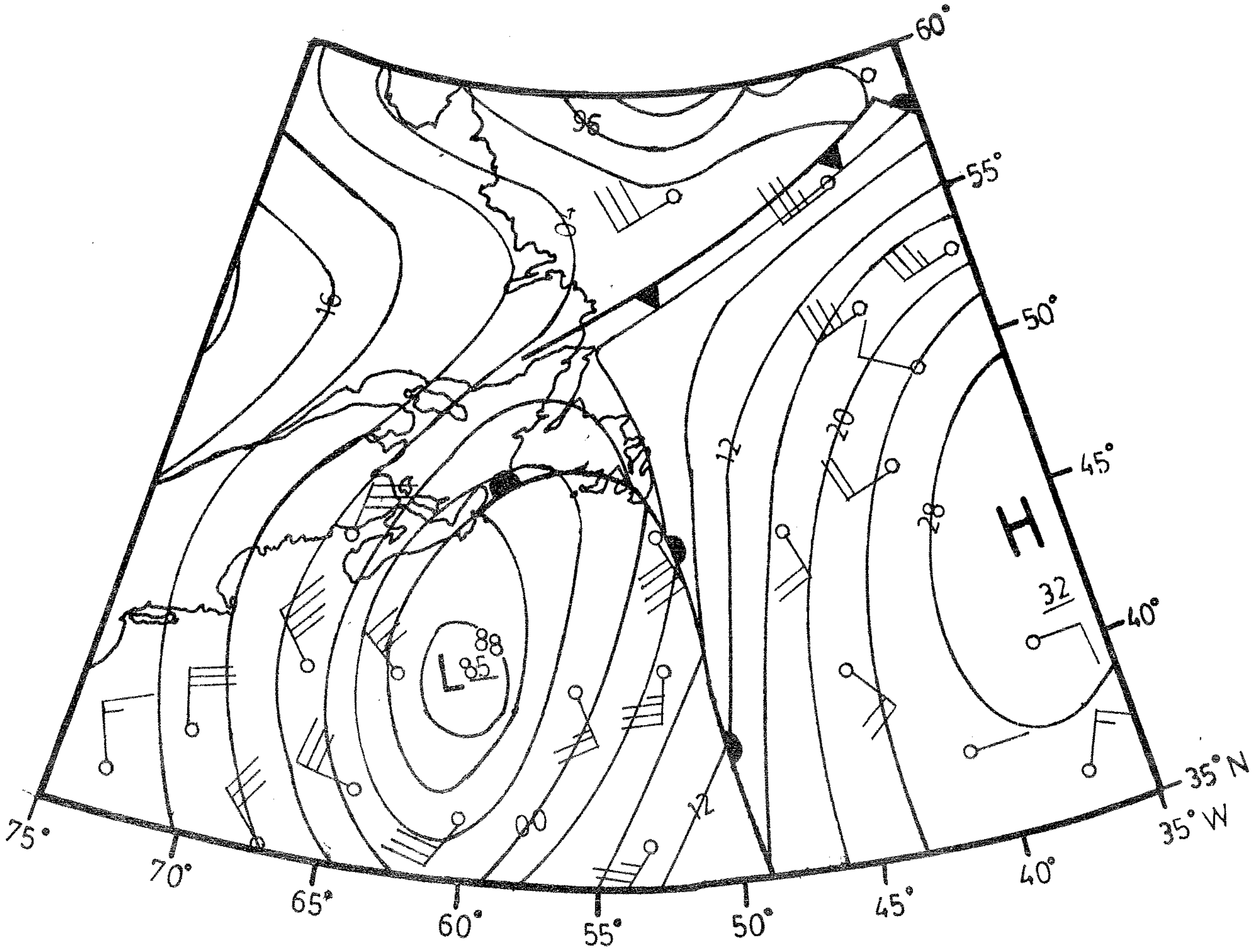
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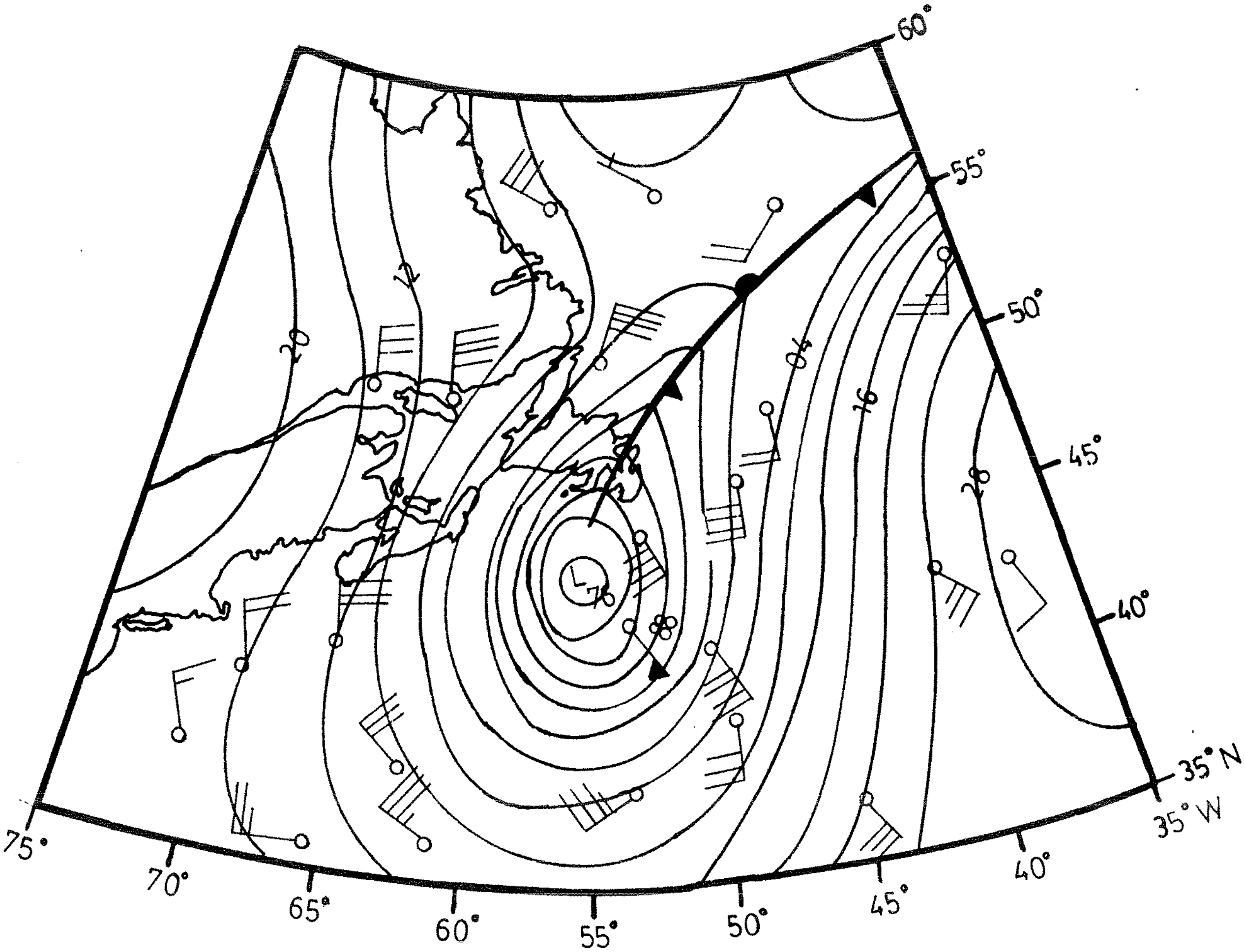

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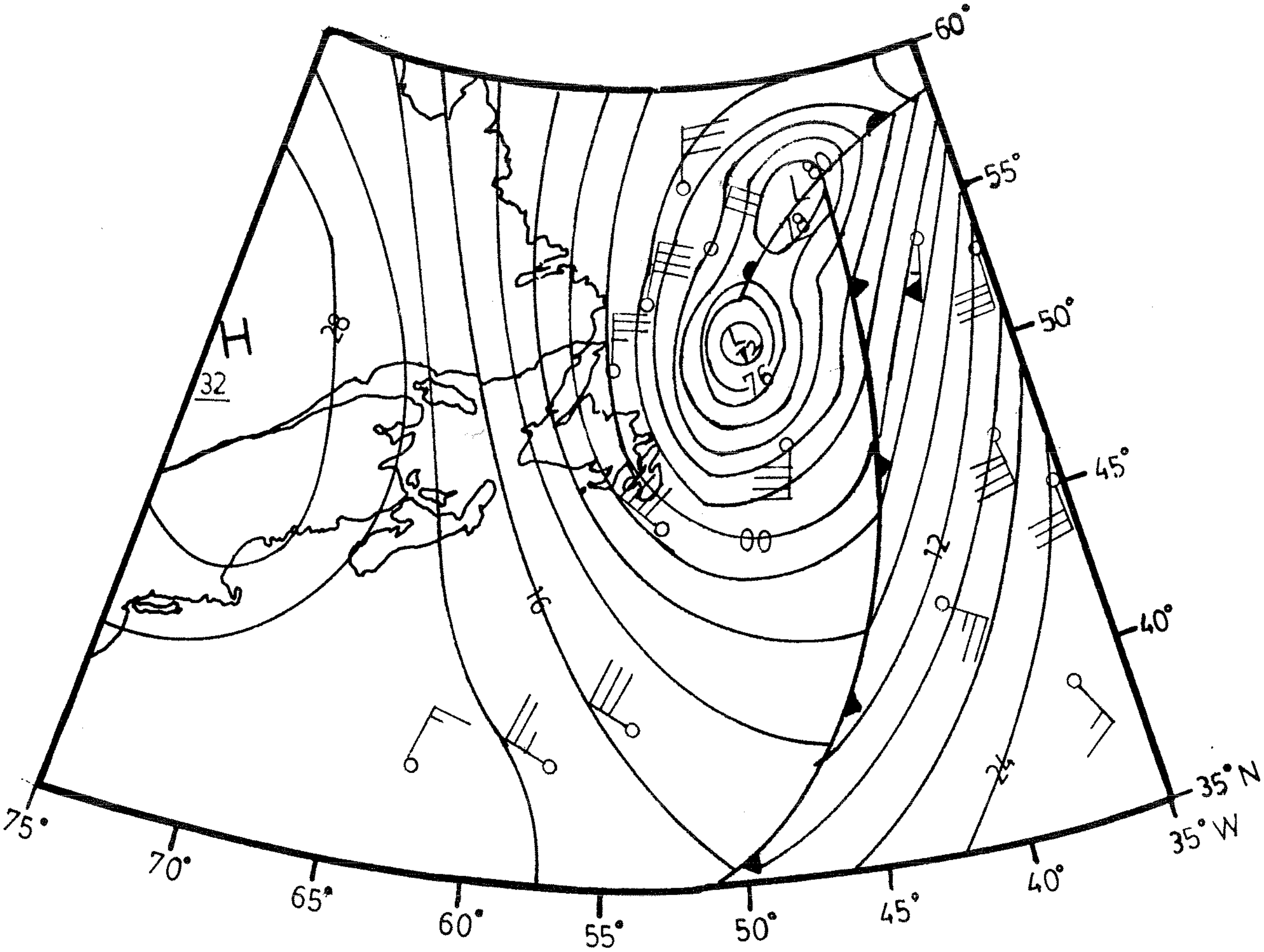
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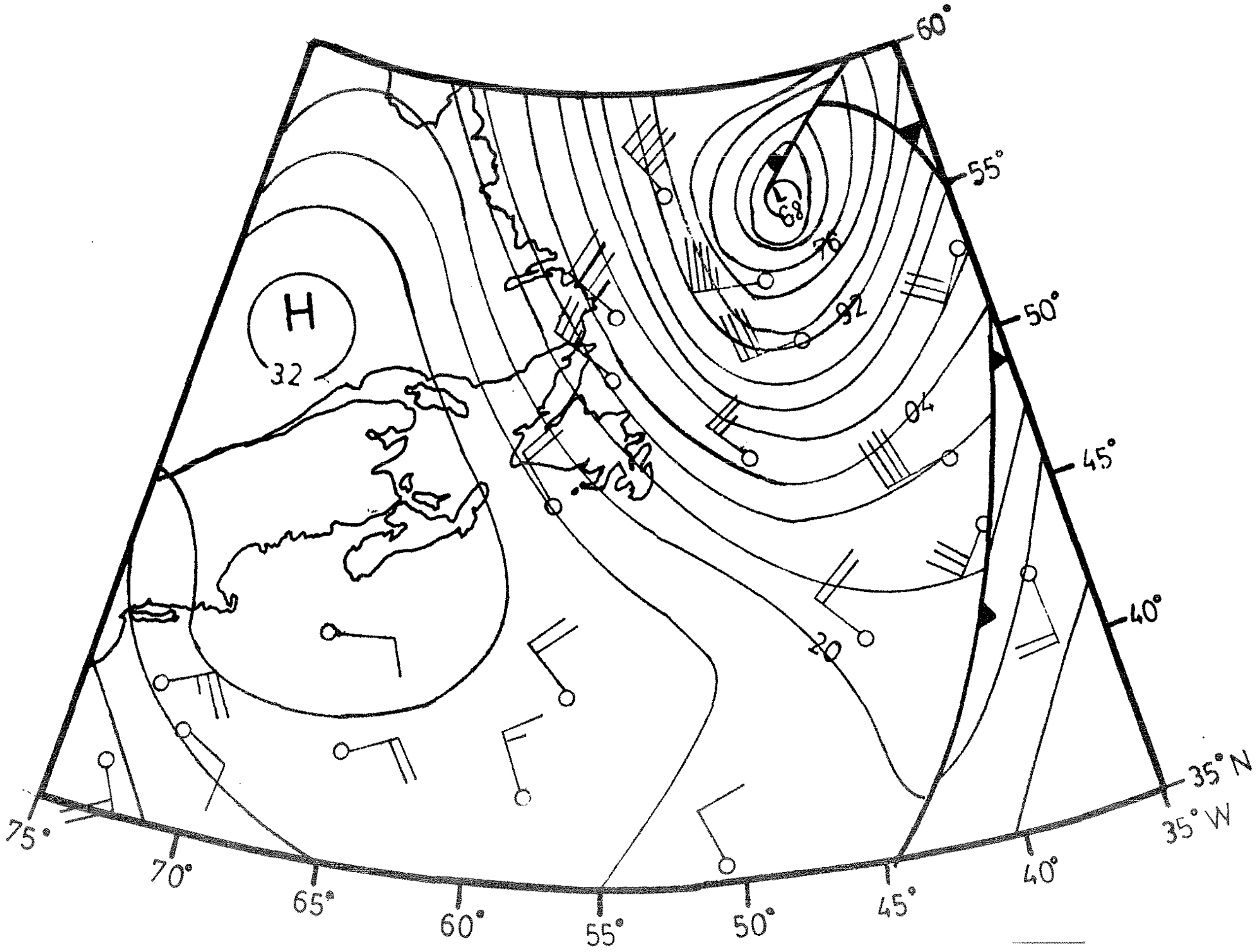

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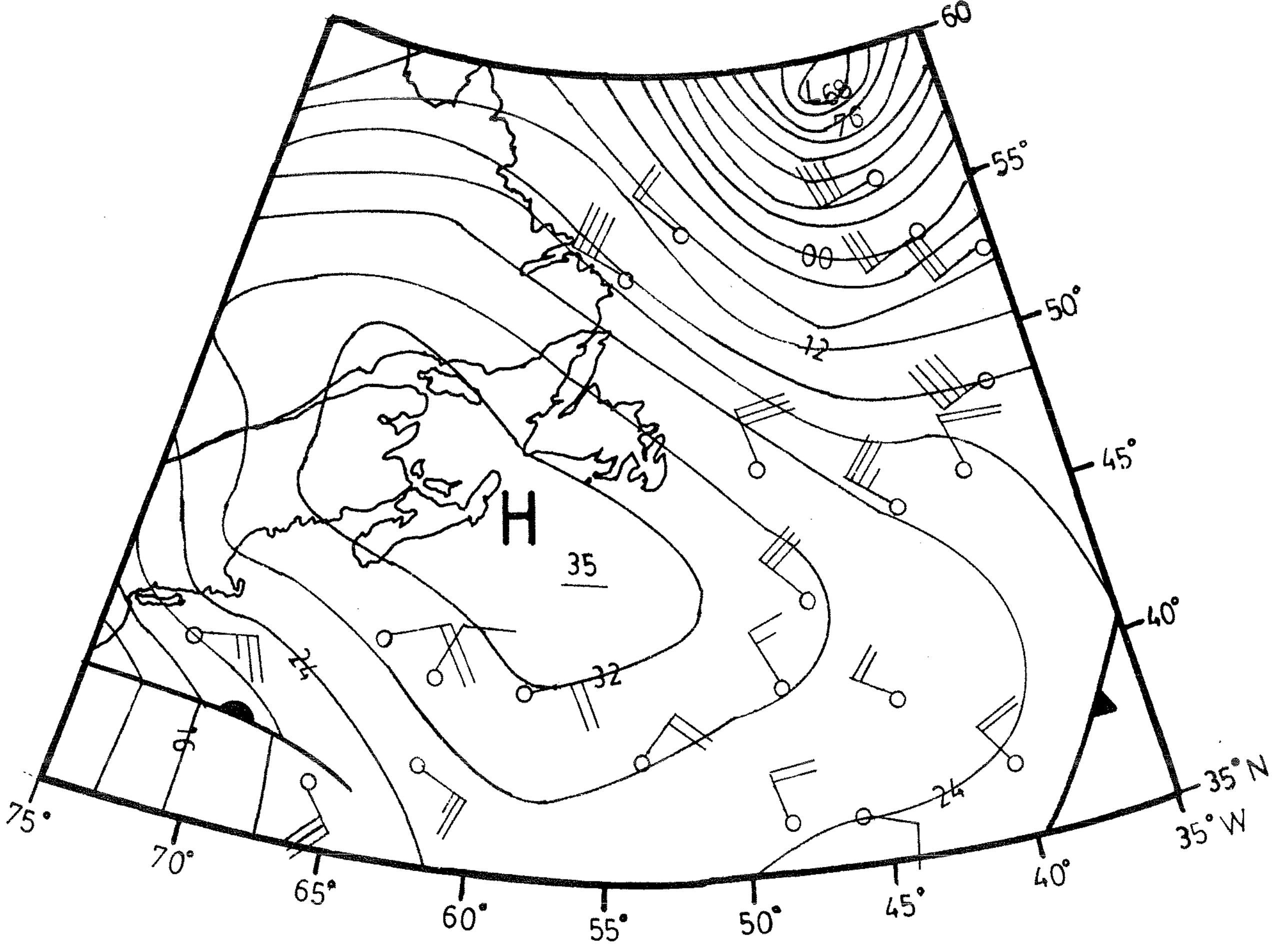
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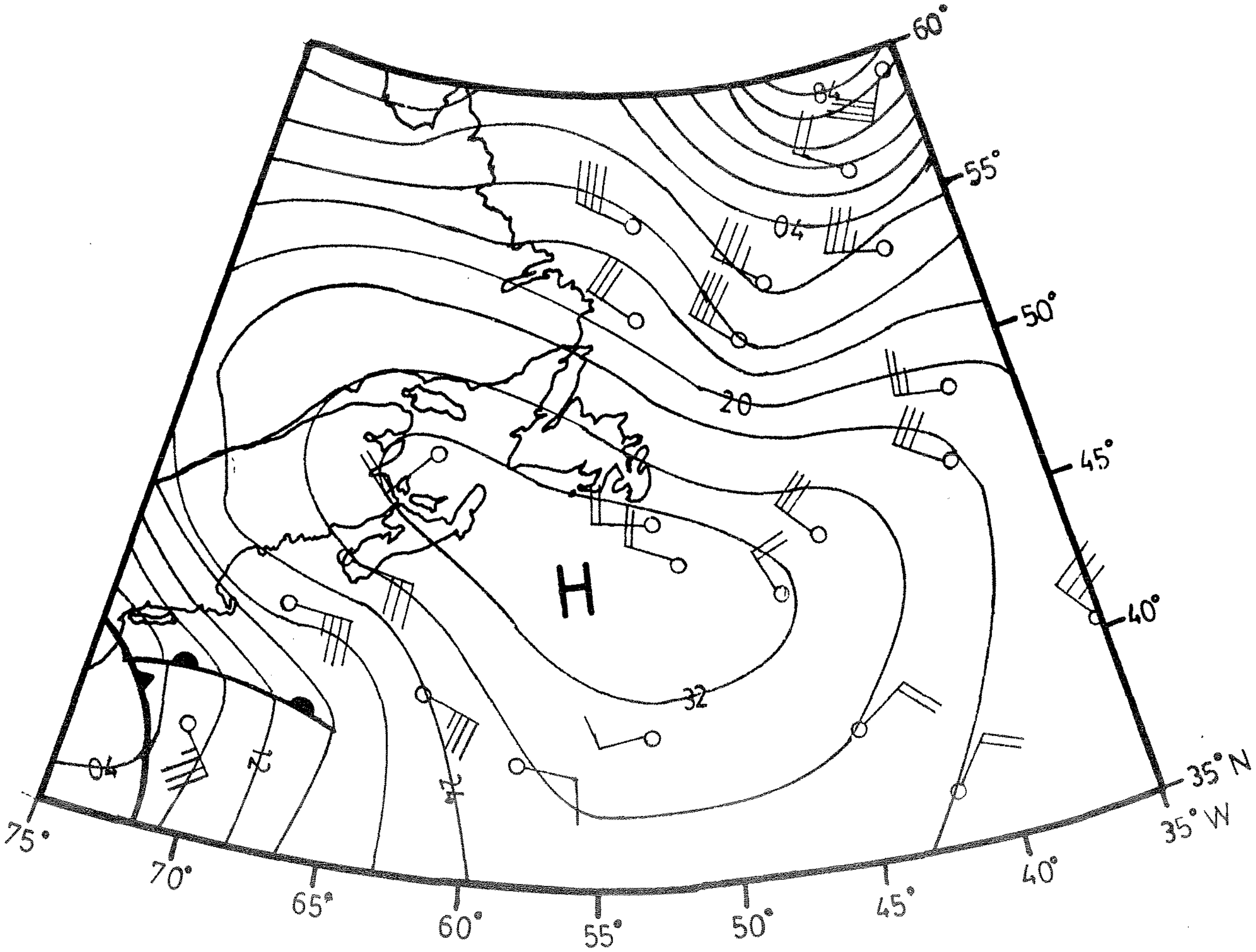

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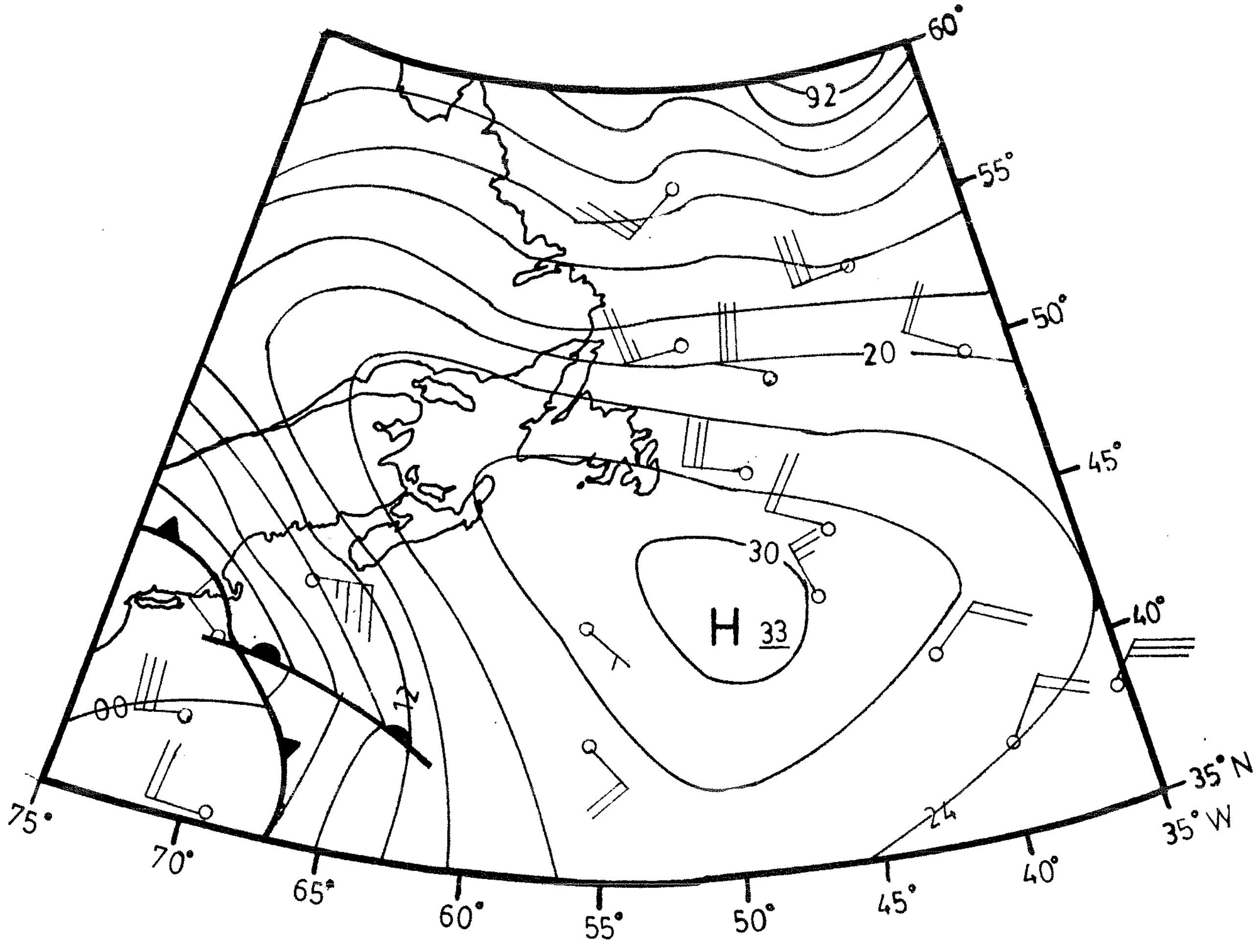

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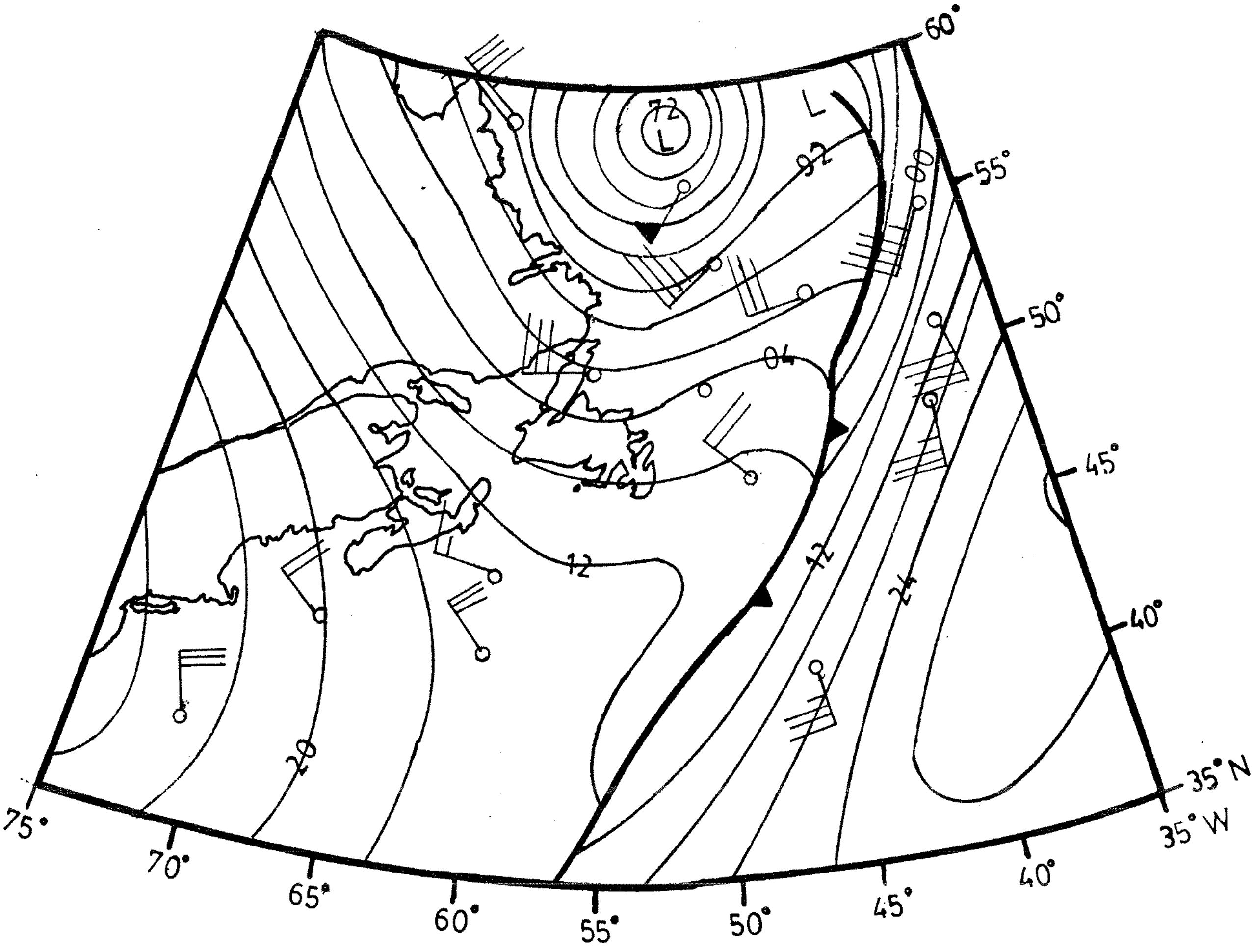
NOVEMBER 11-15, 1973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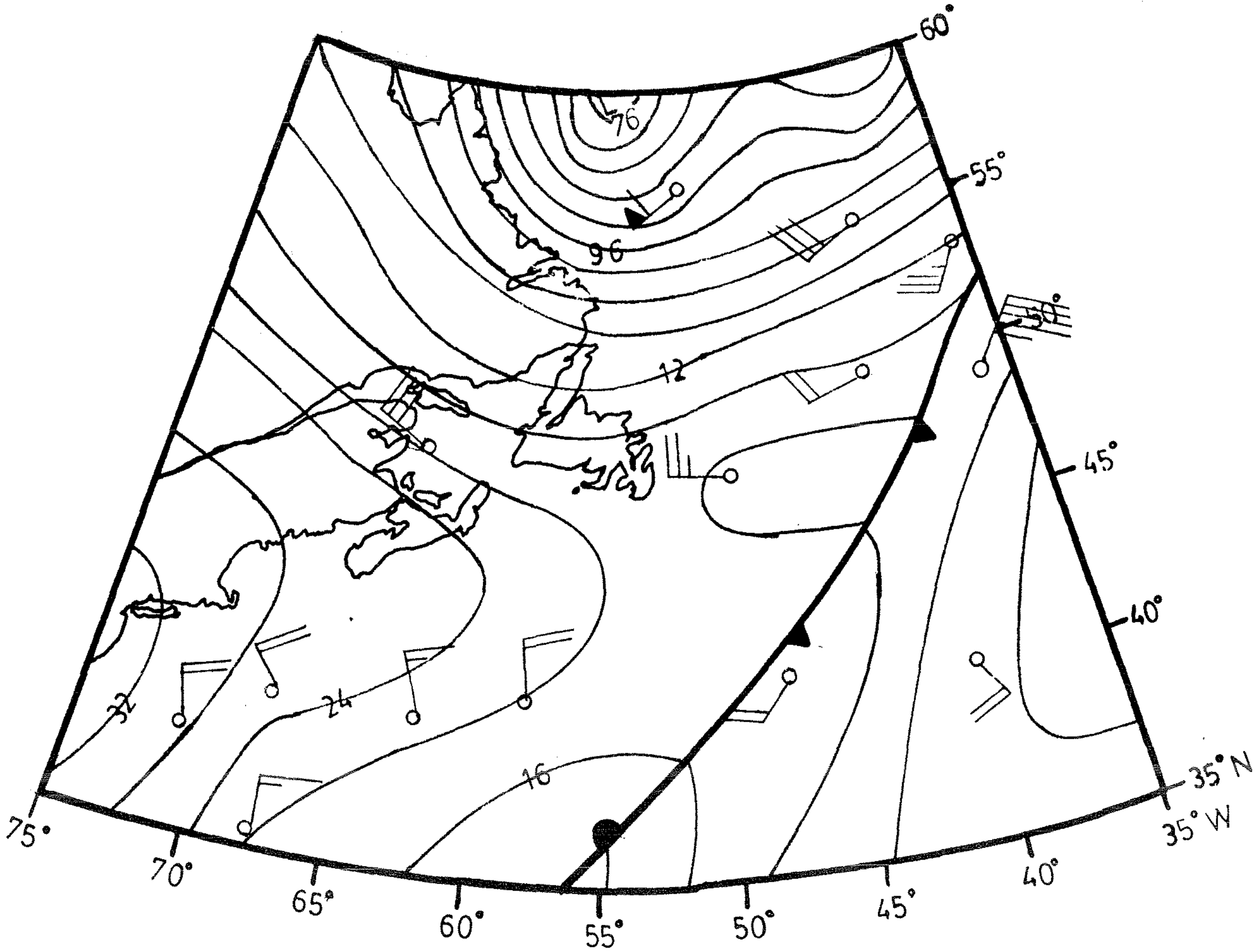

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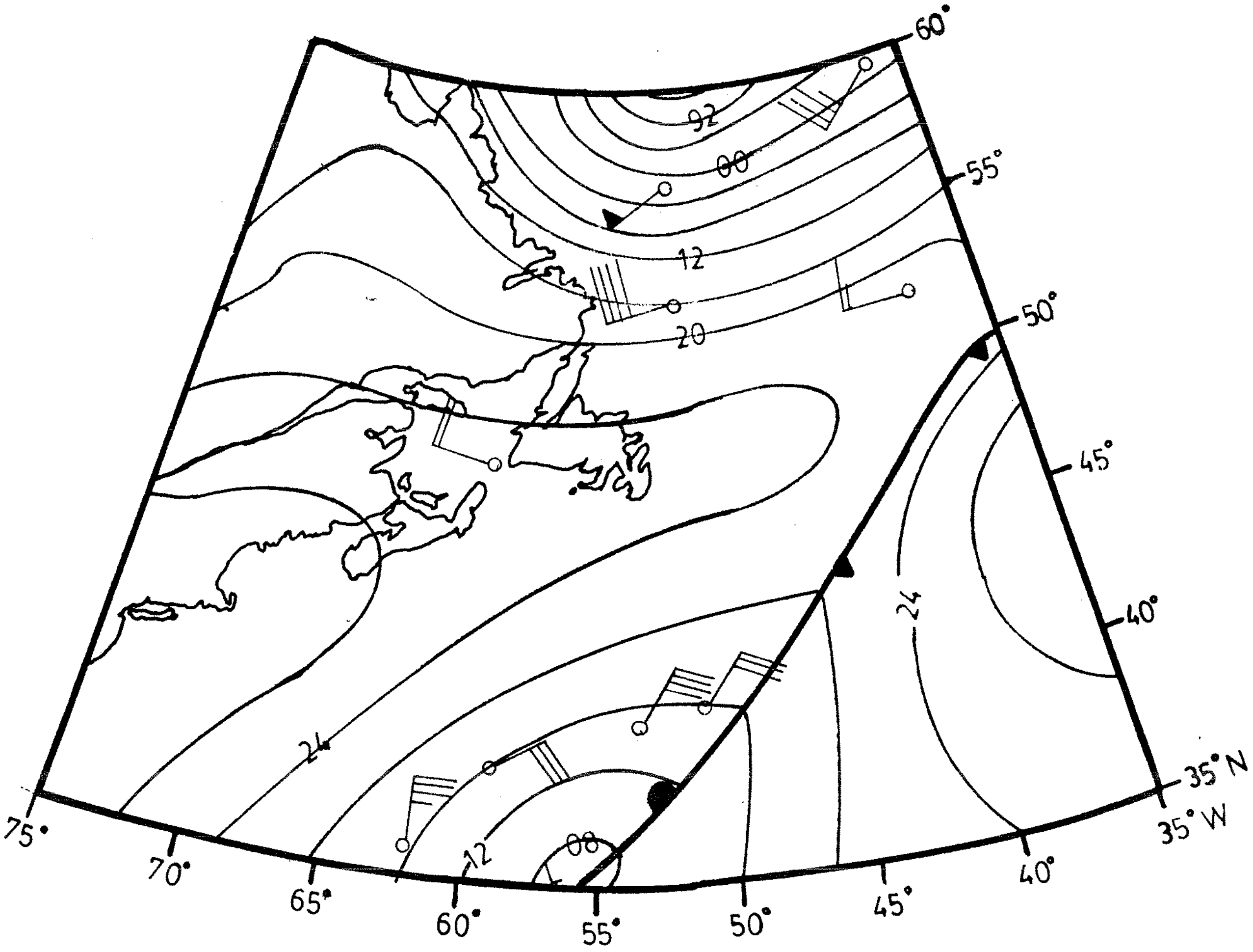

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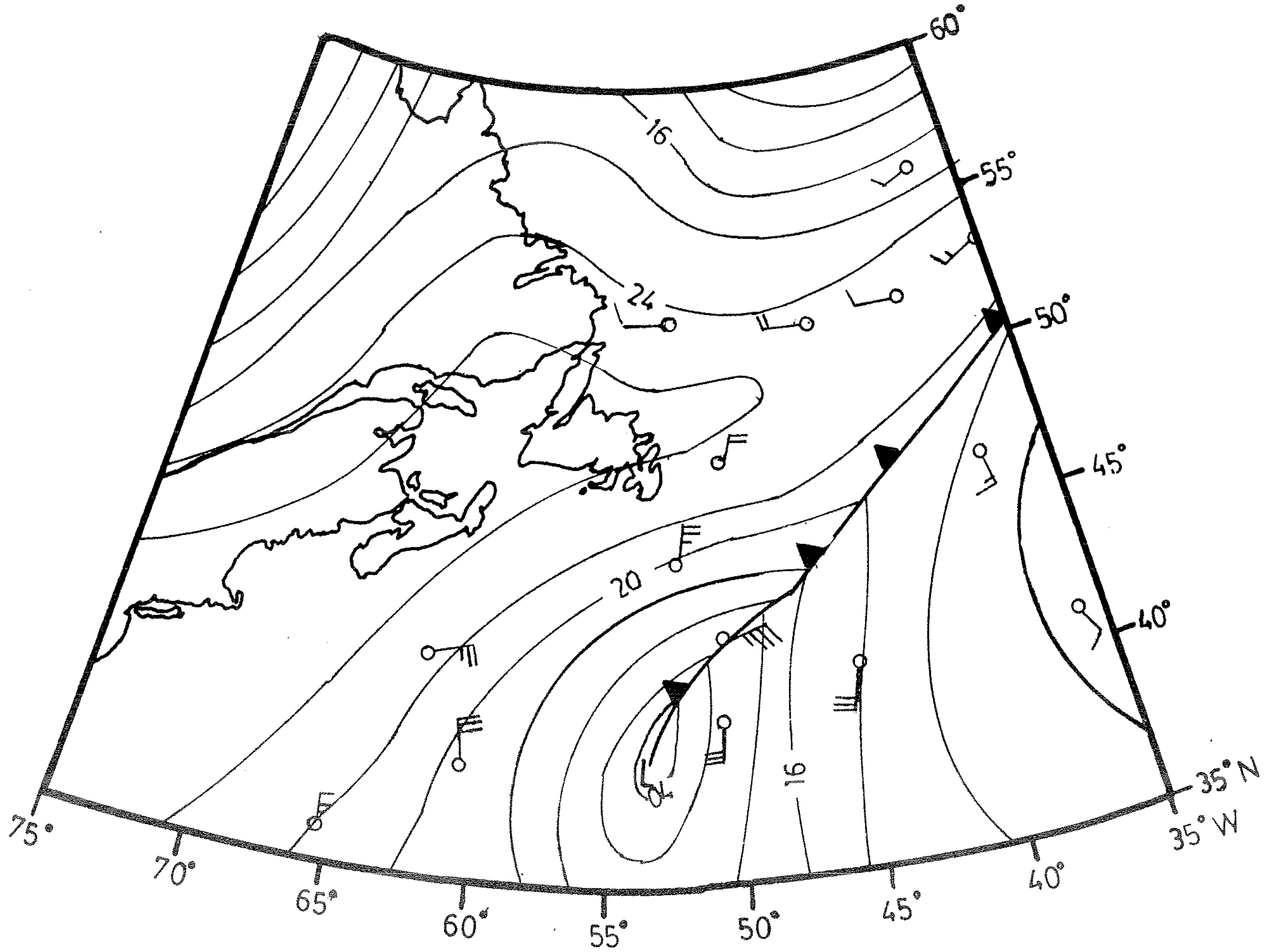

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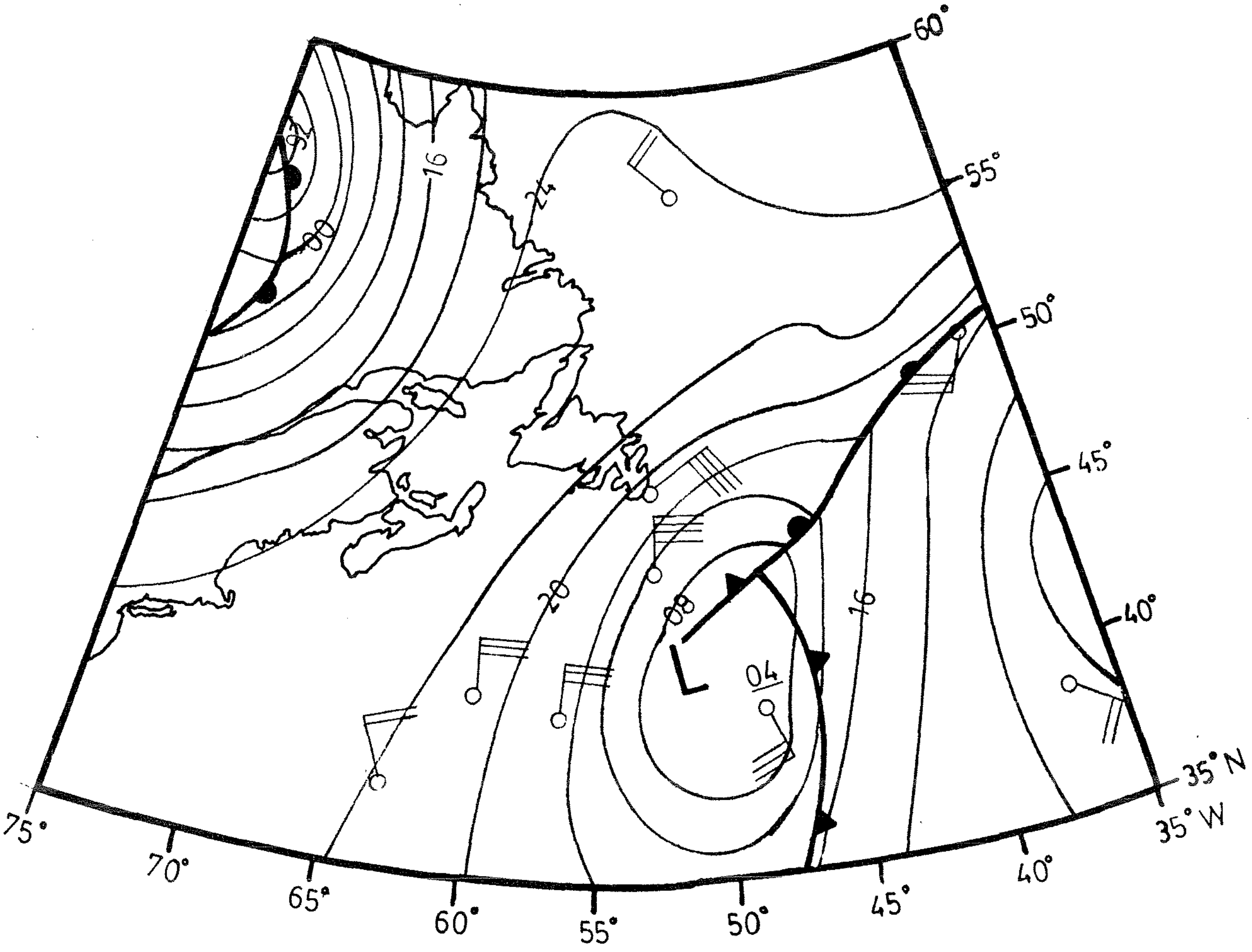

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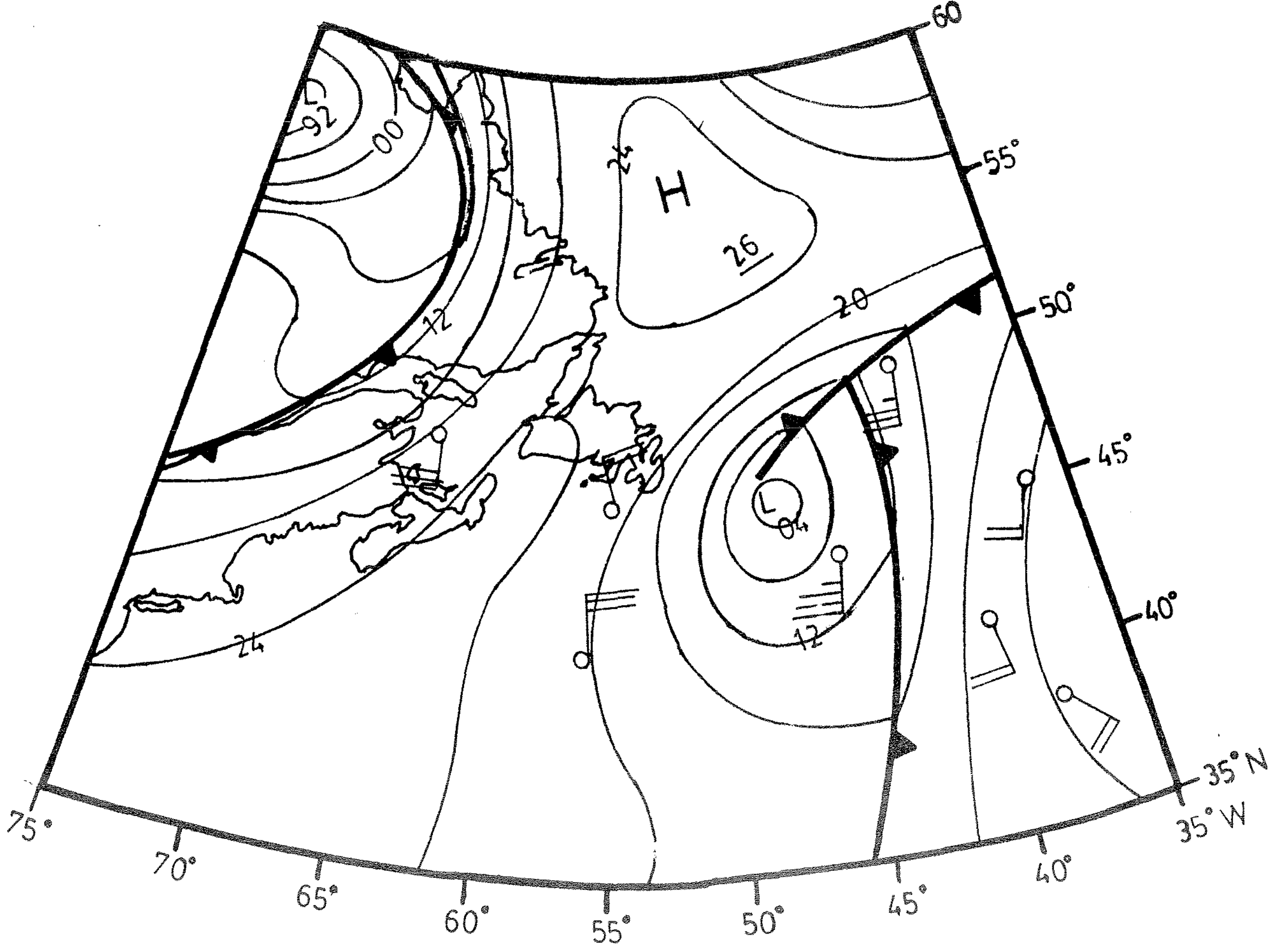
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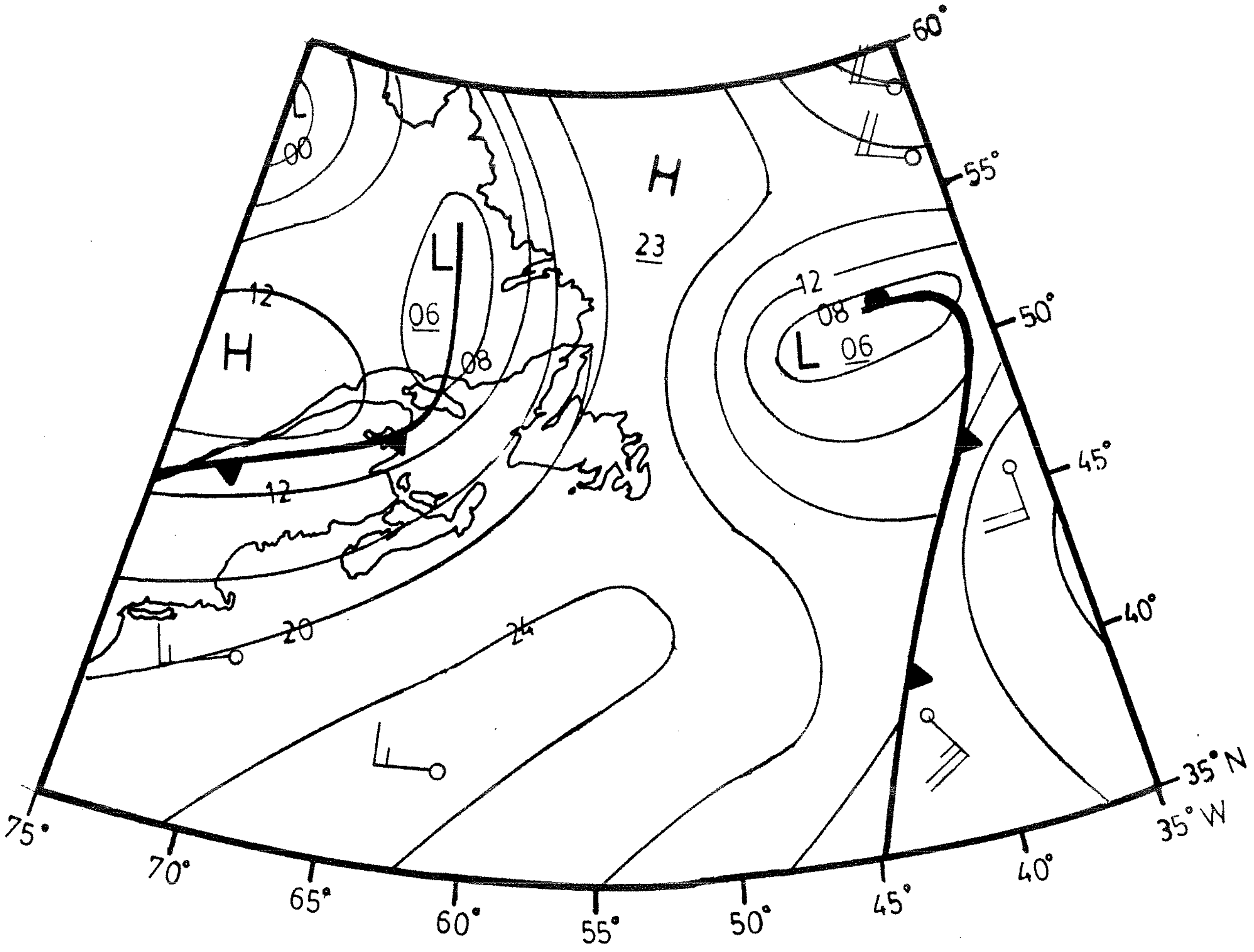
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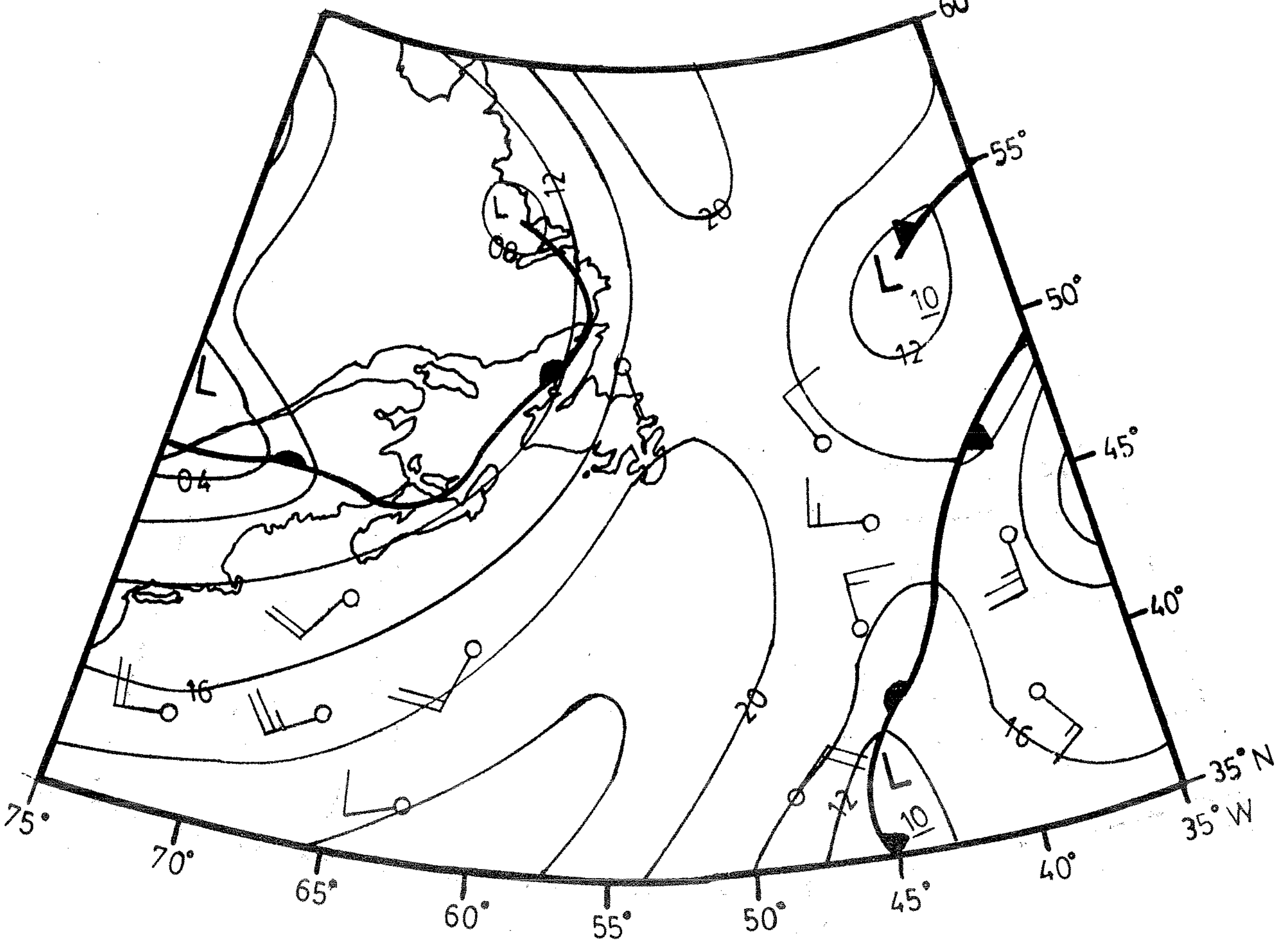
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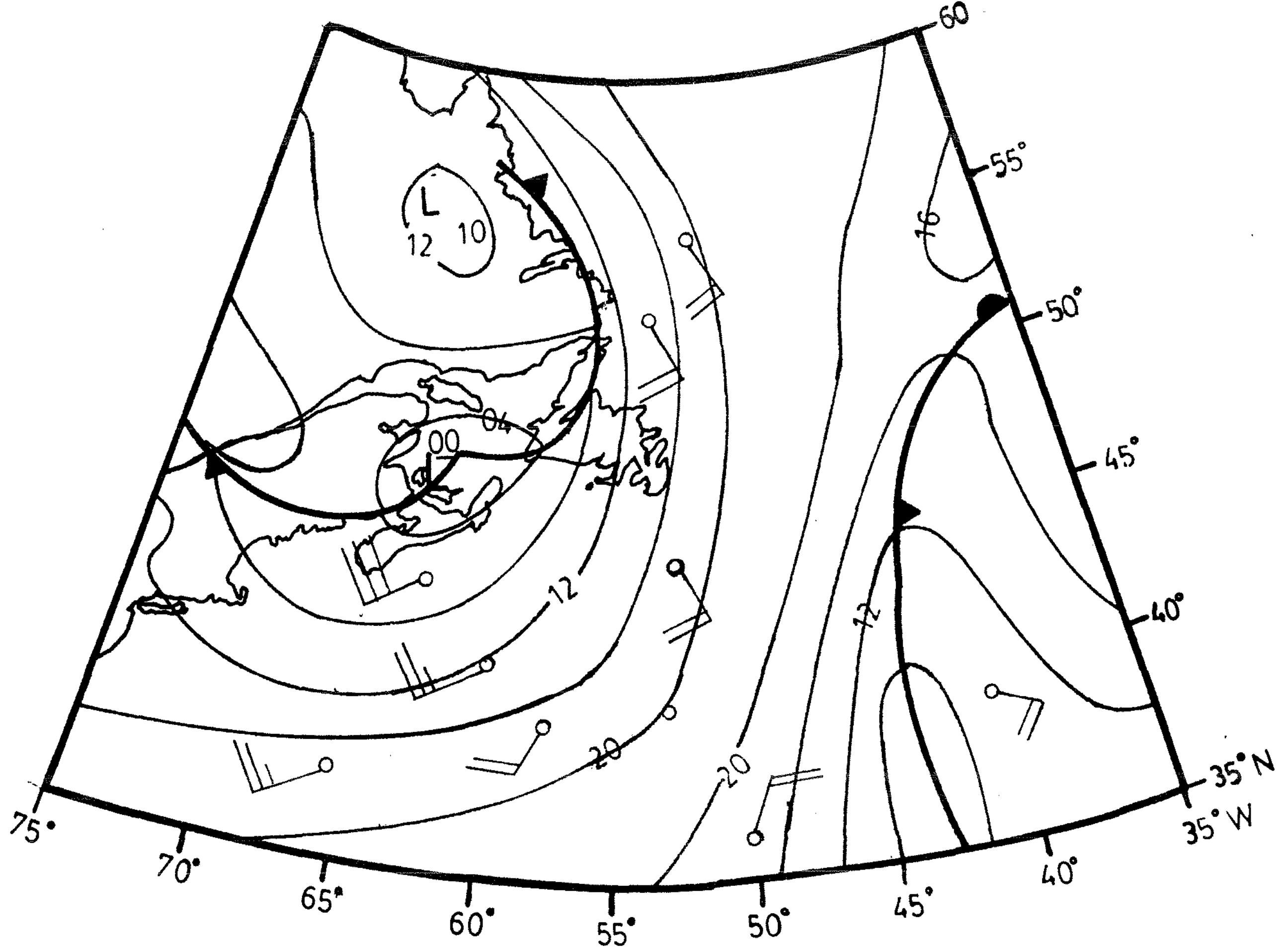
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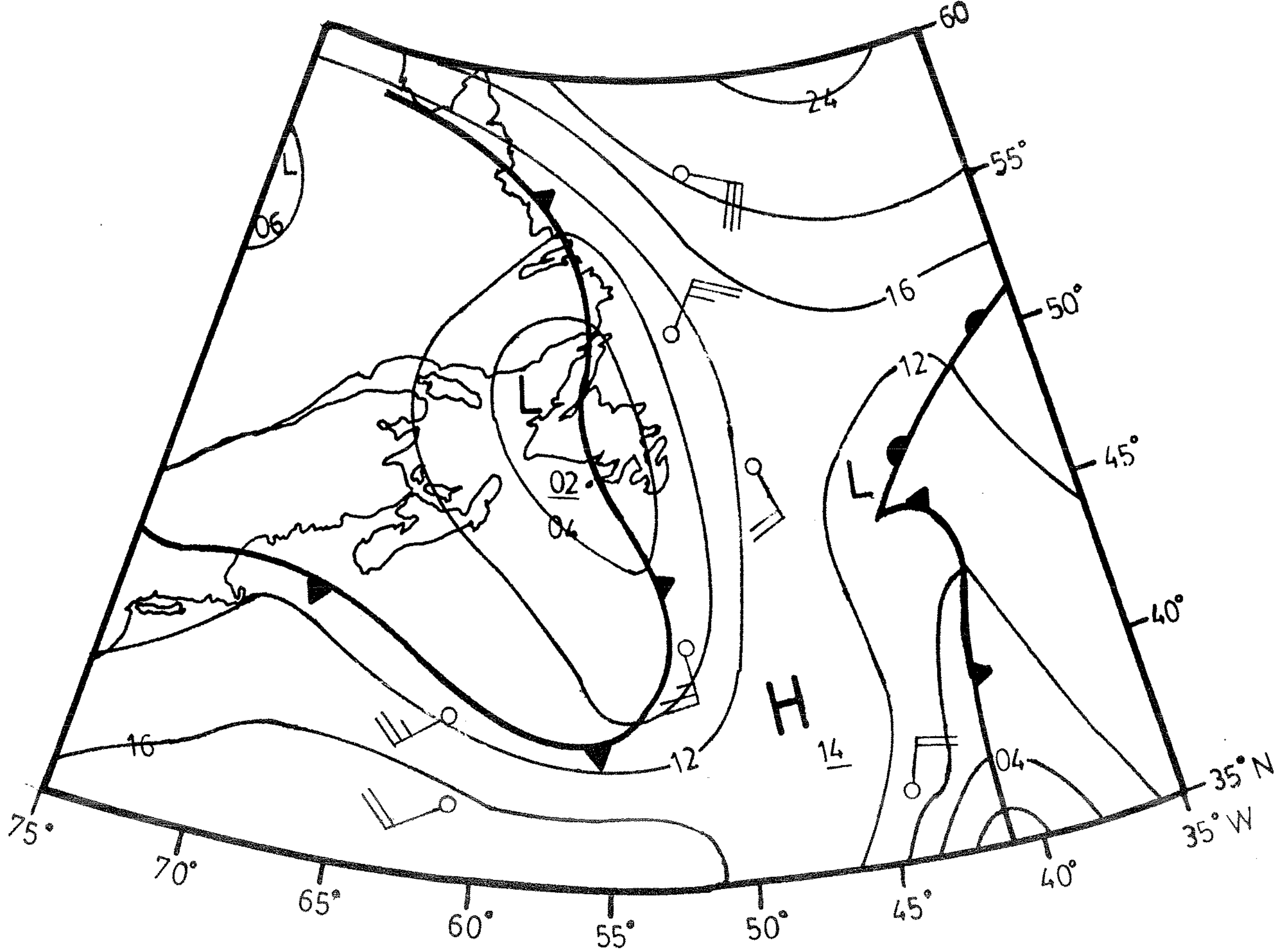
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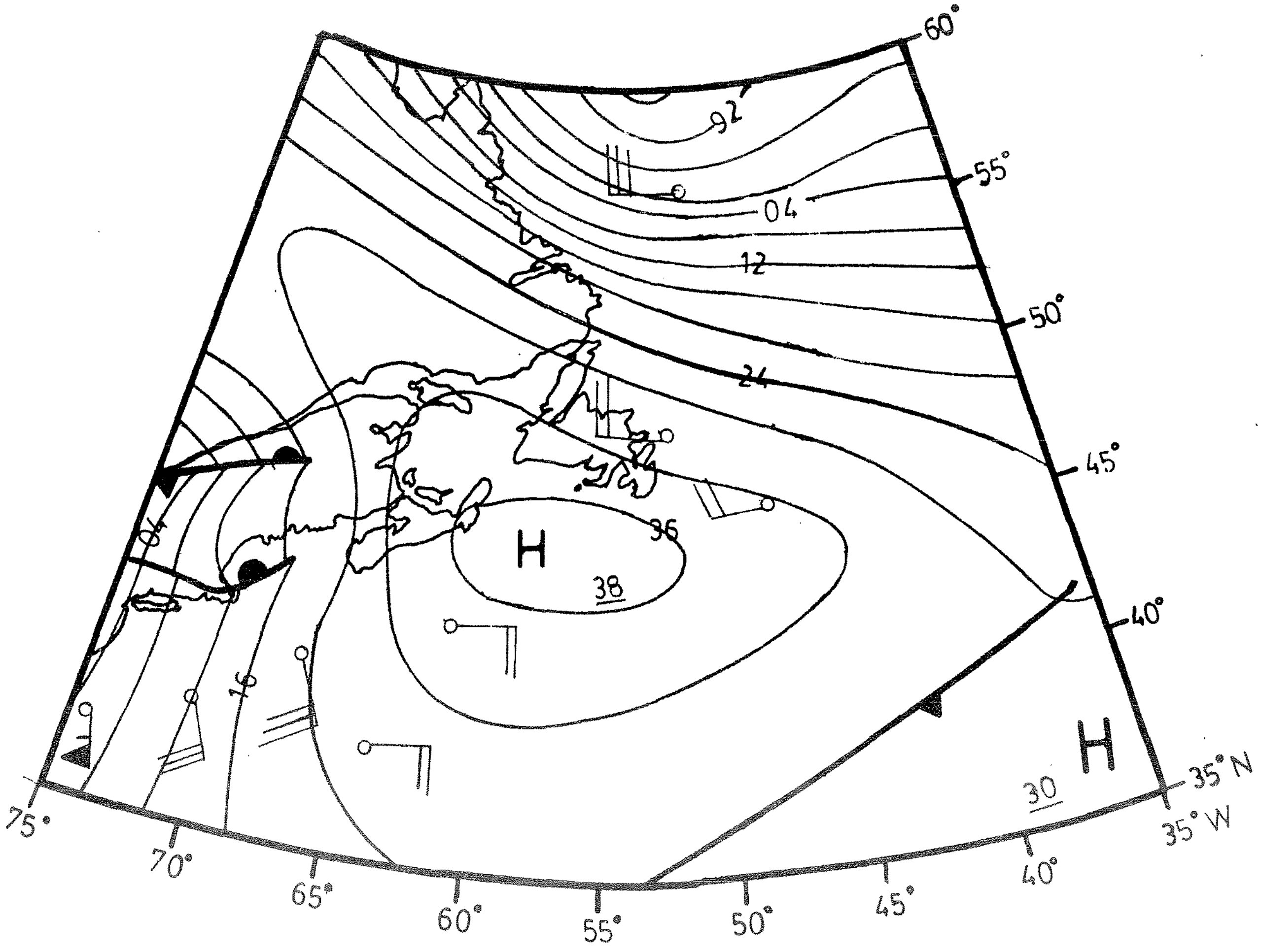
DECEMBER 21-25, 1973



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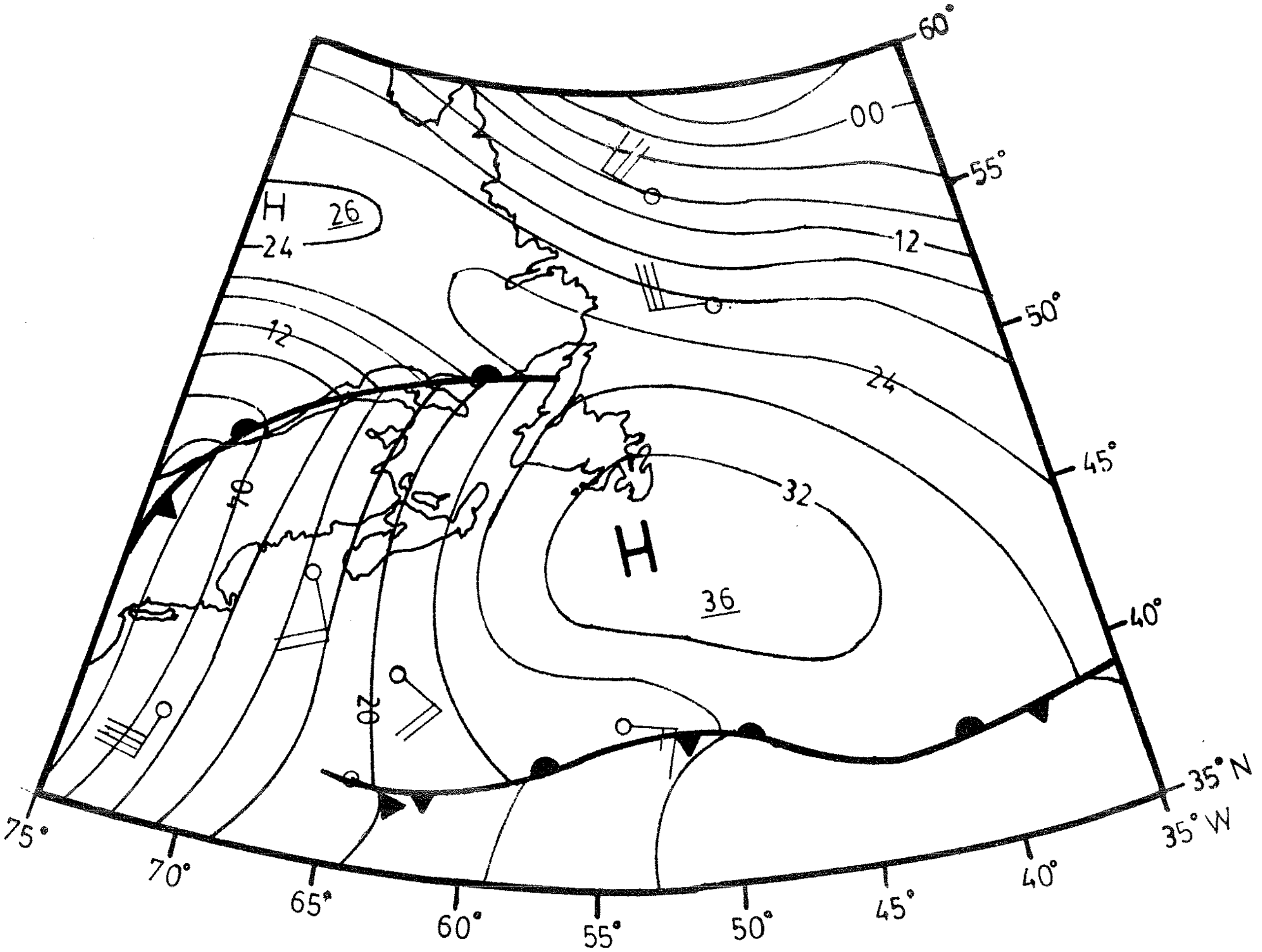
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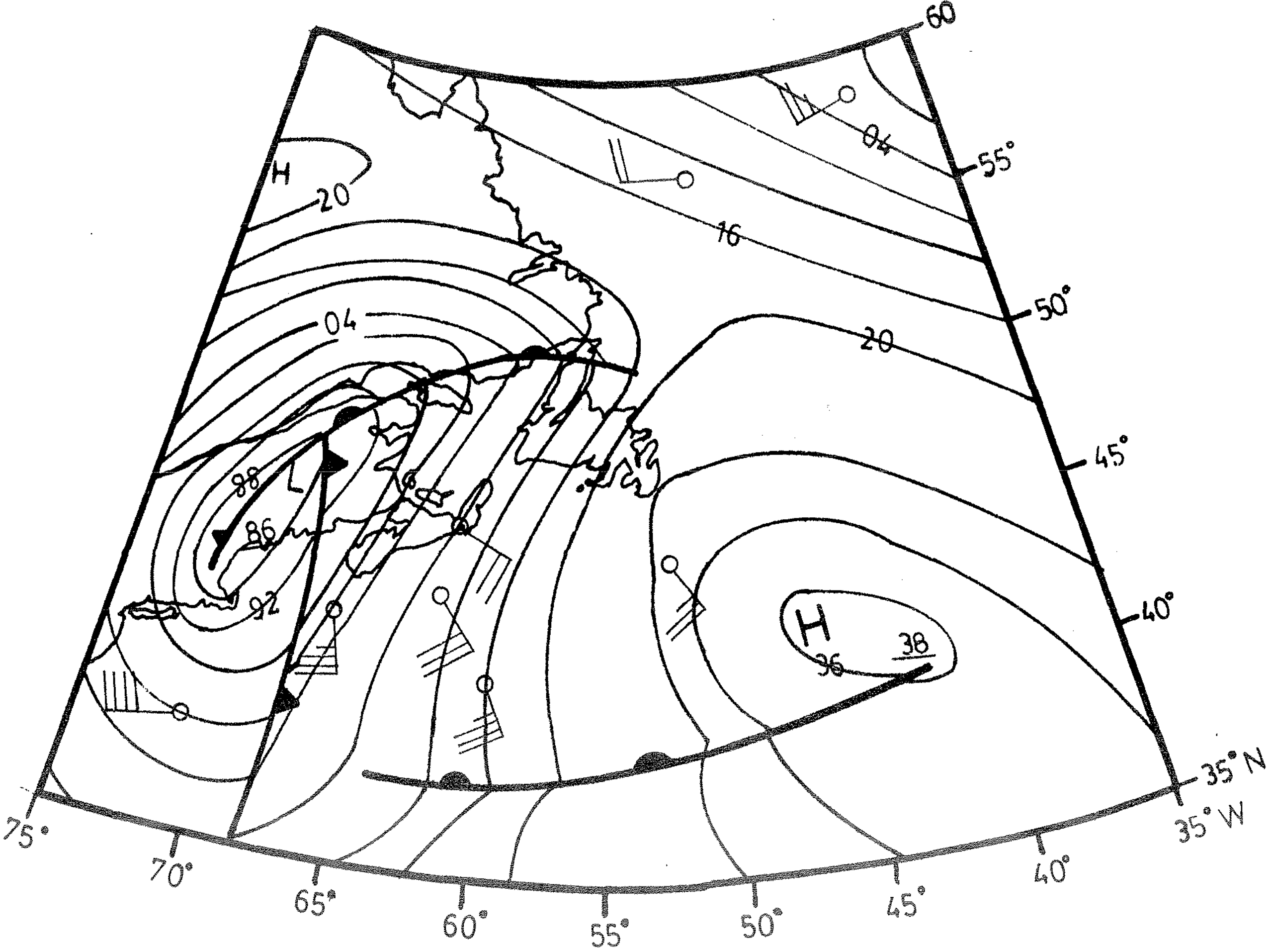
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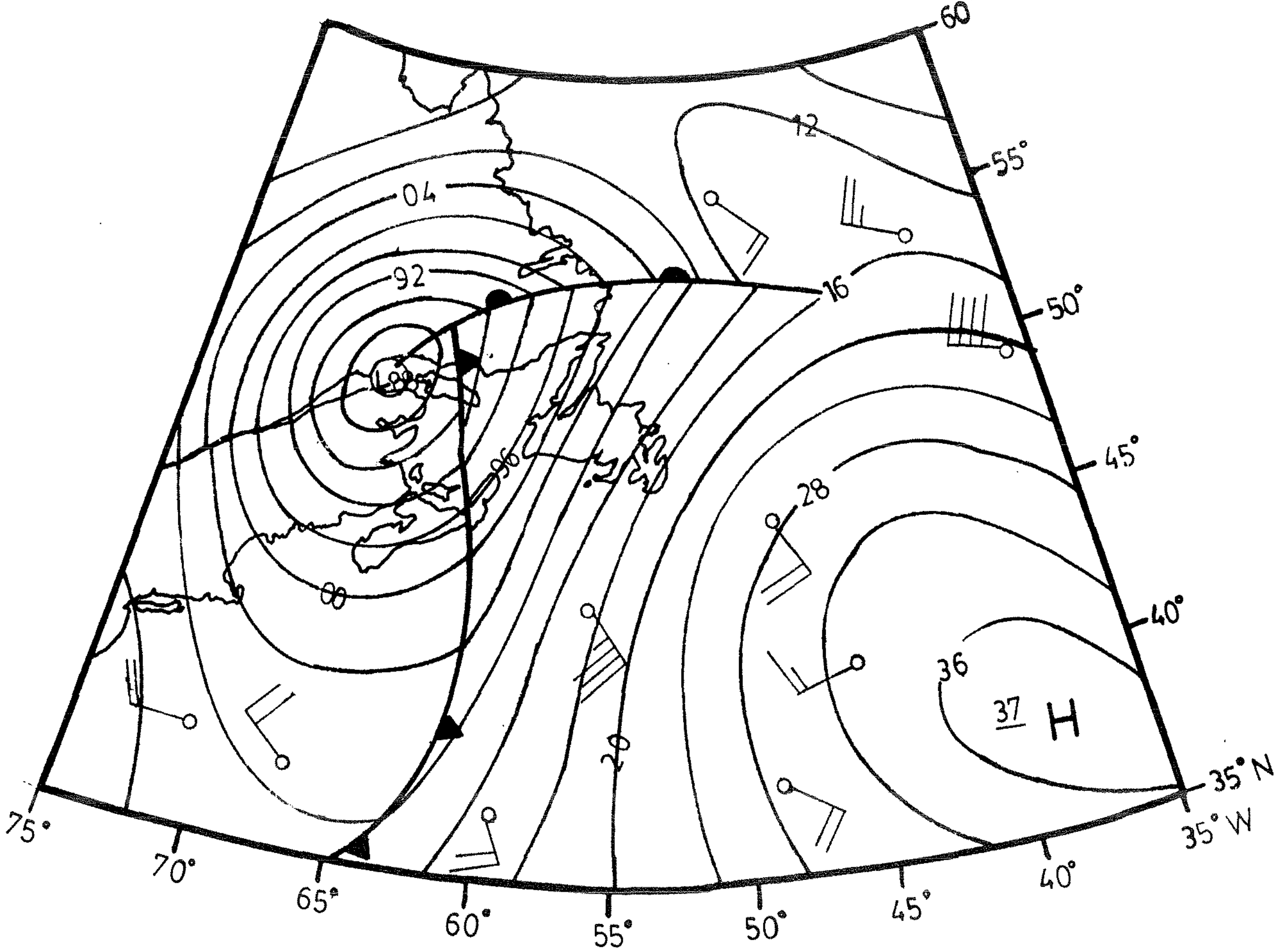
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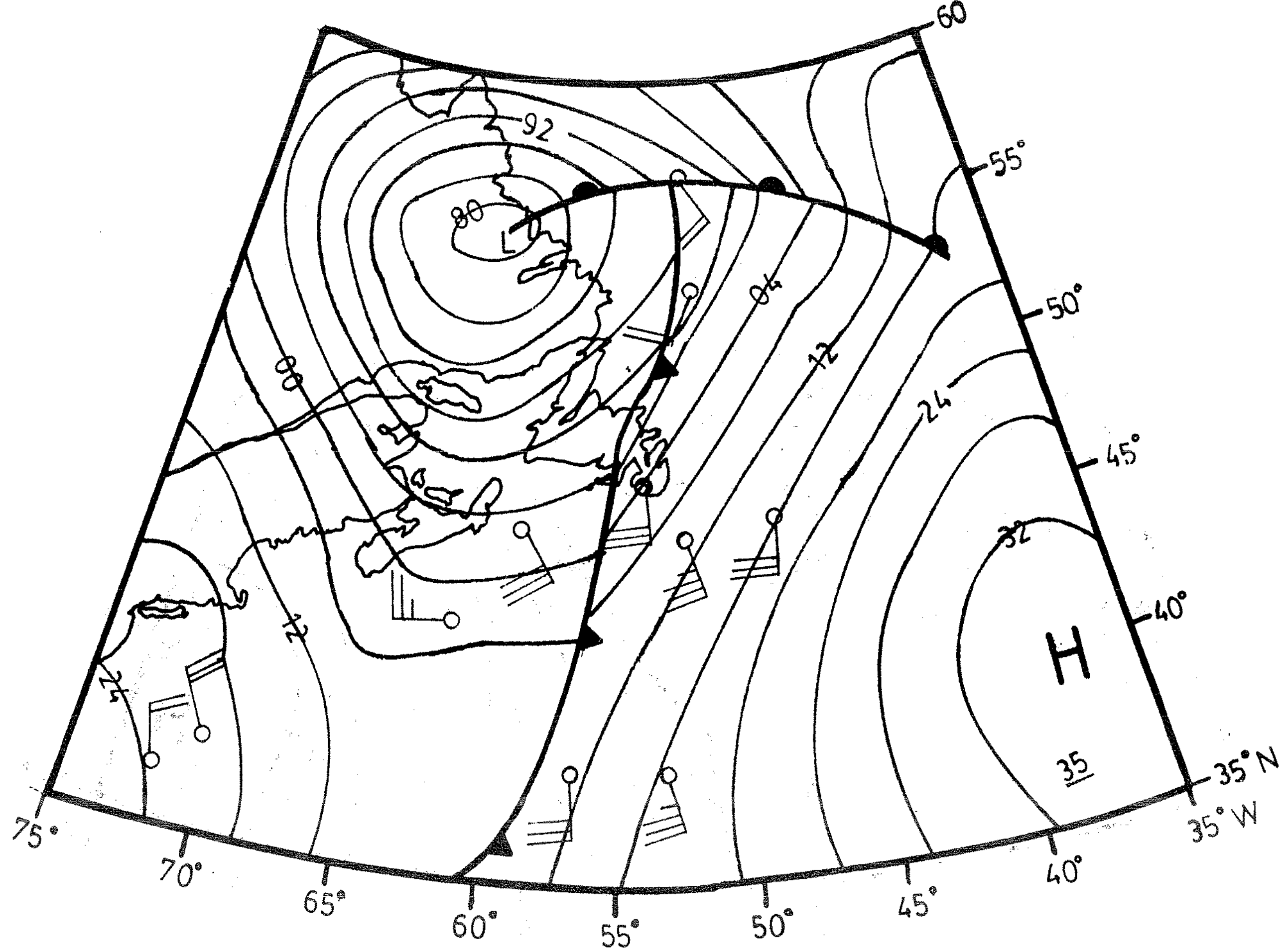

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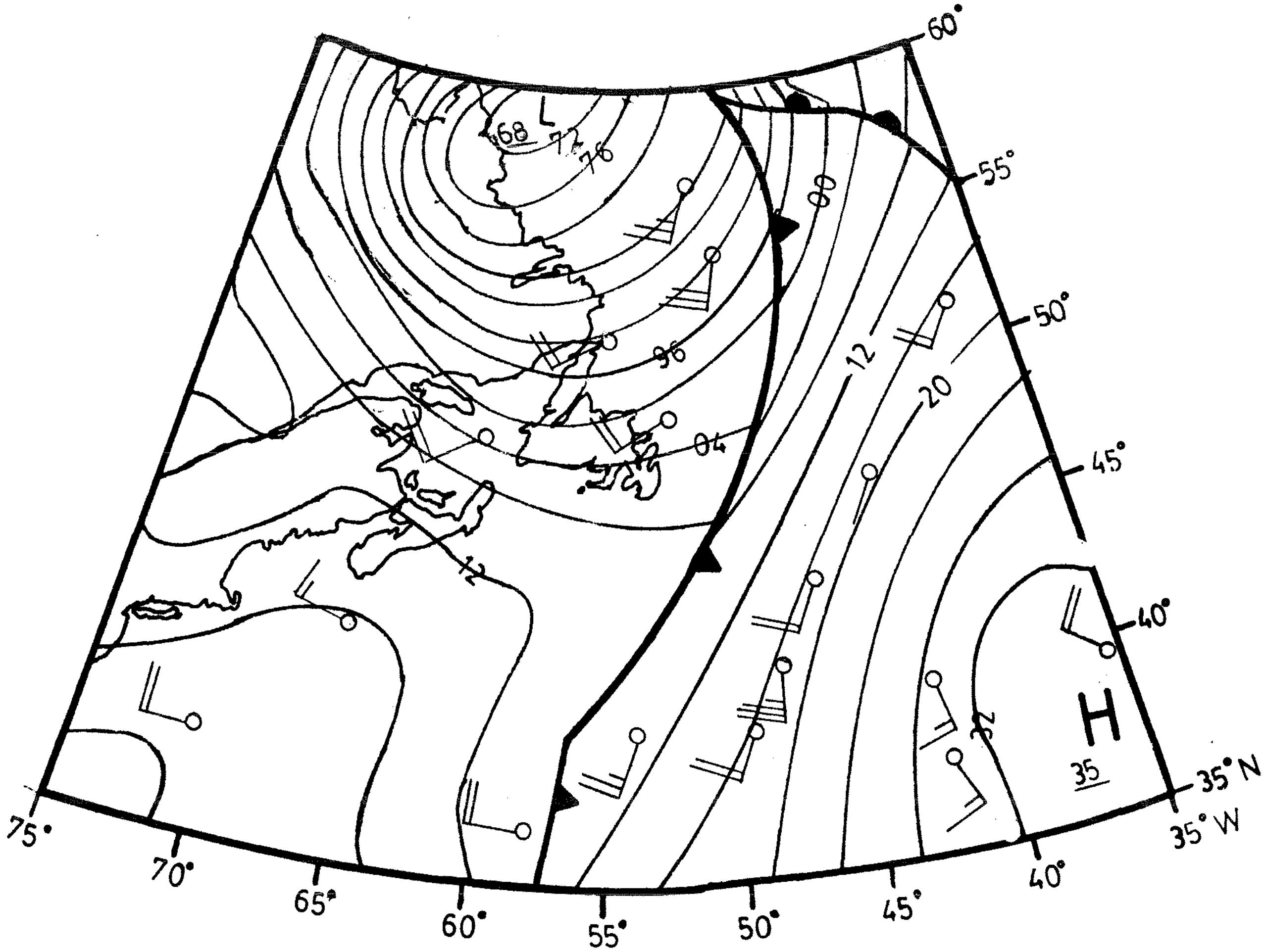
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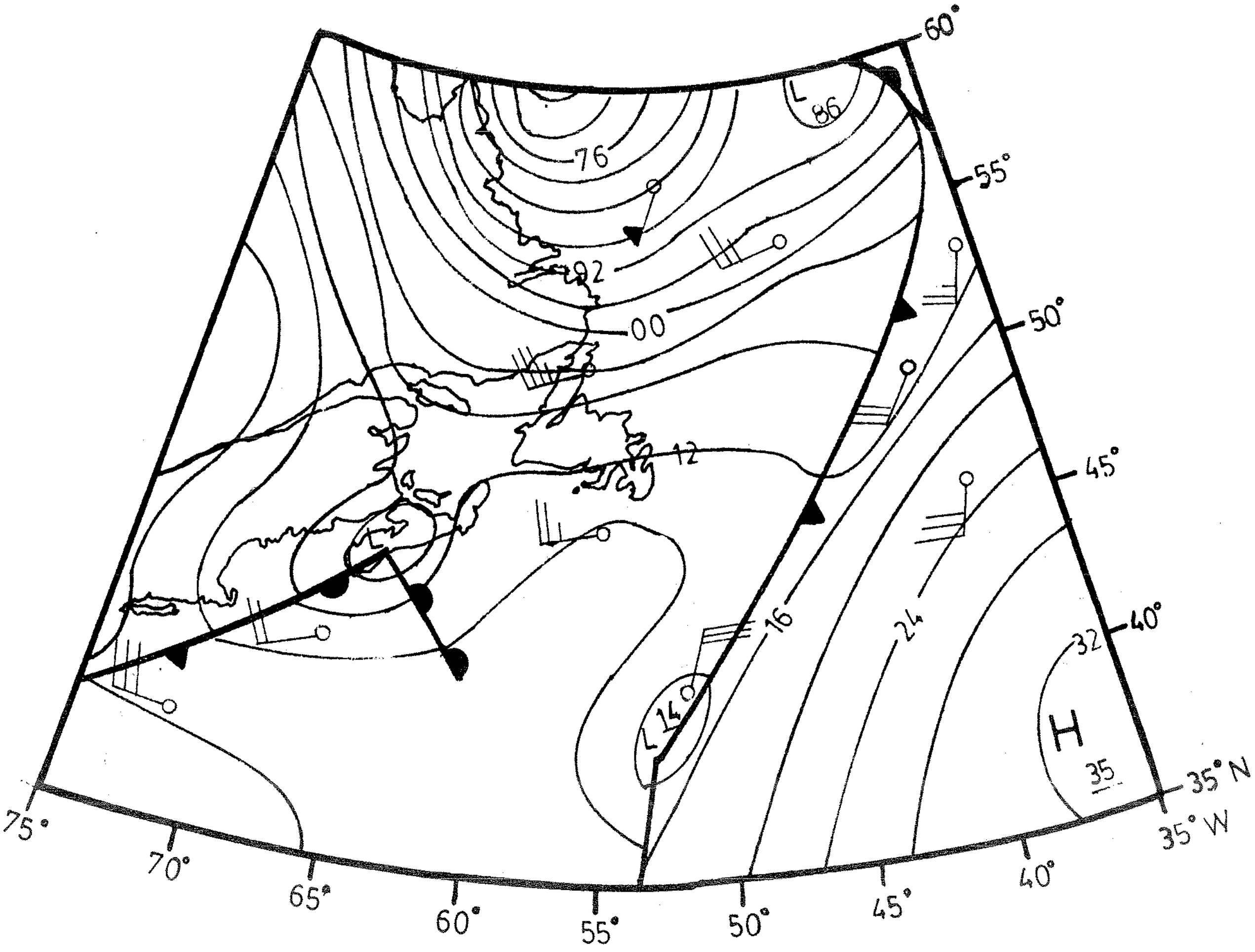

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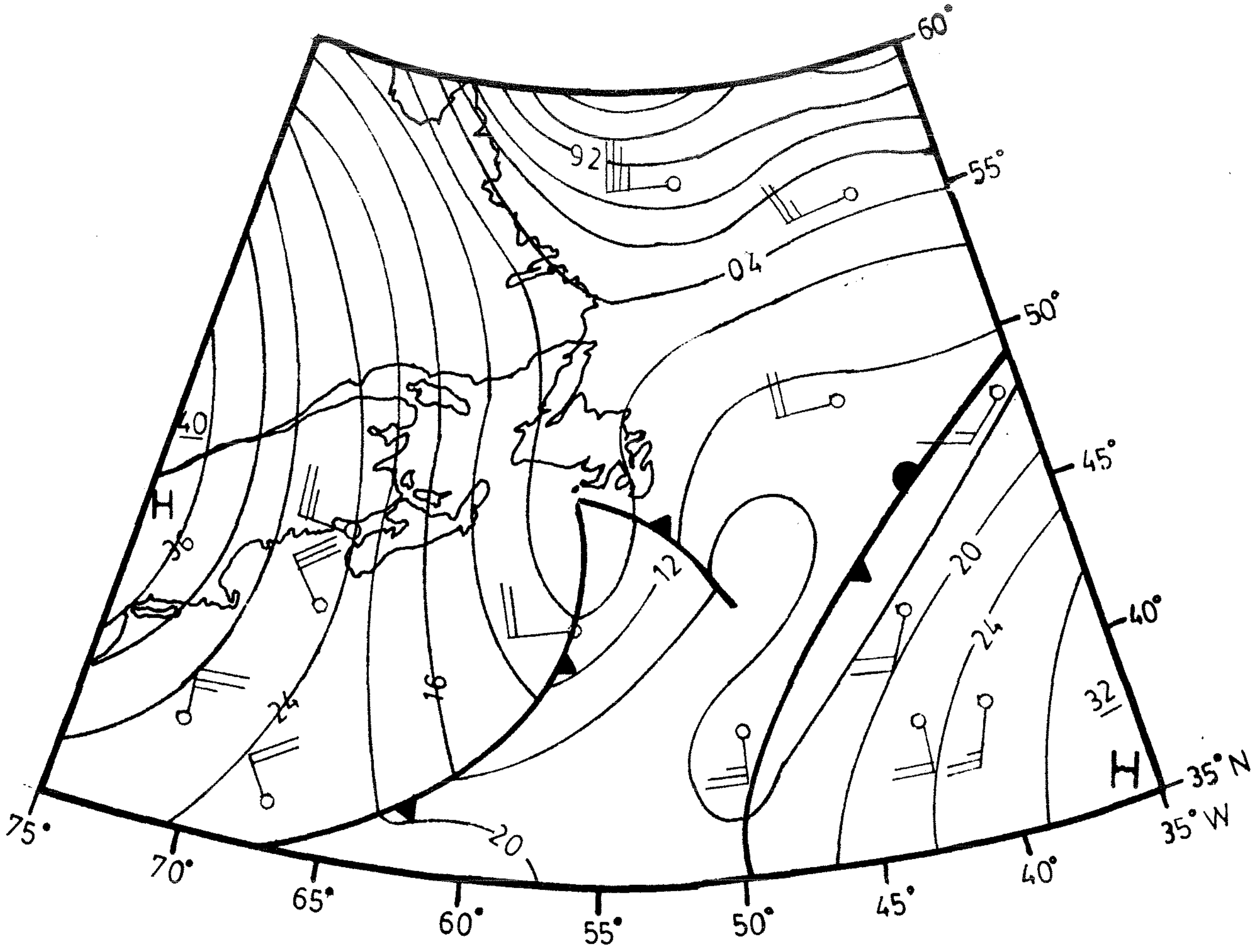

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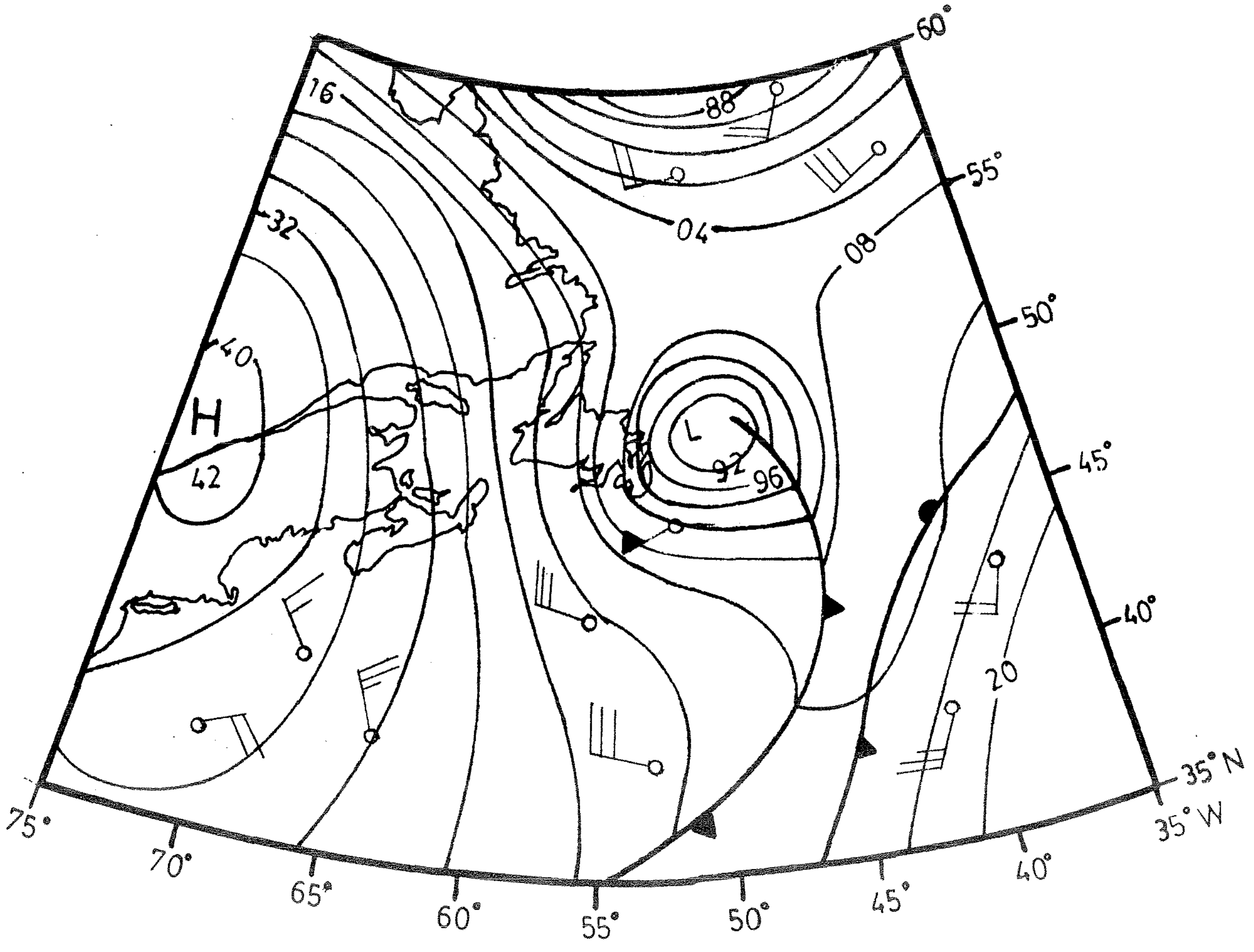
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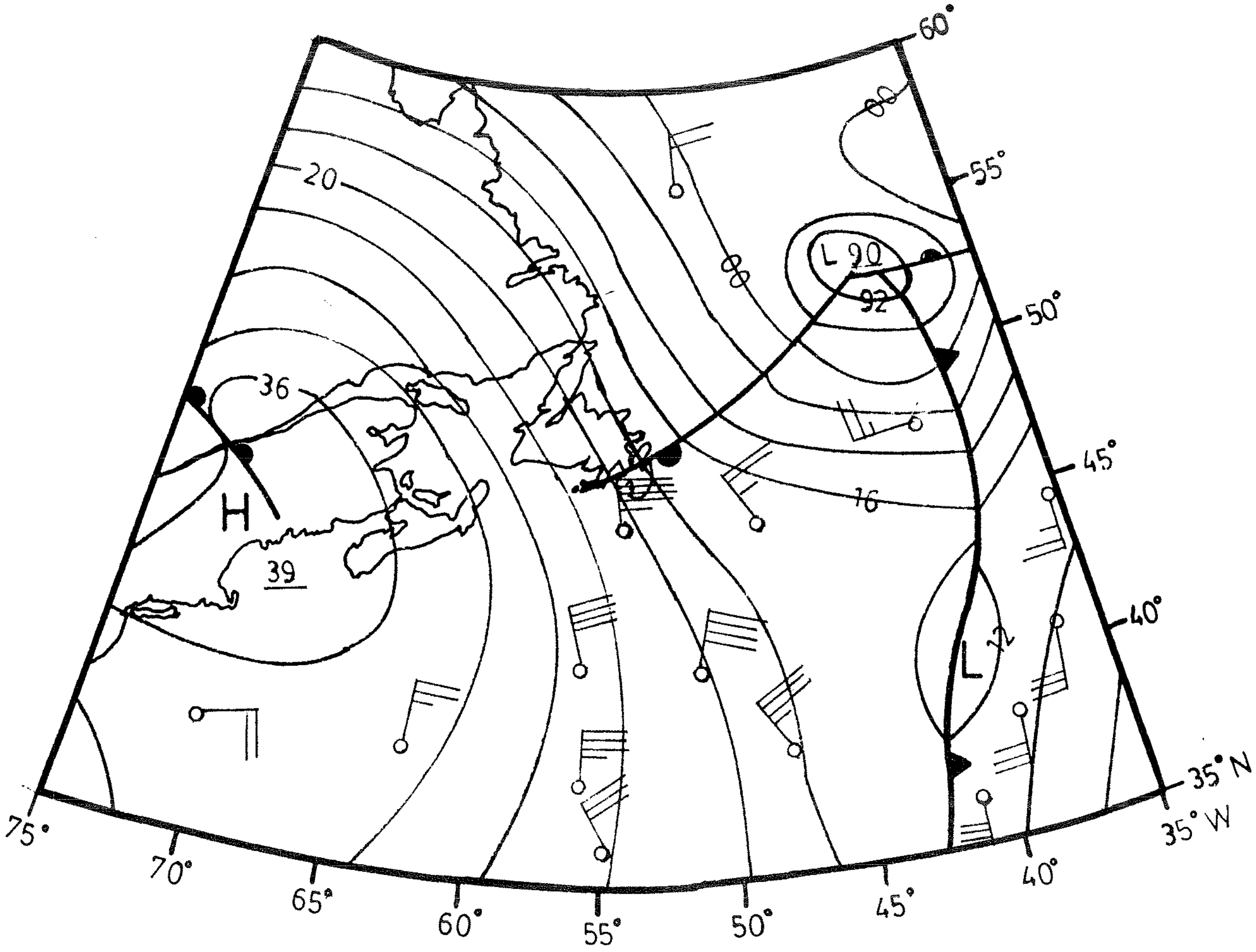

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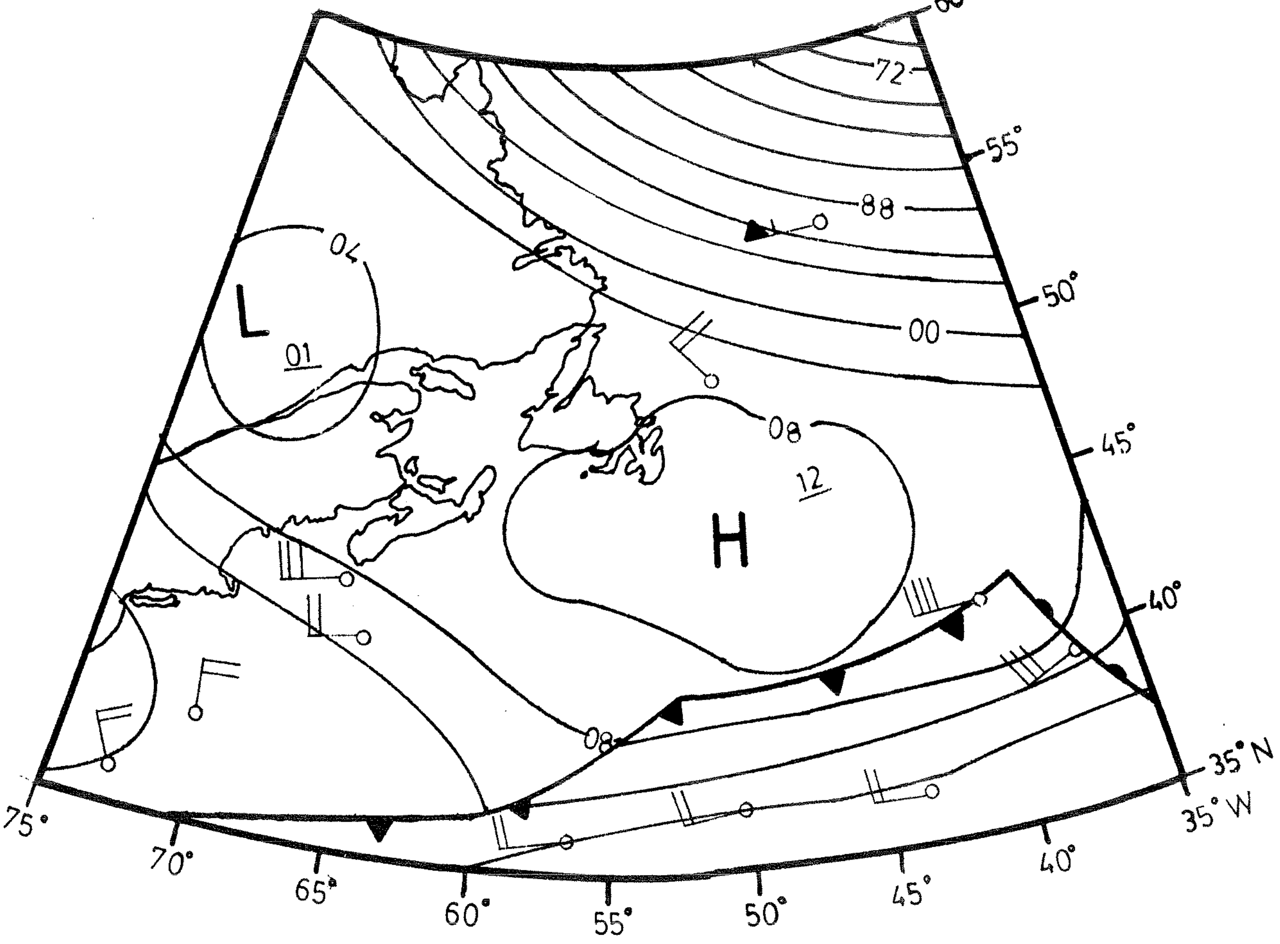
JANUARY 8-11, 1974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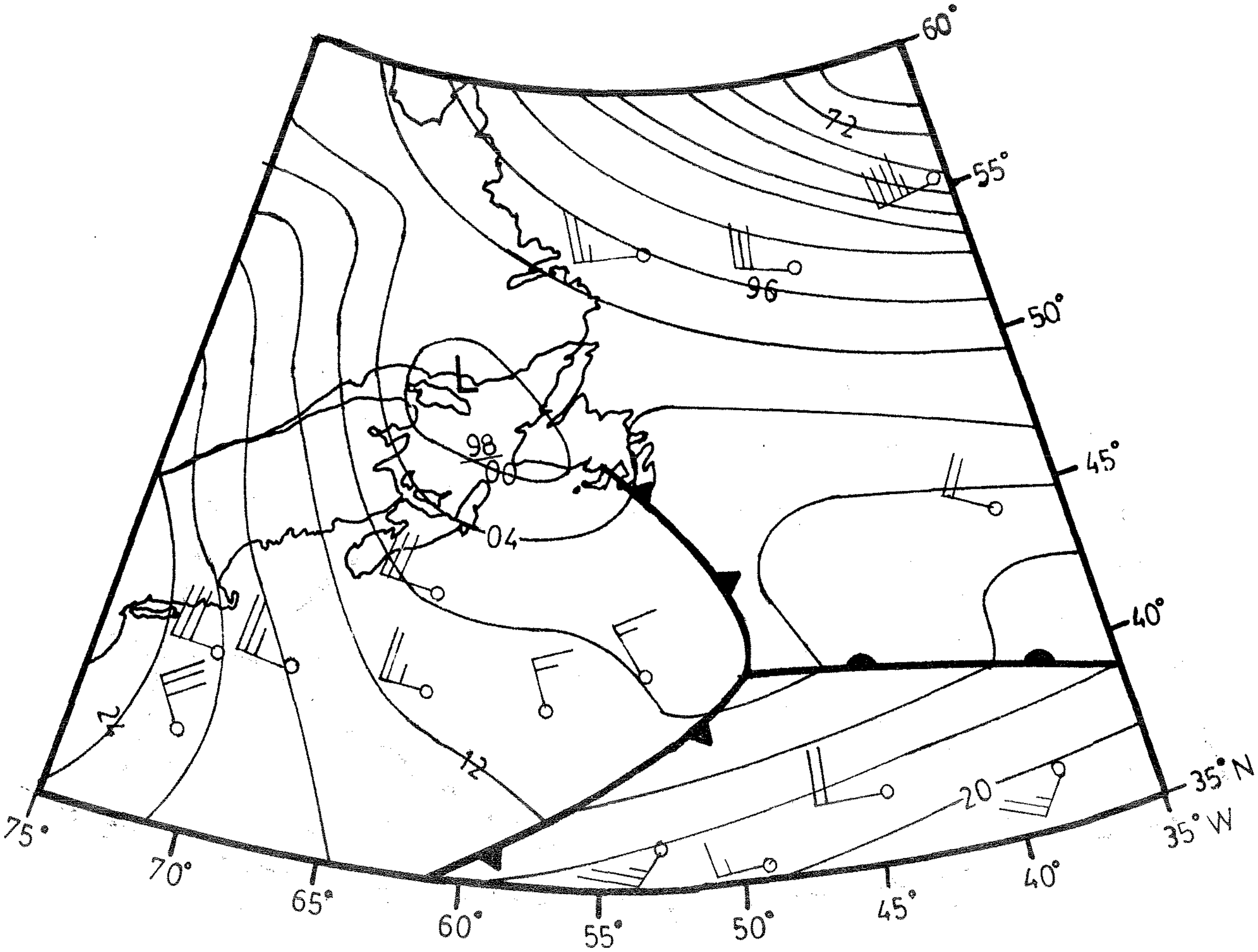

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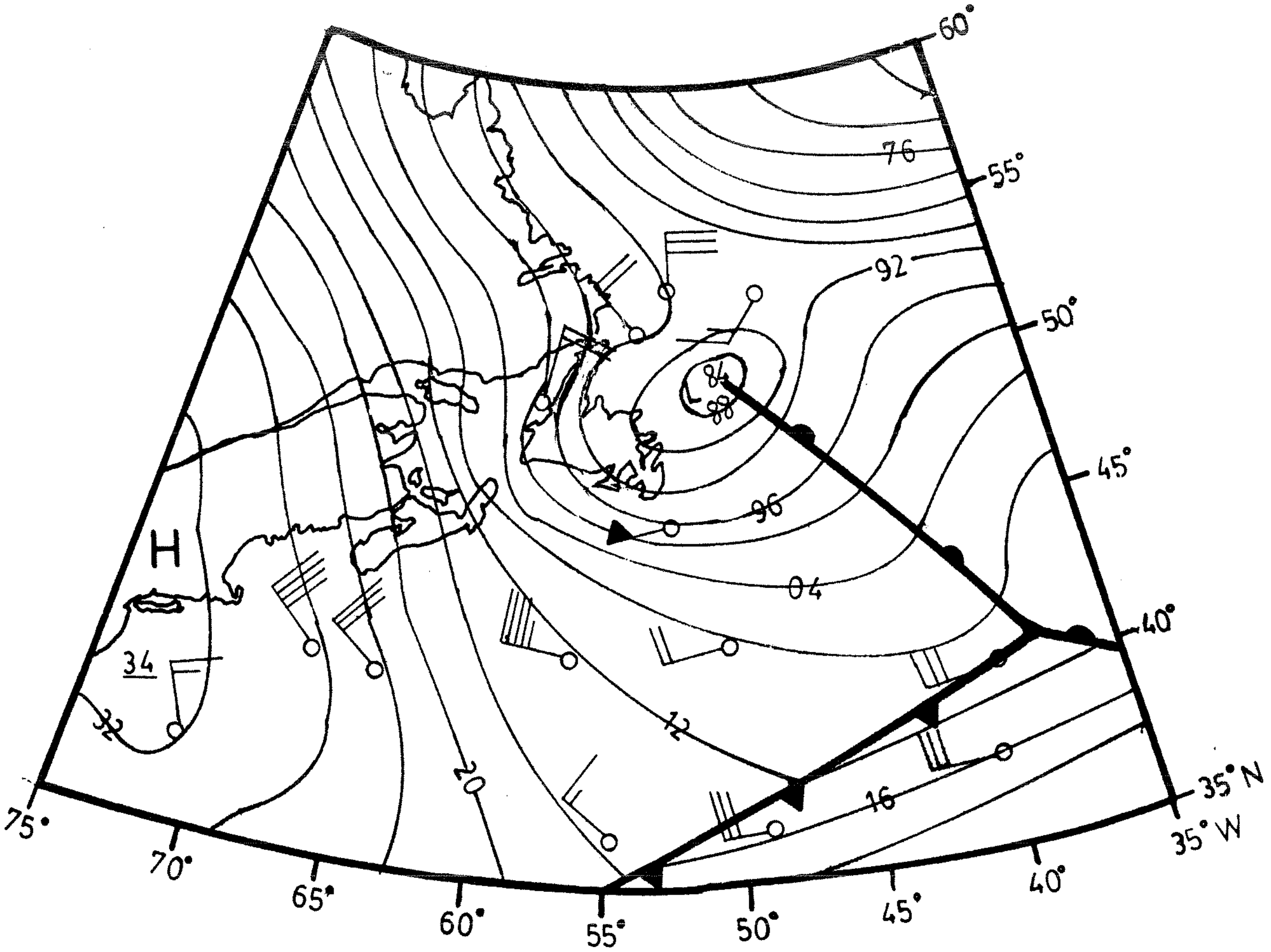
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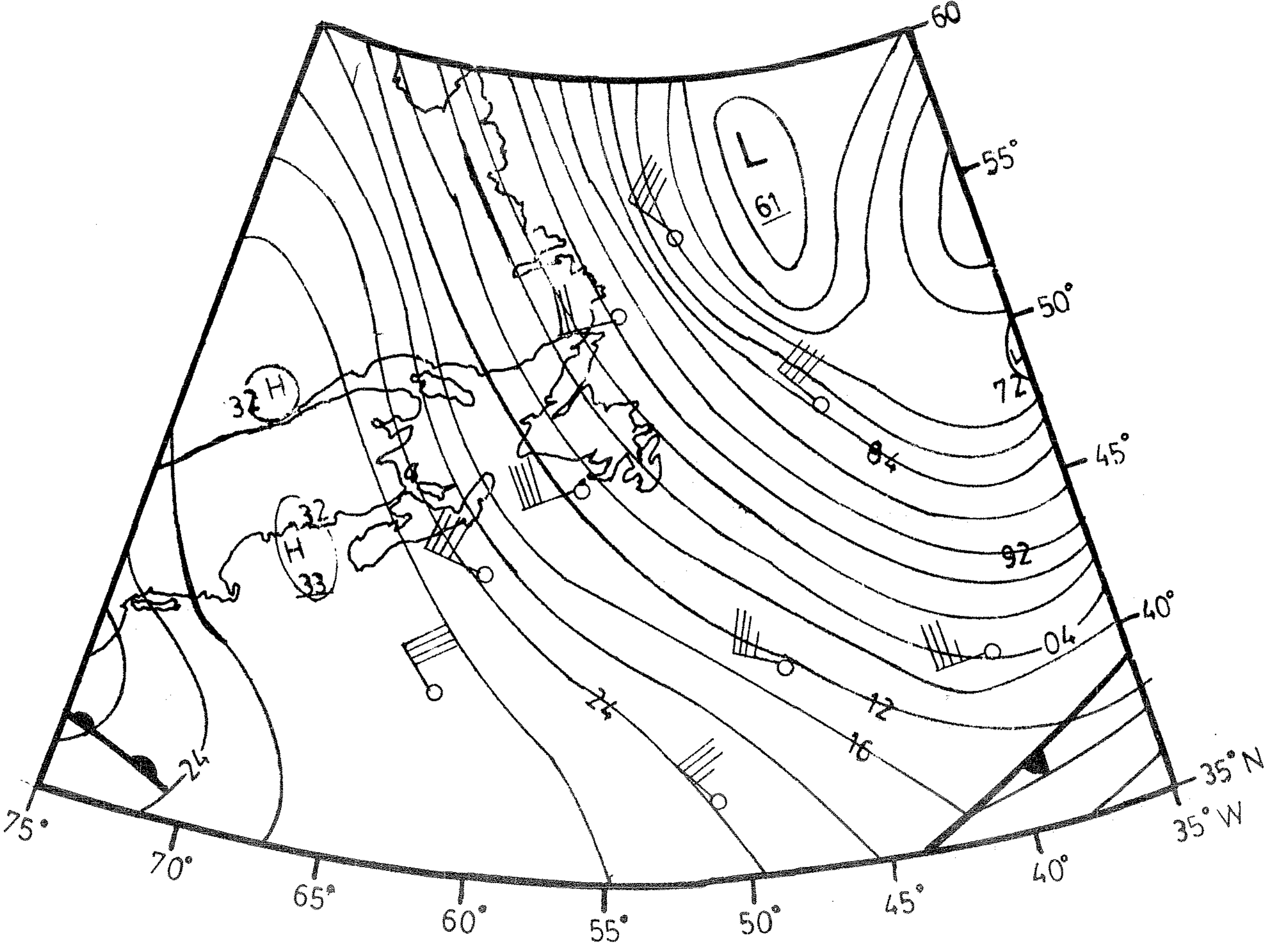
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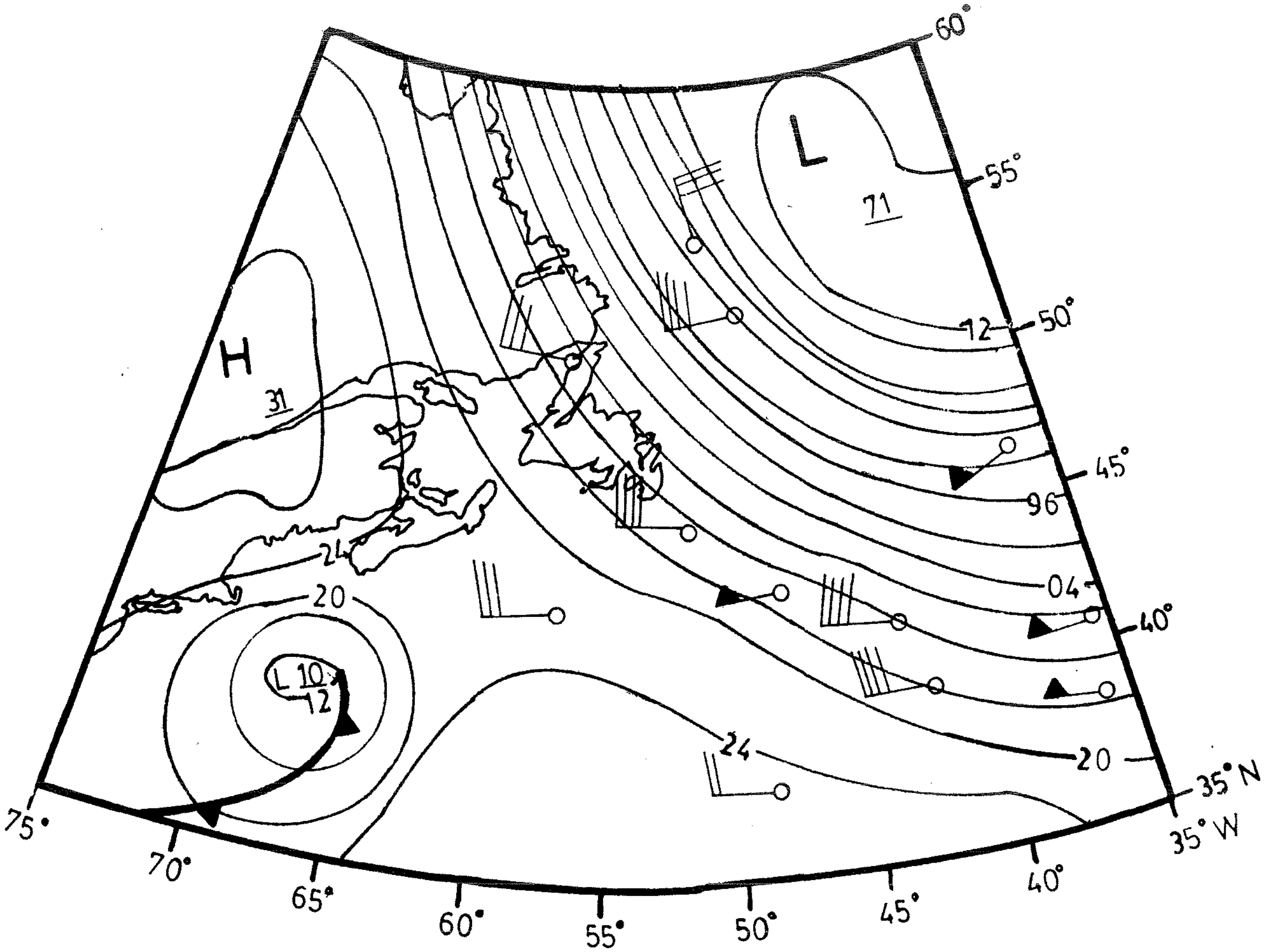
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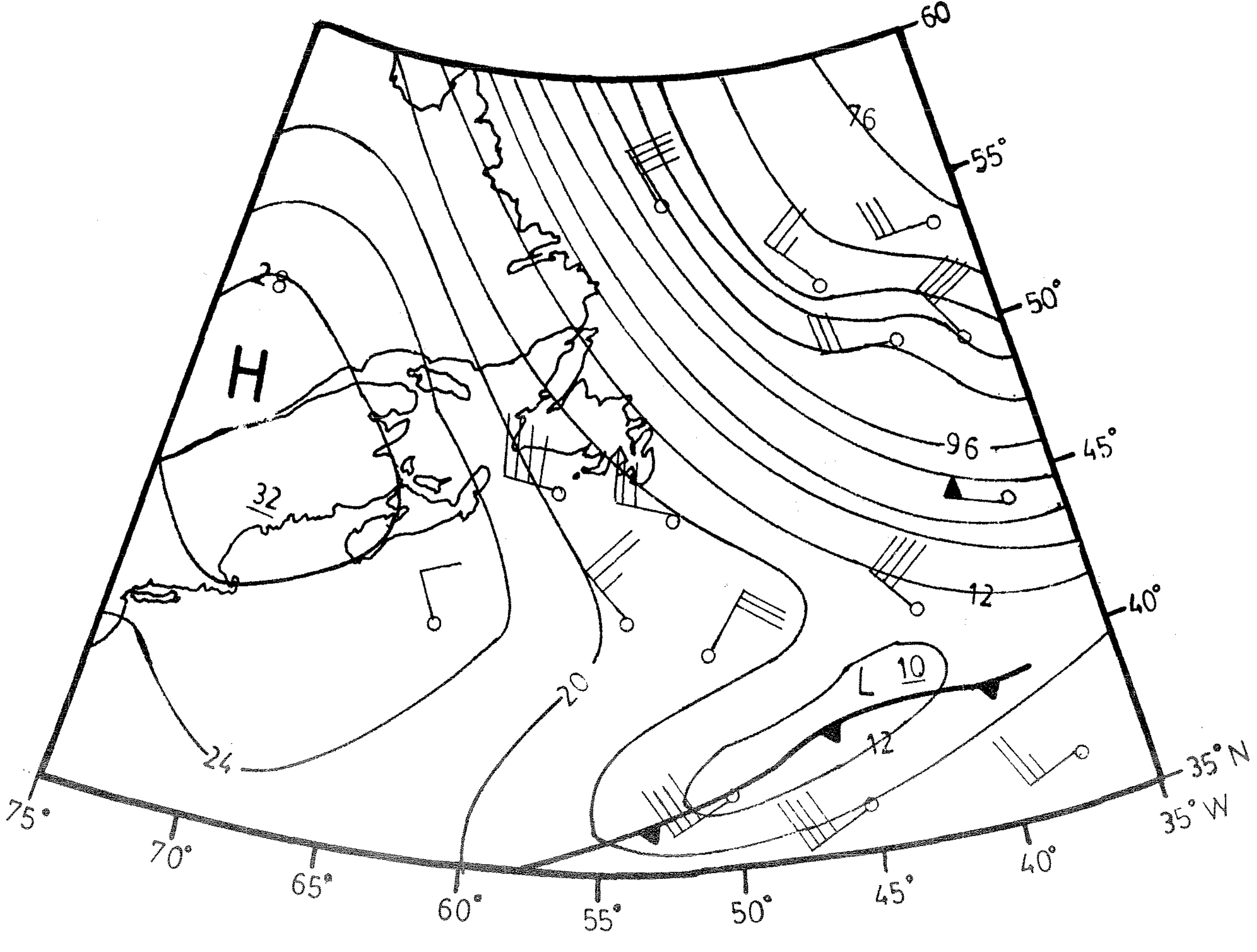
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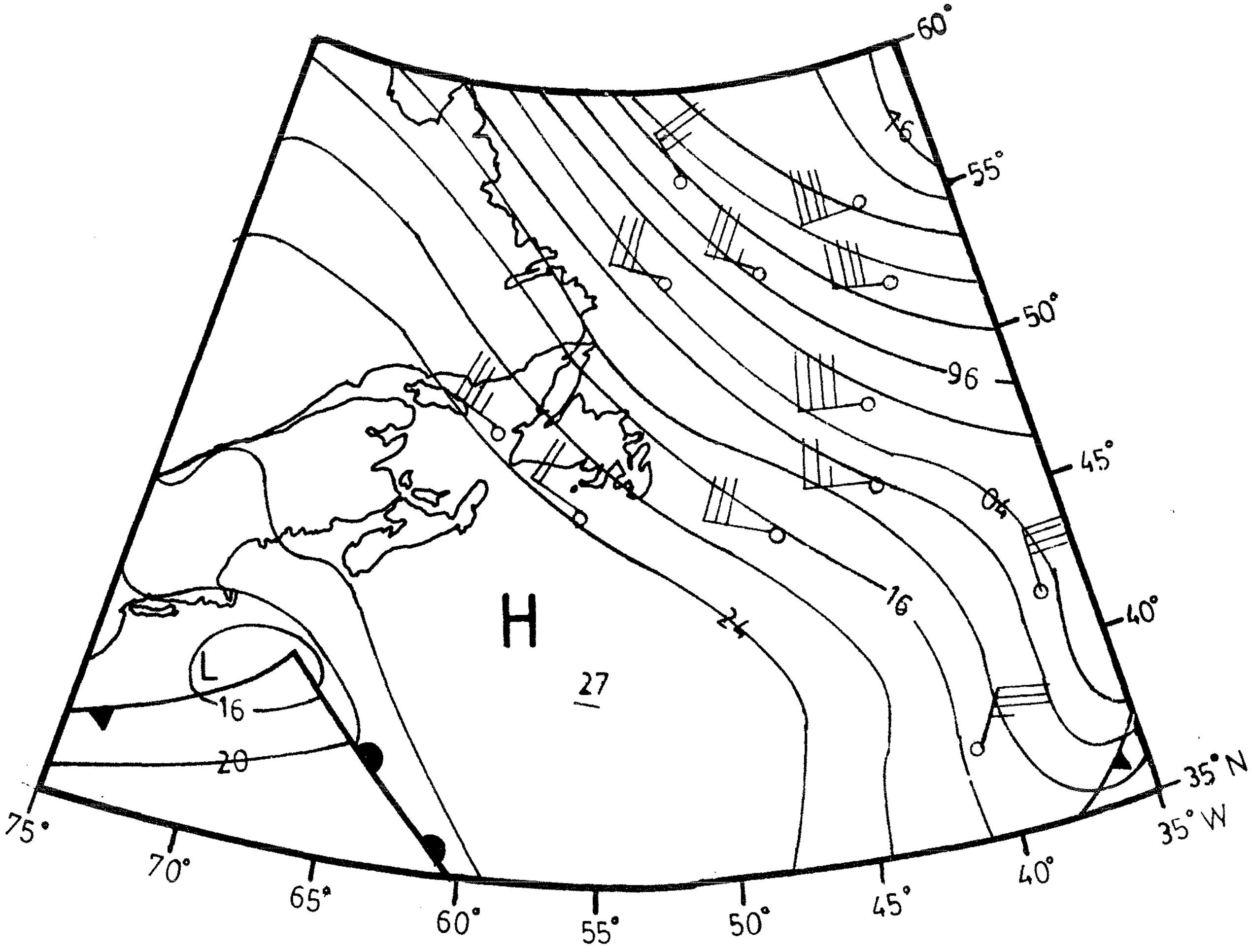
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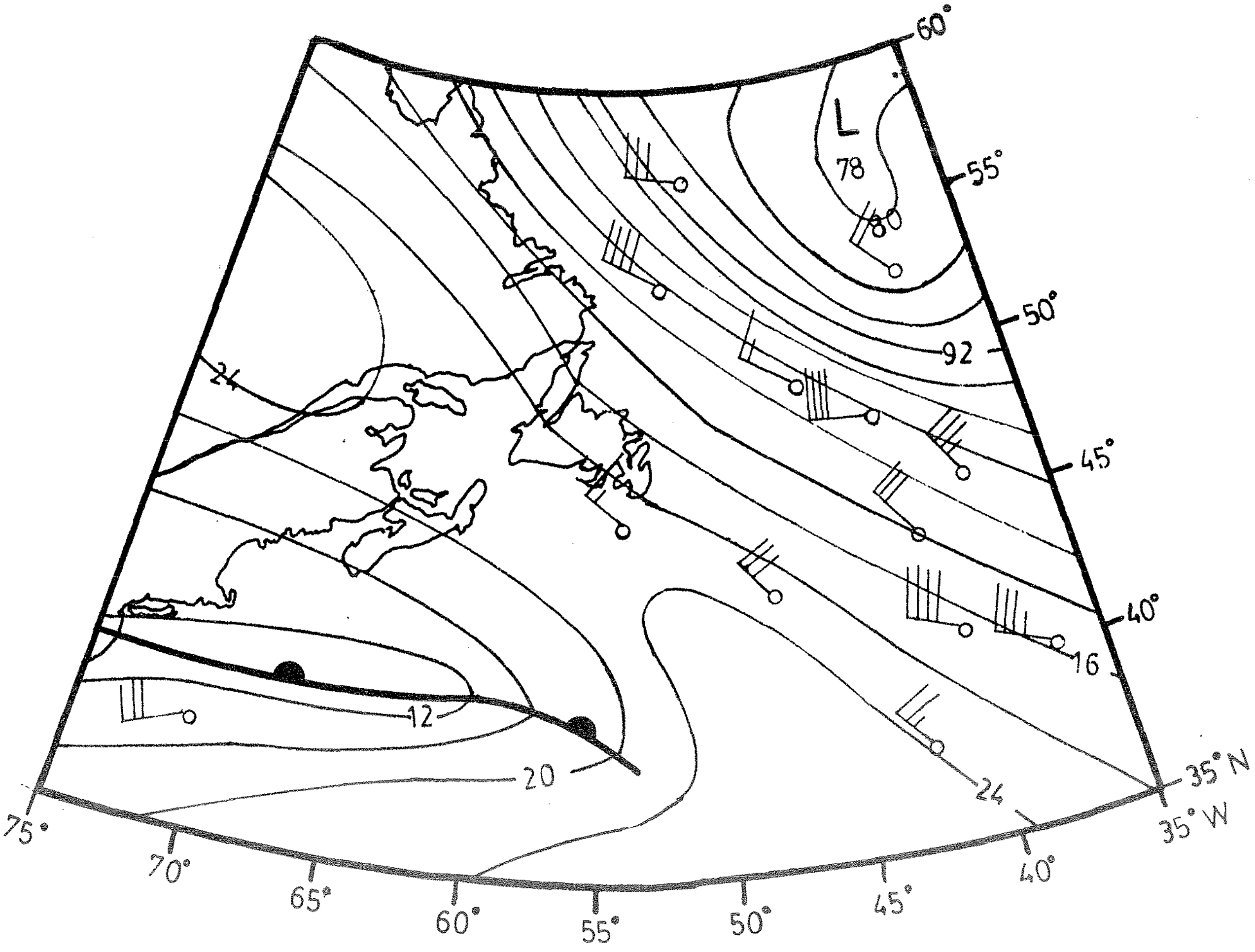

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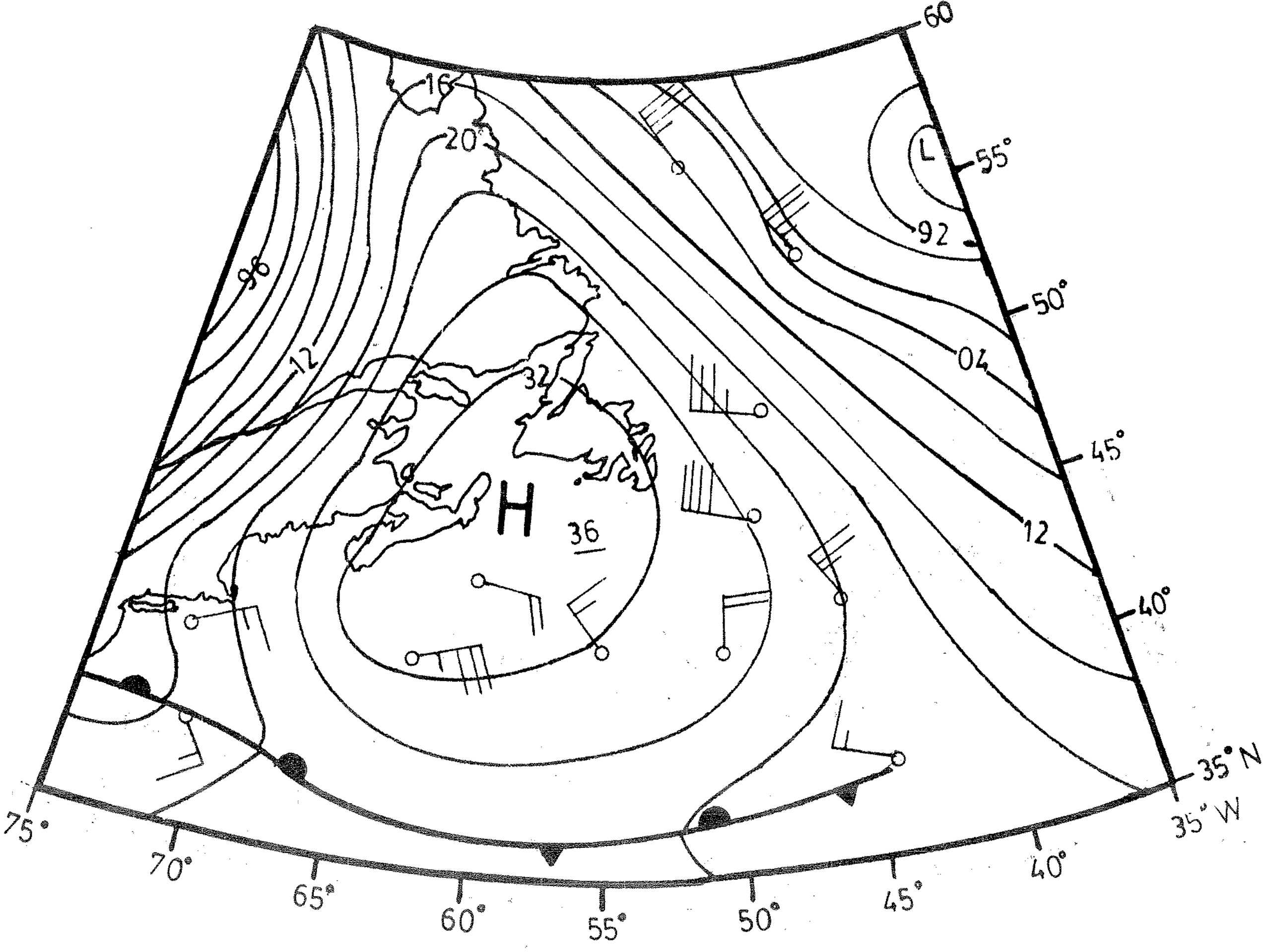
MARCH 4-8, 1974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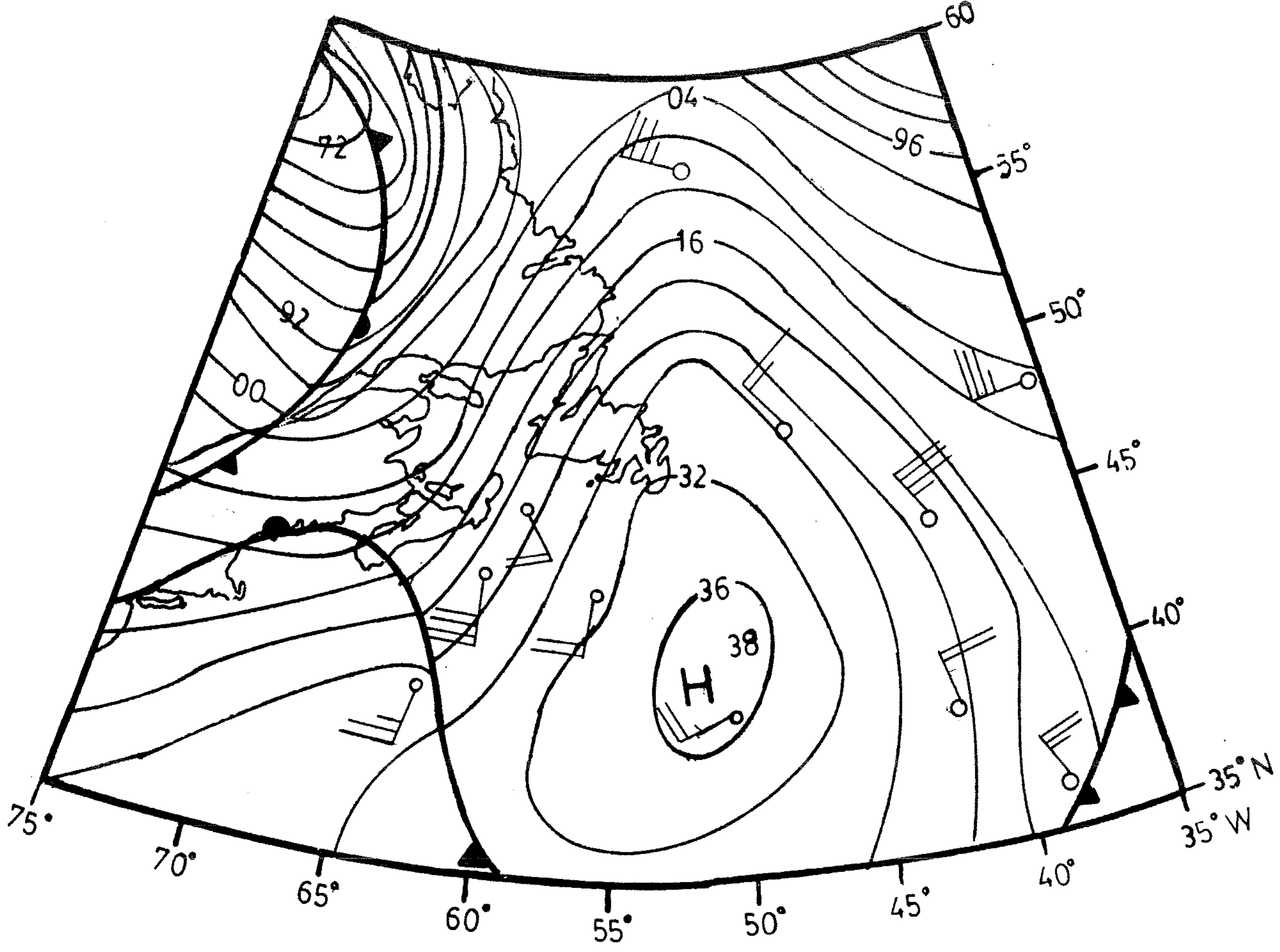

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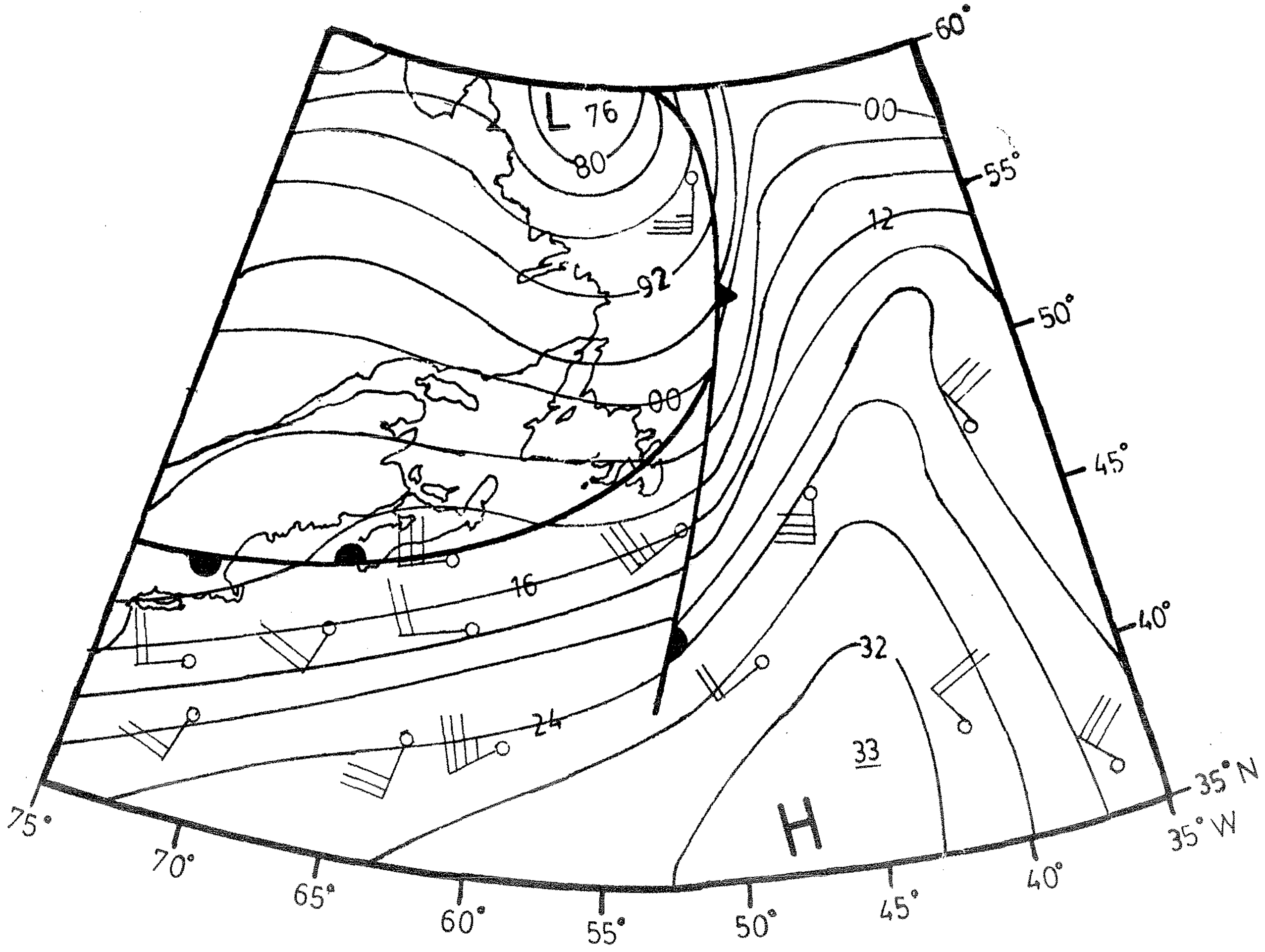

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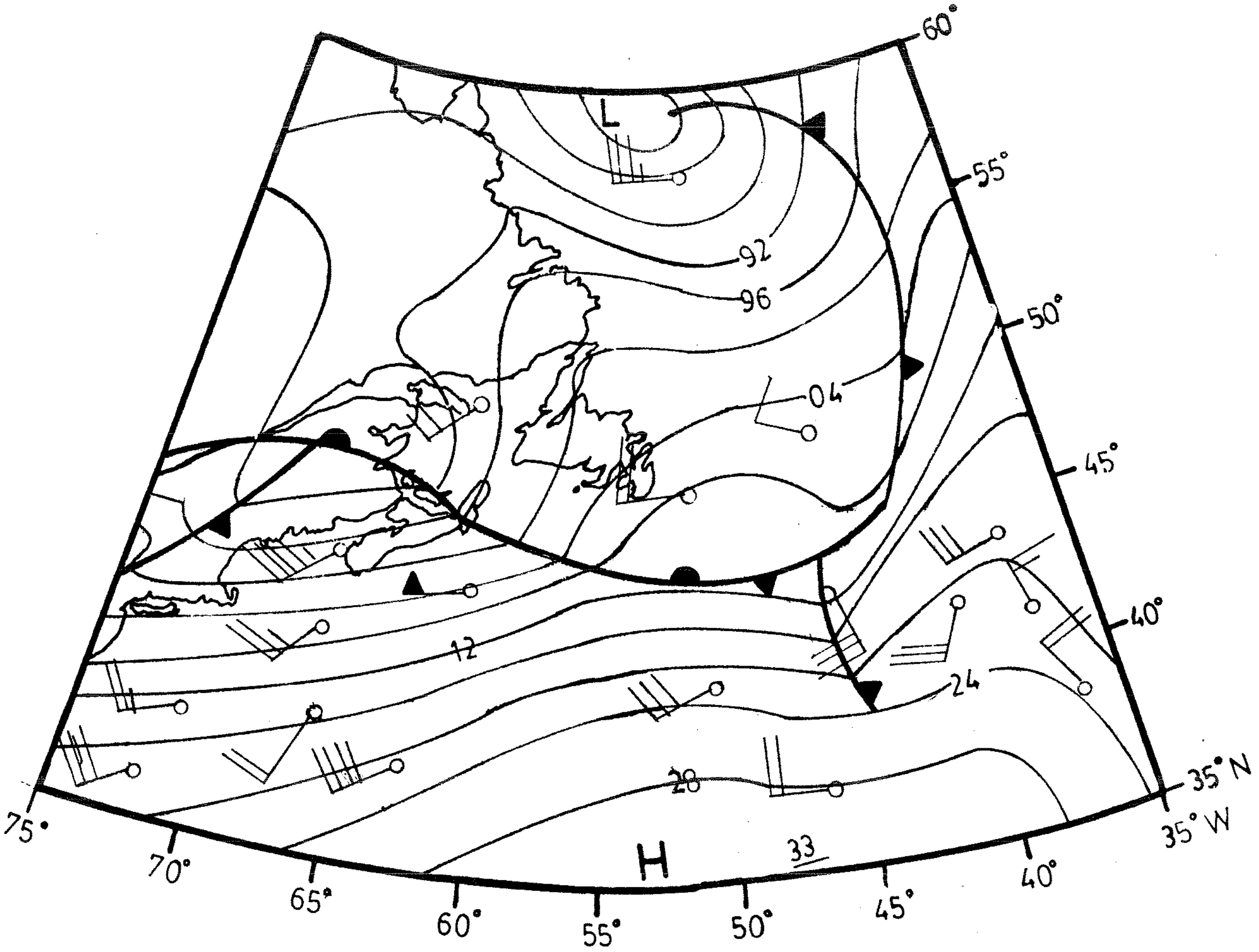

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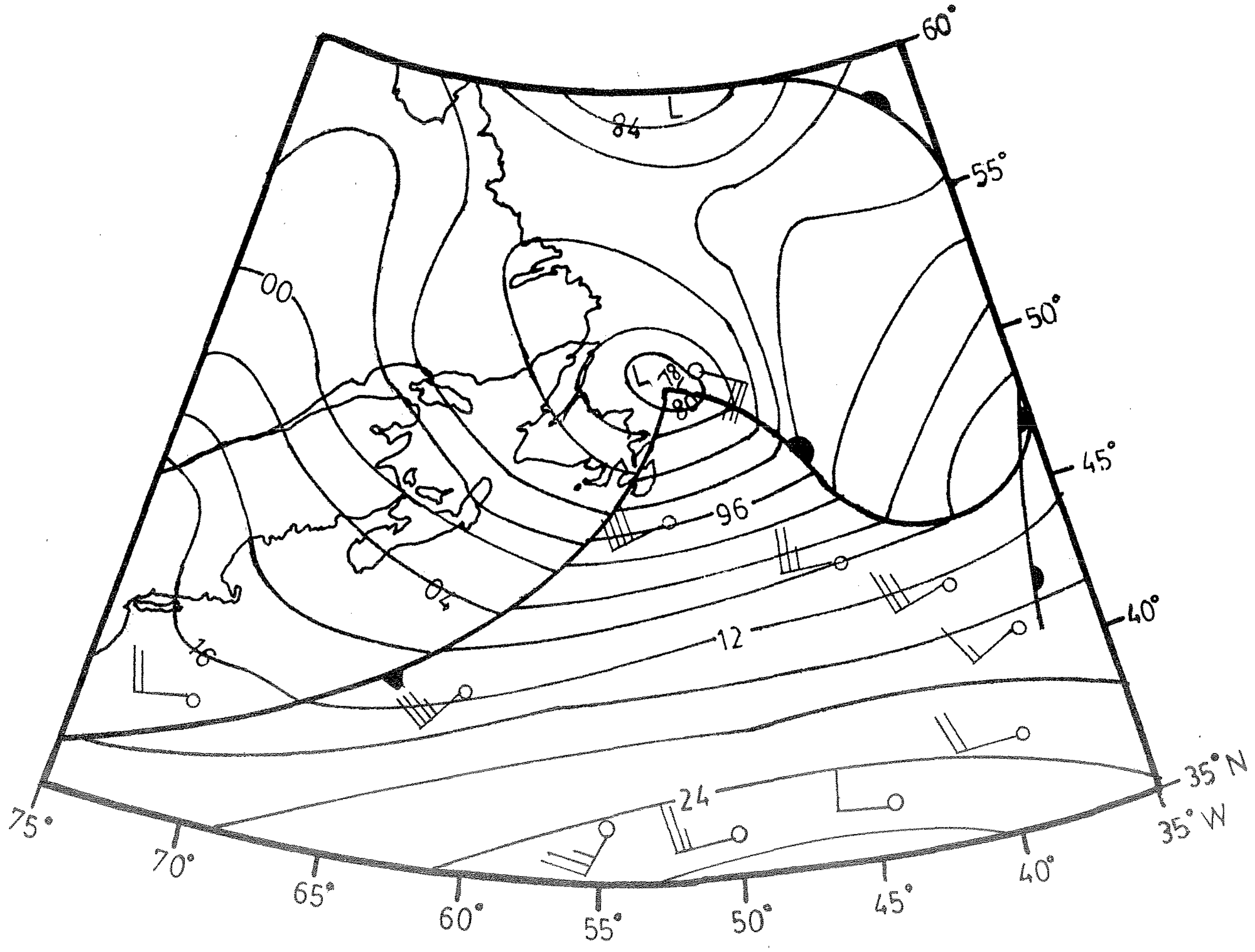

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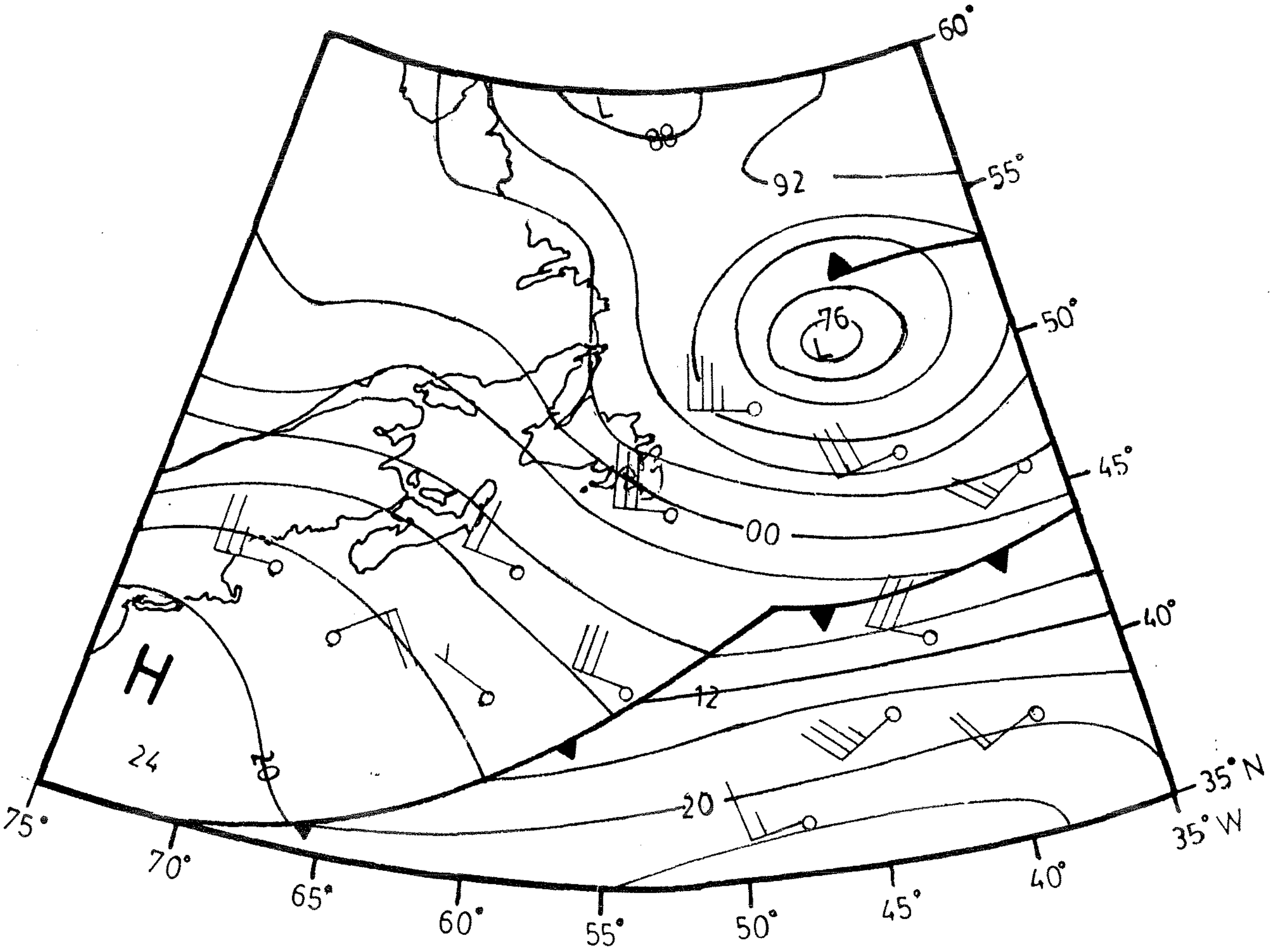
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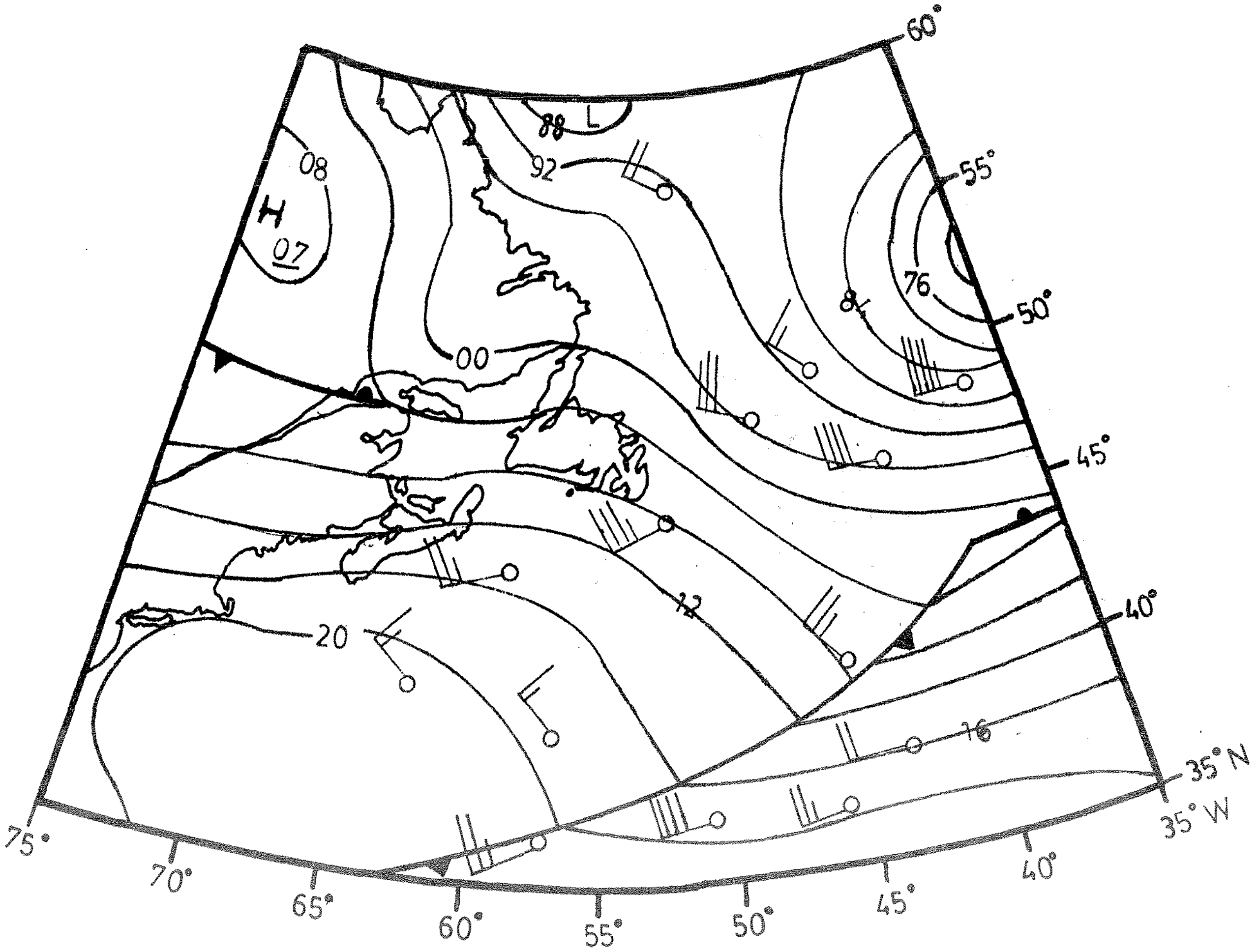
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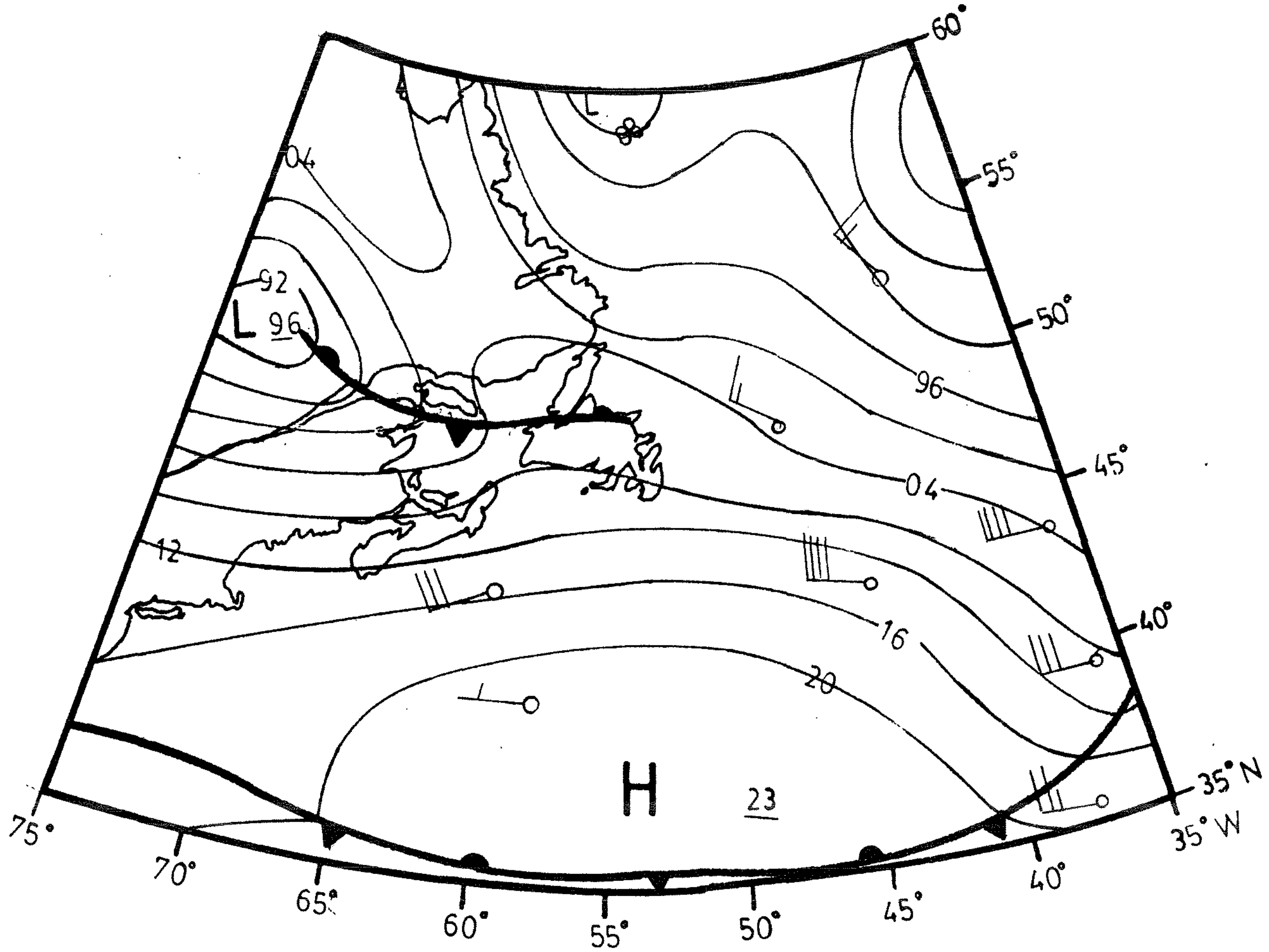
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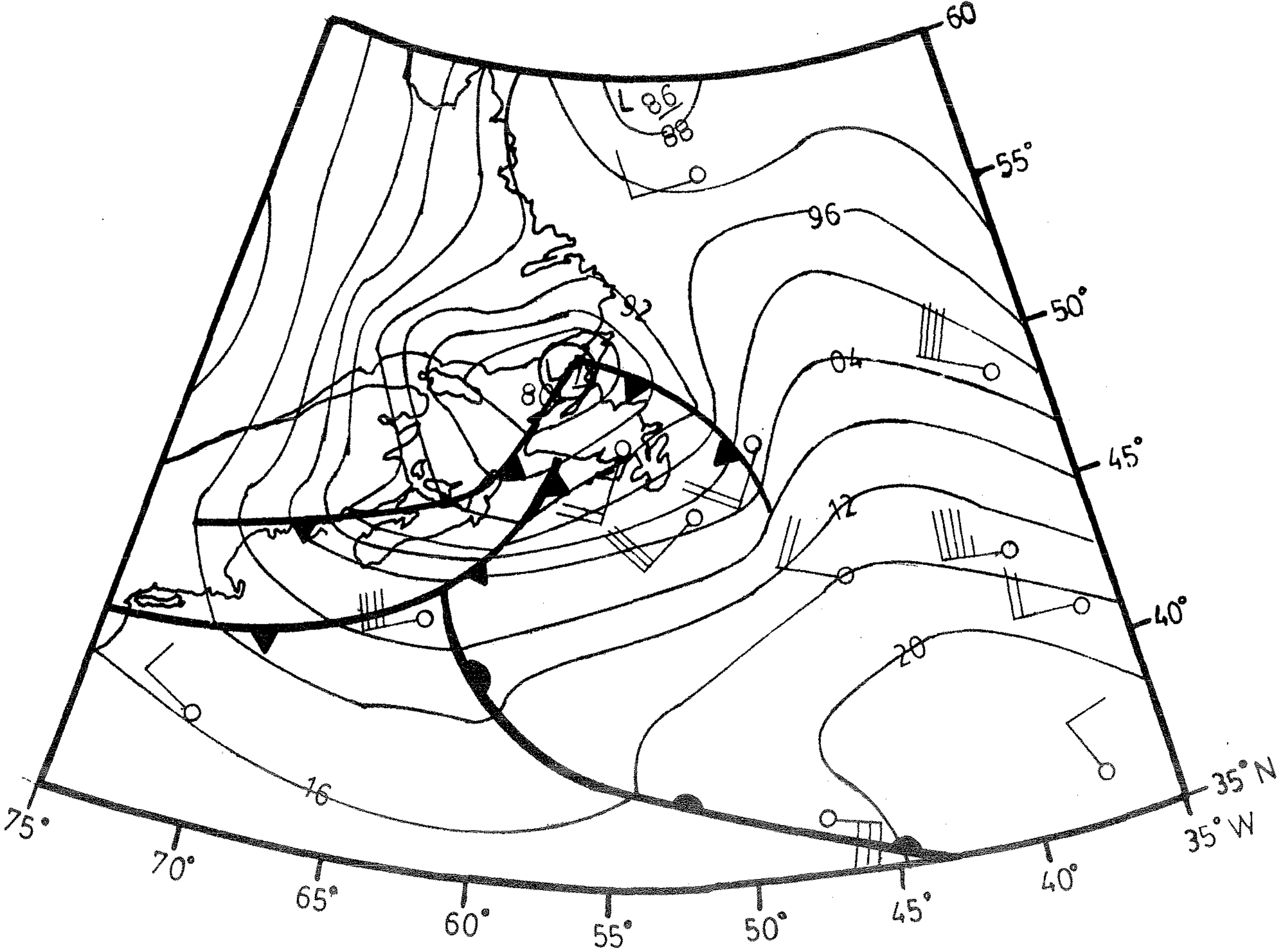
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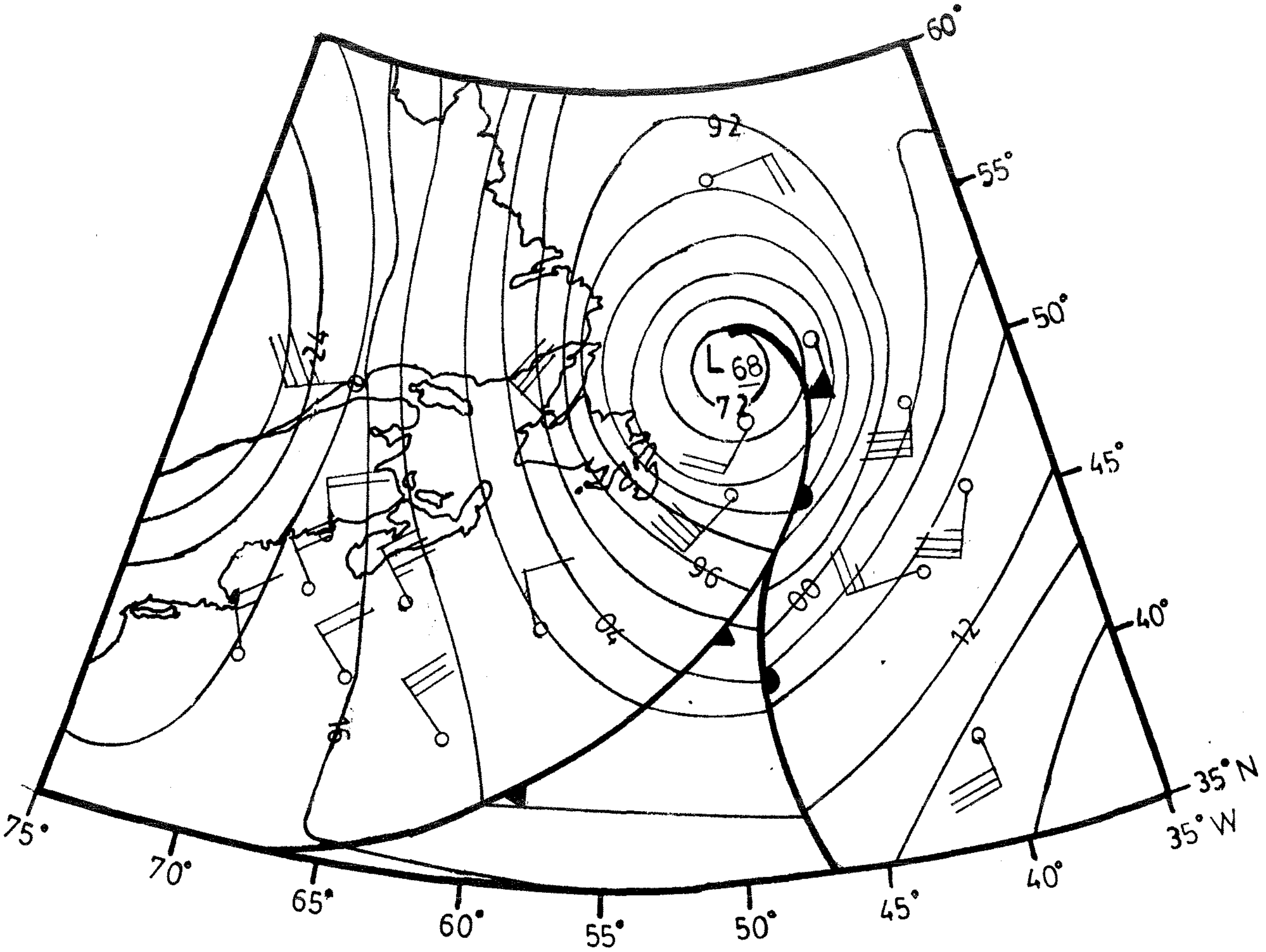

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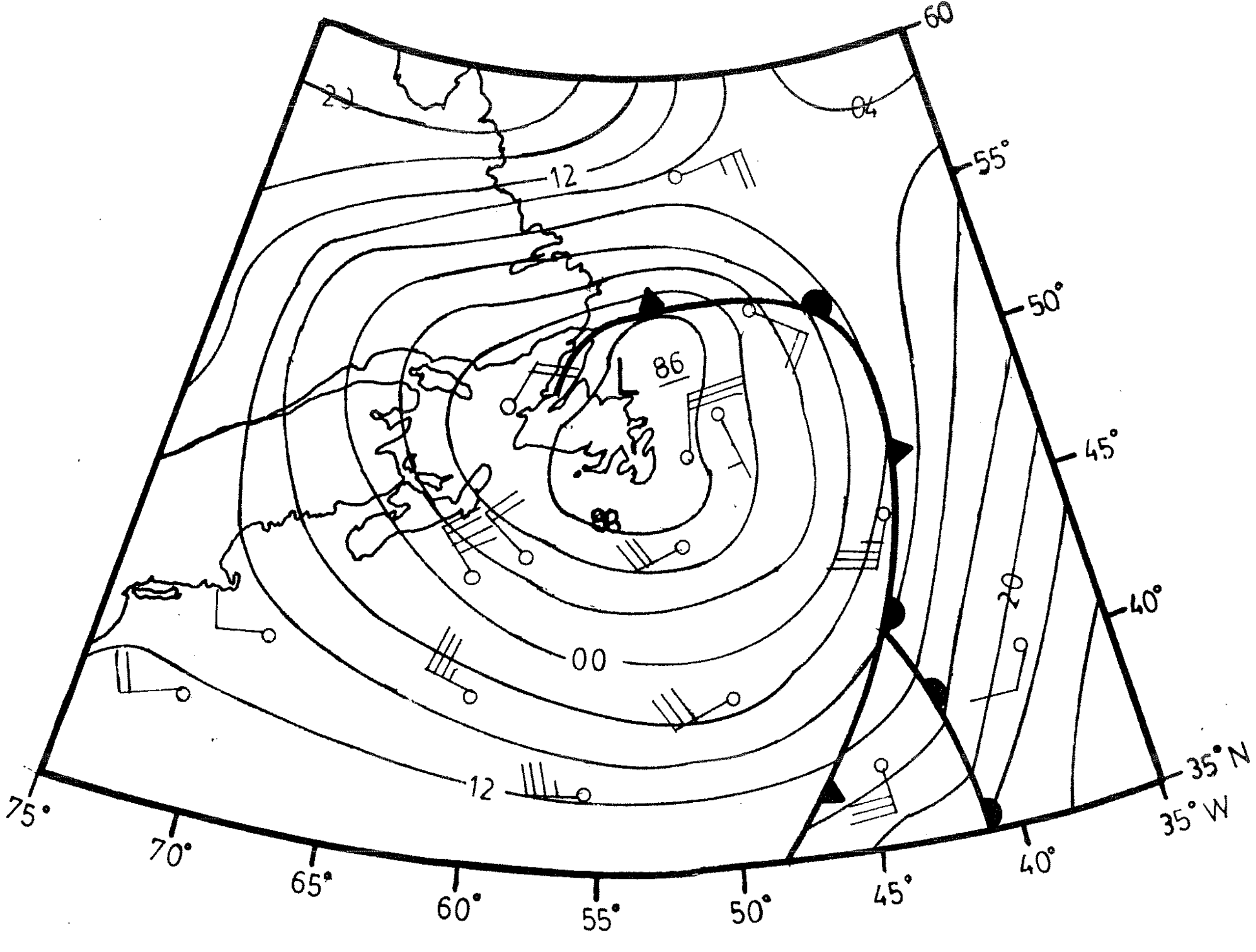
APRIL 2-11,1974



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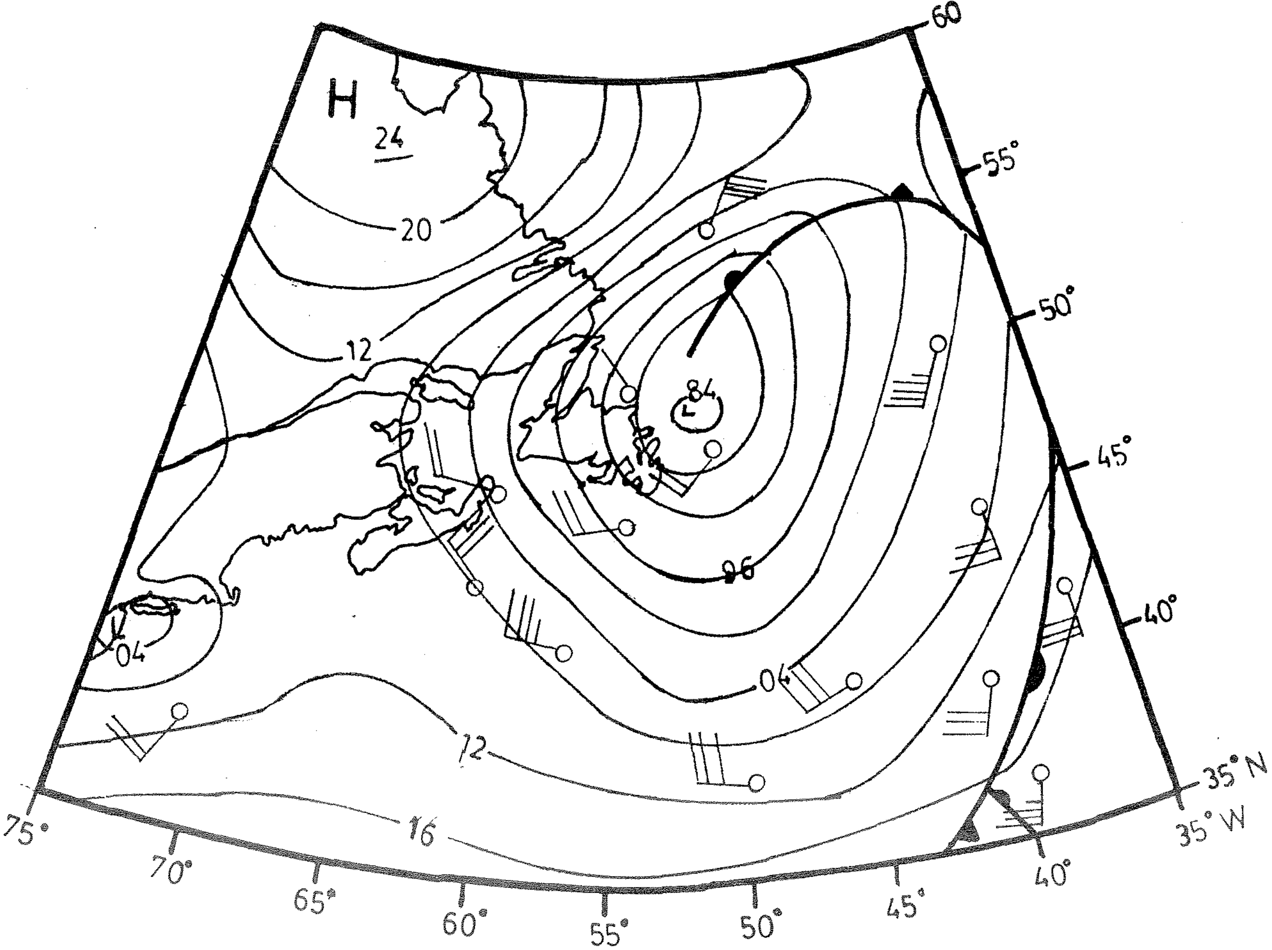
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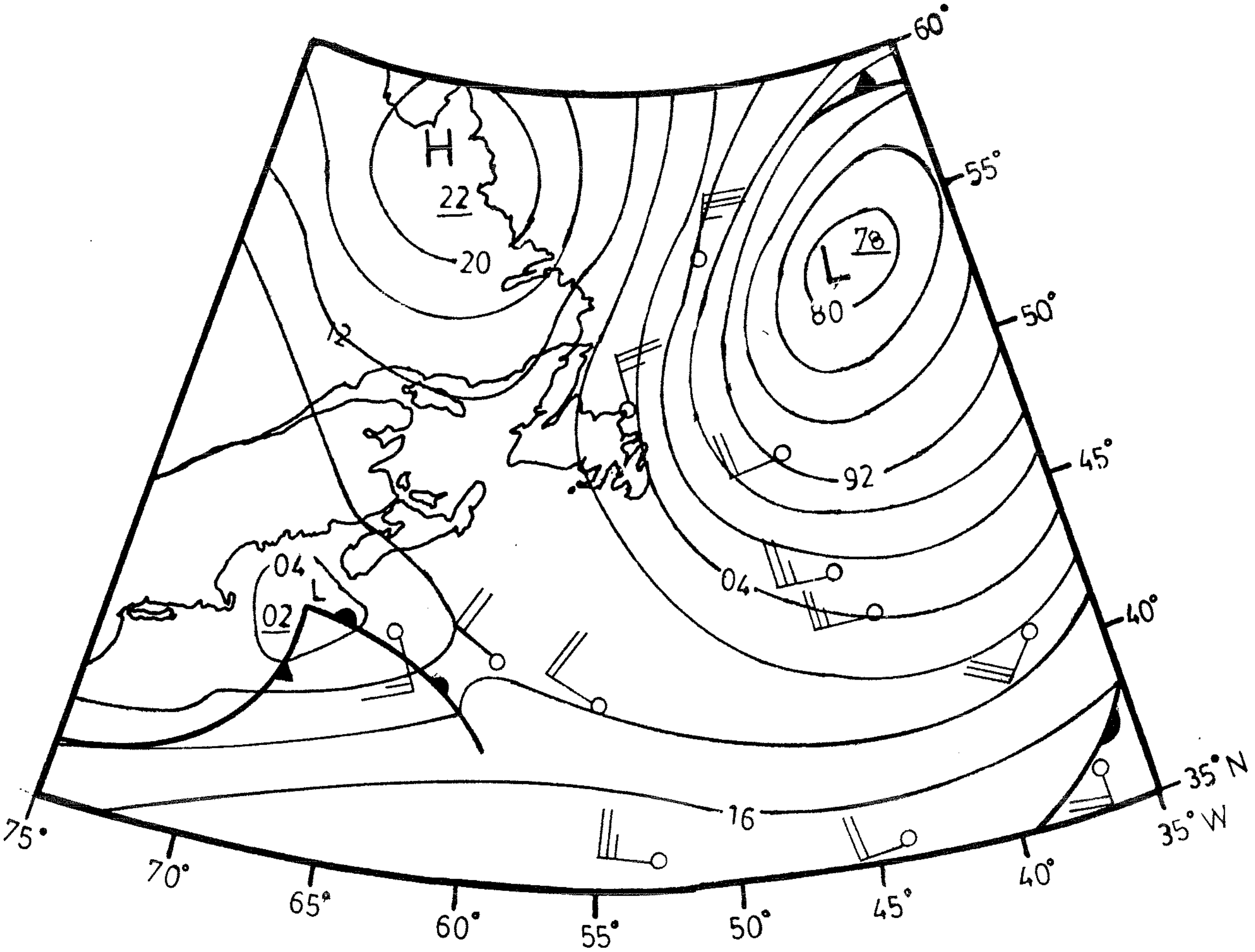
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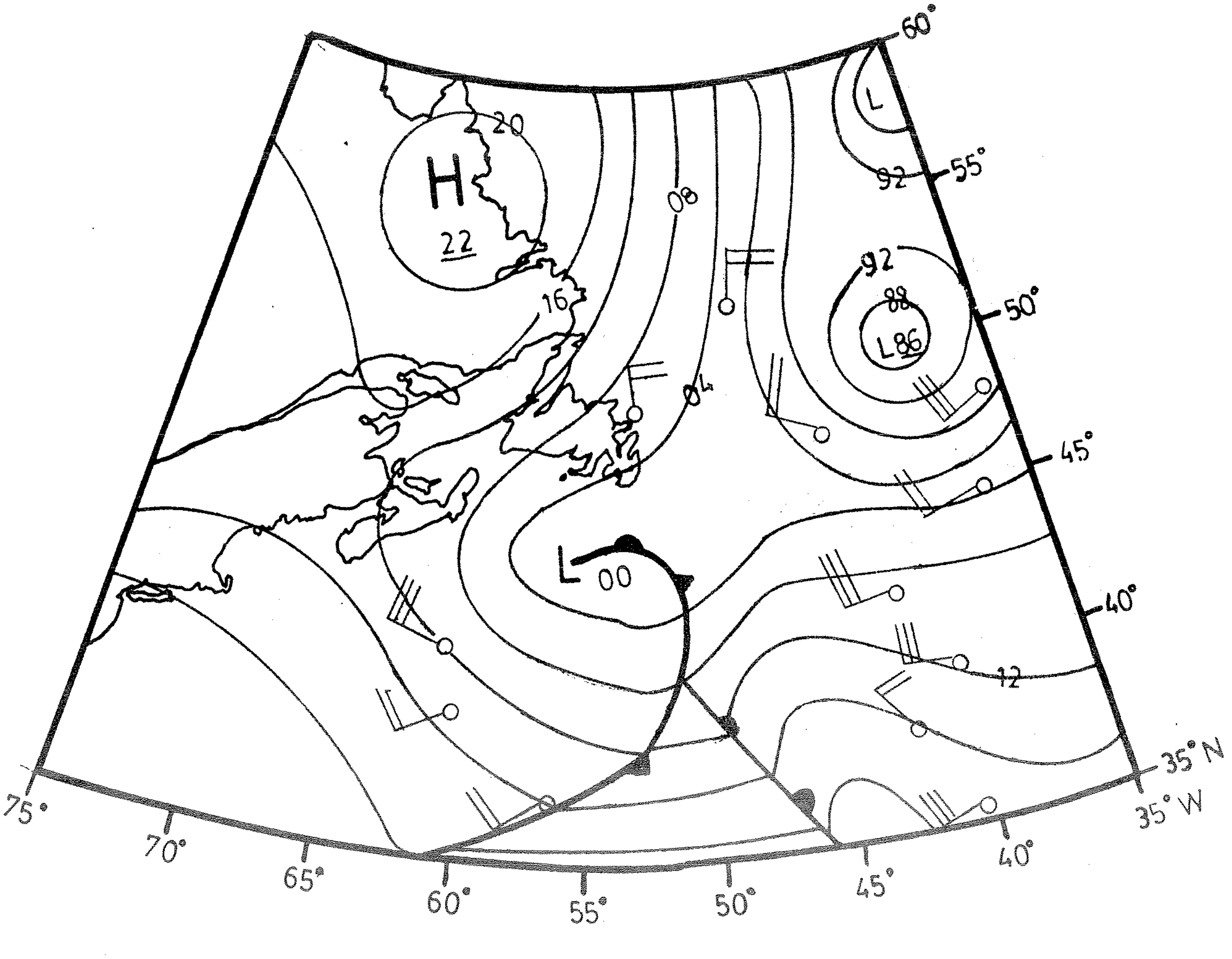

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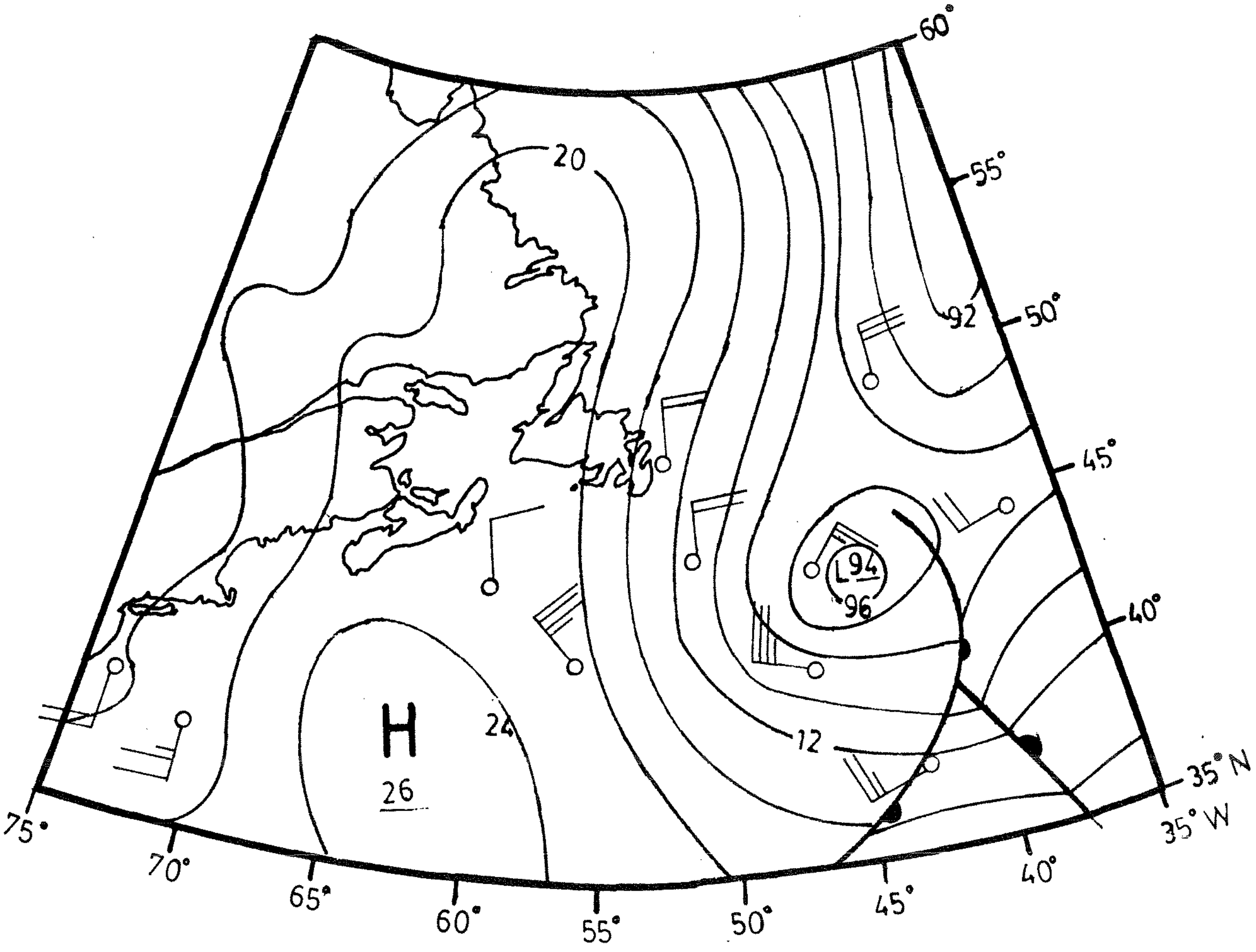

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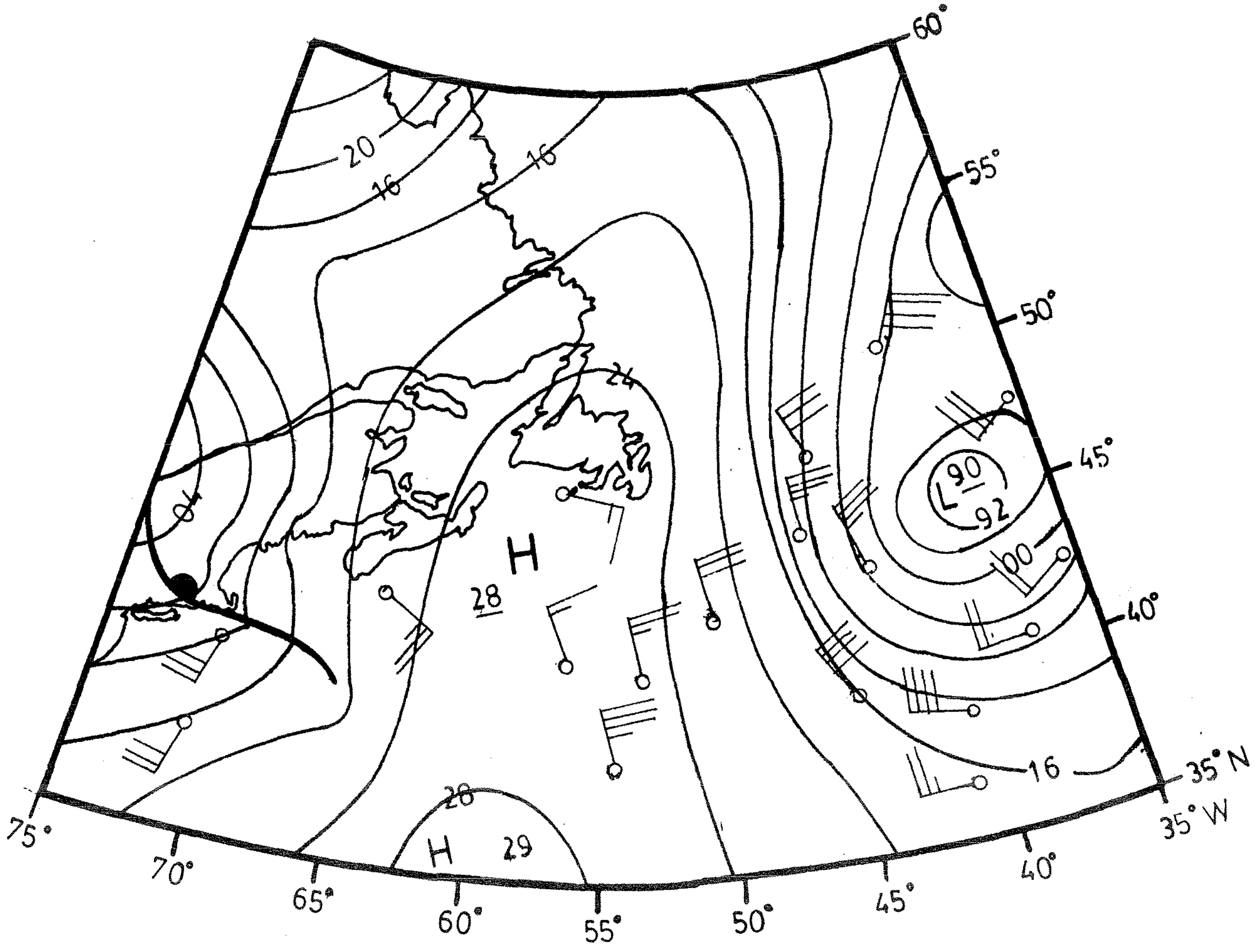
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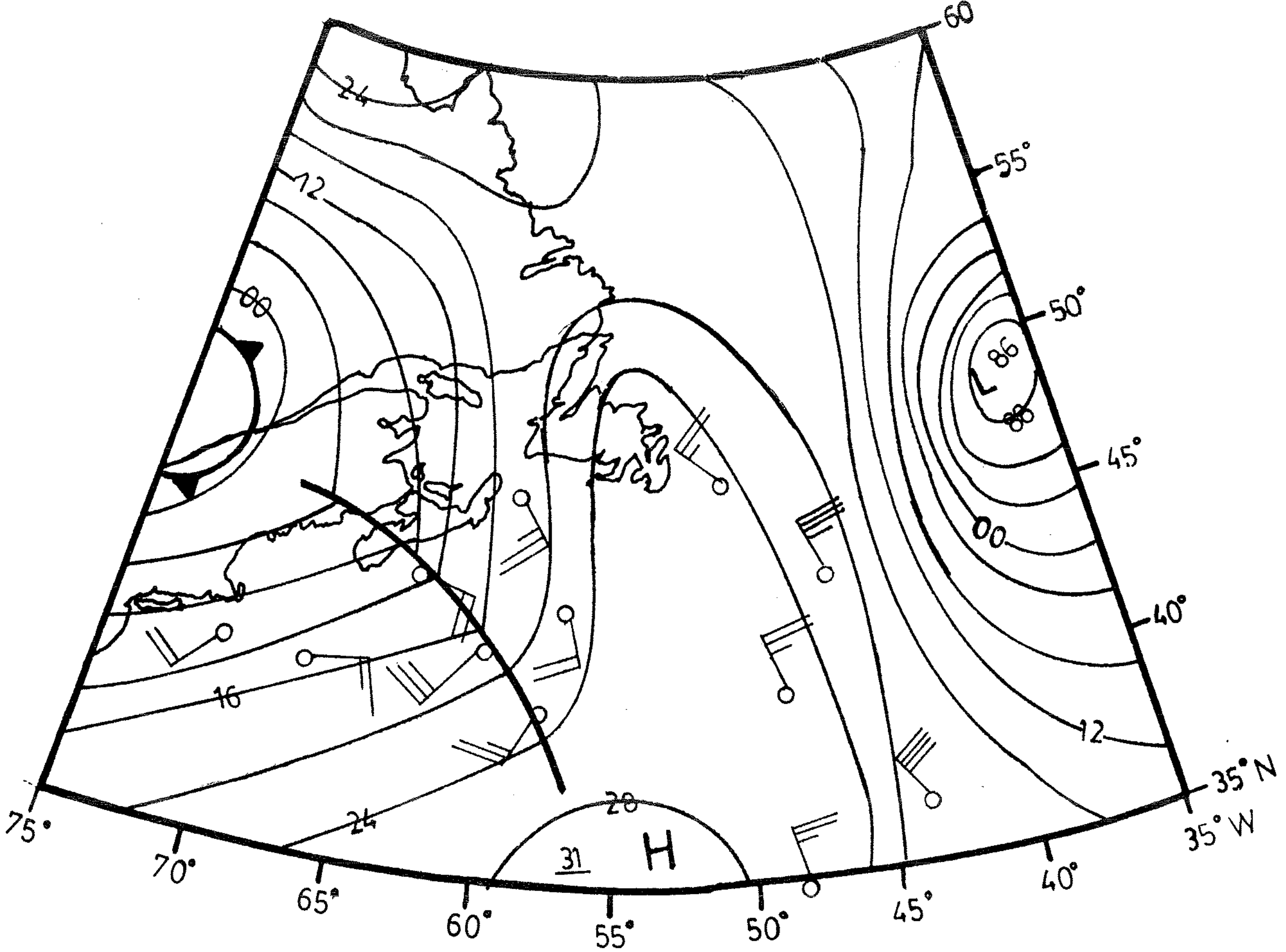

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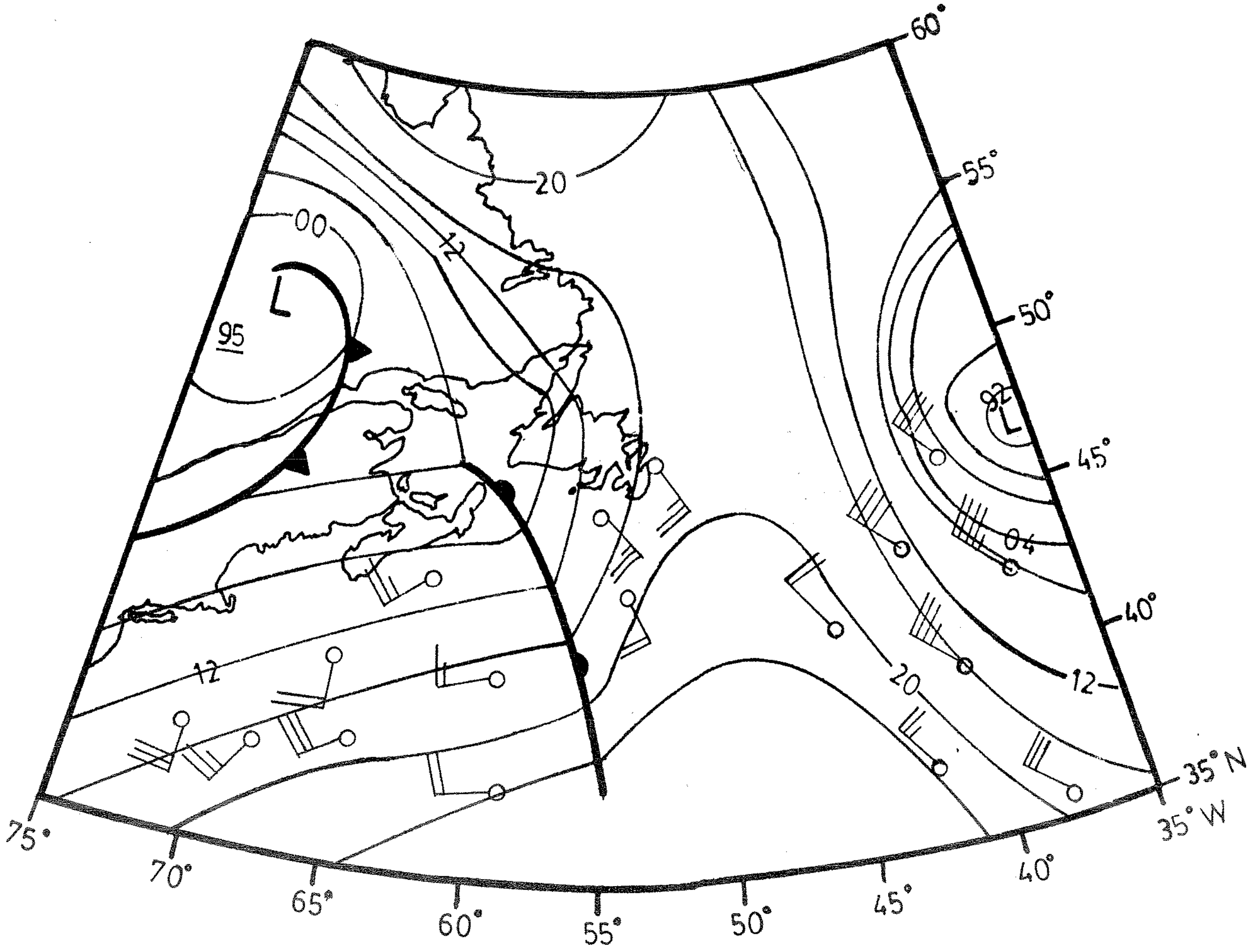

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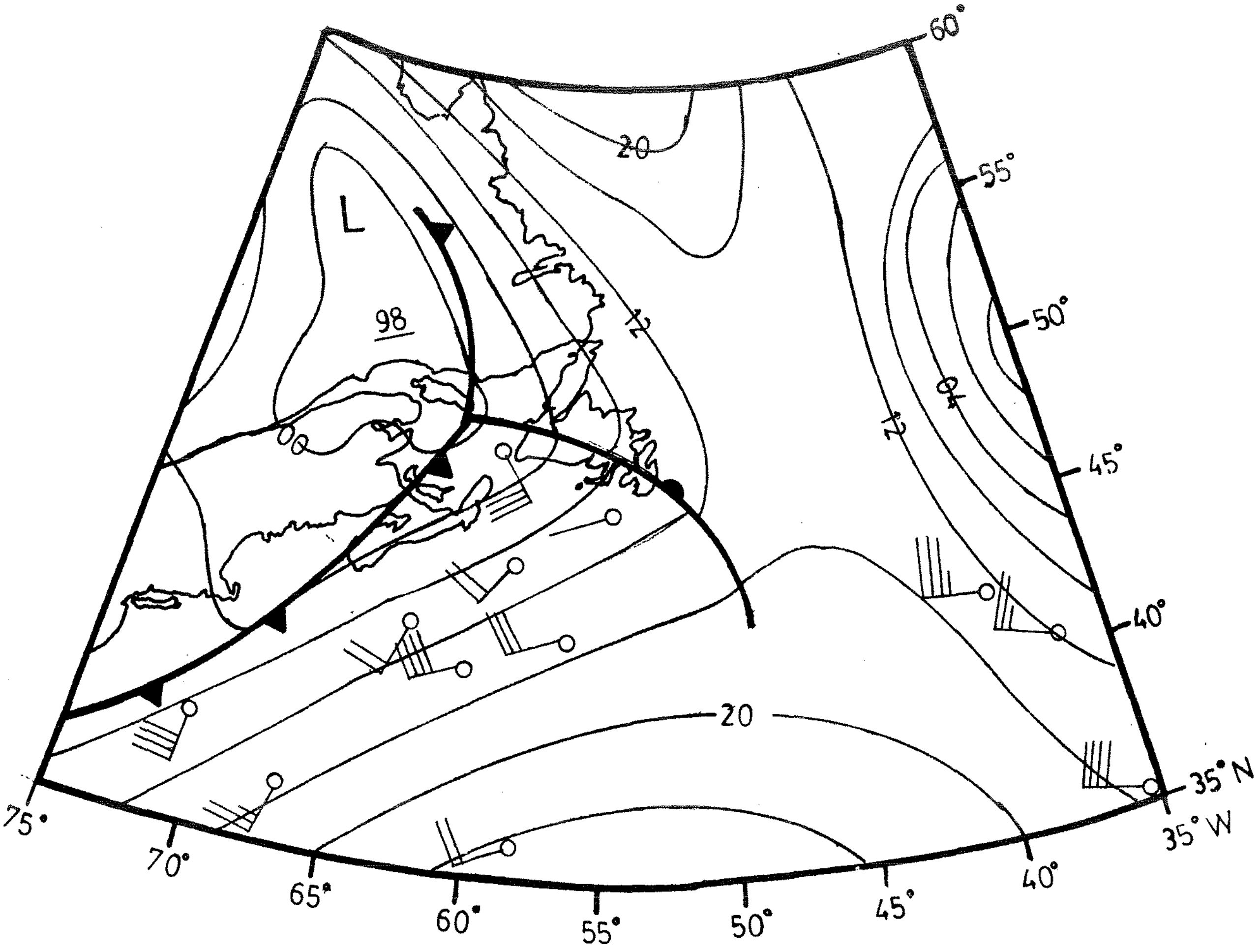

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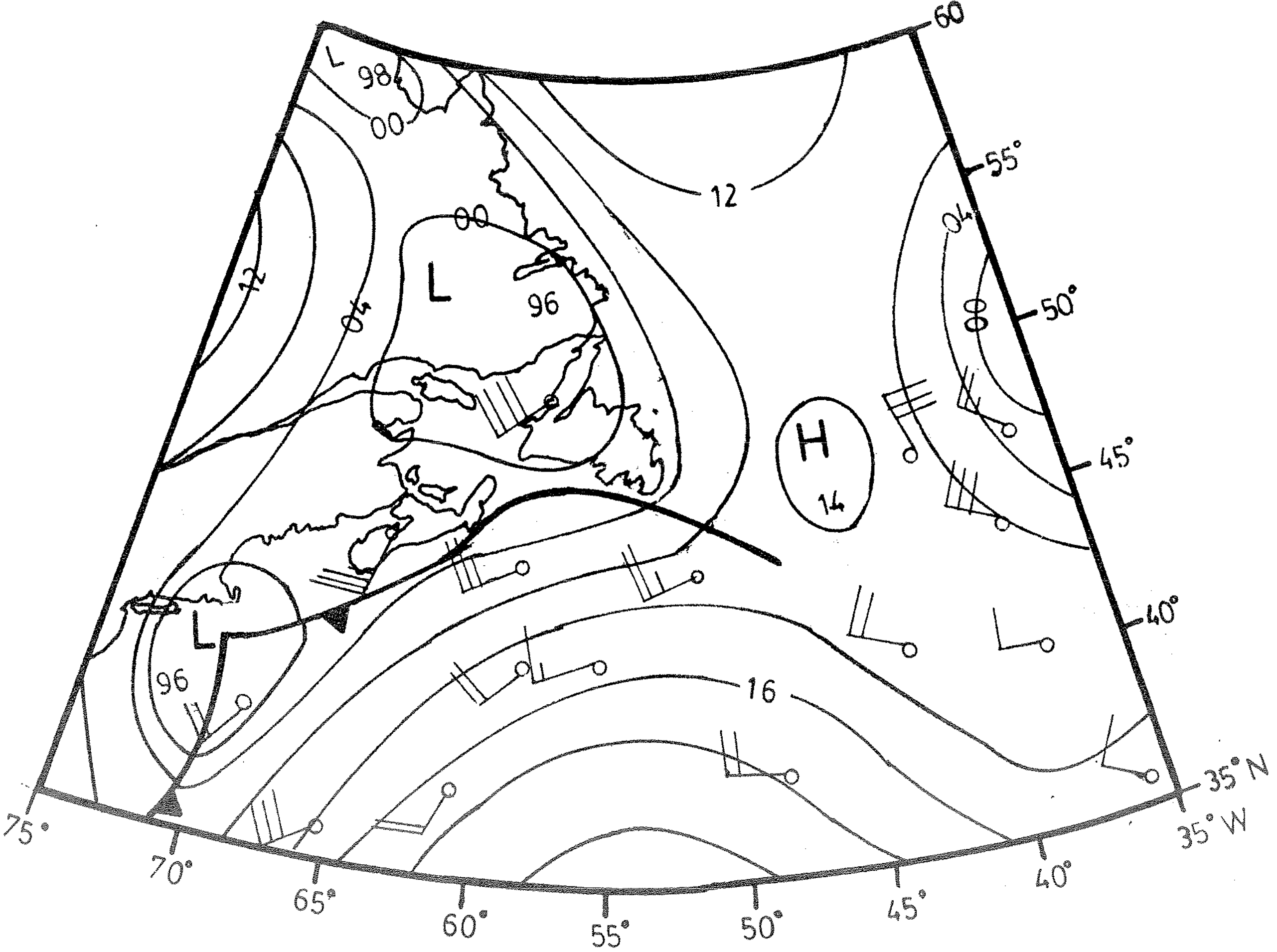
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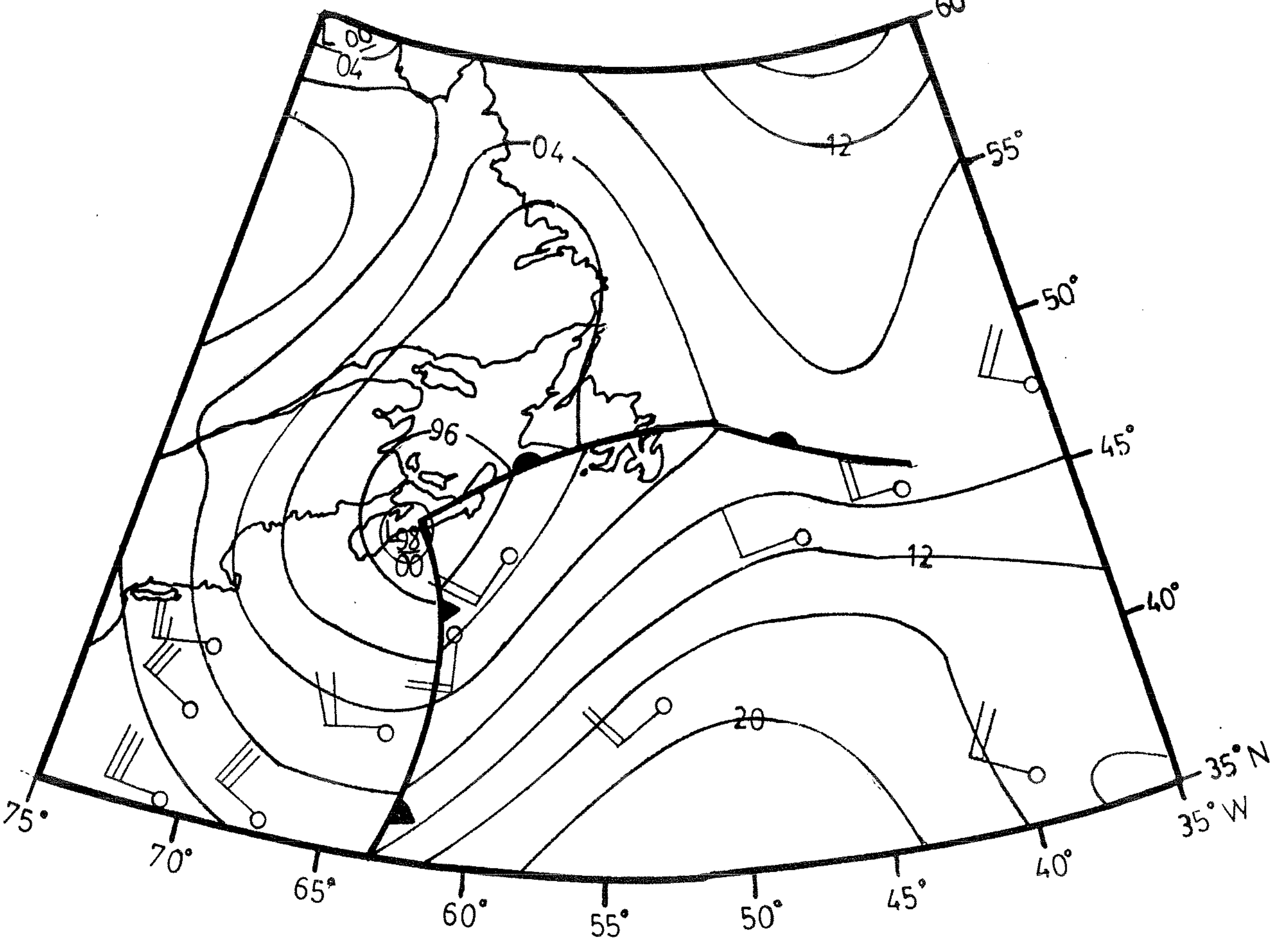

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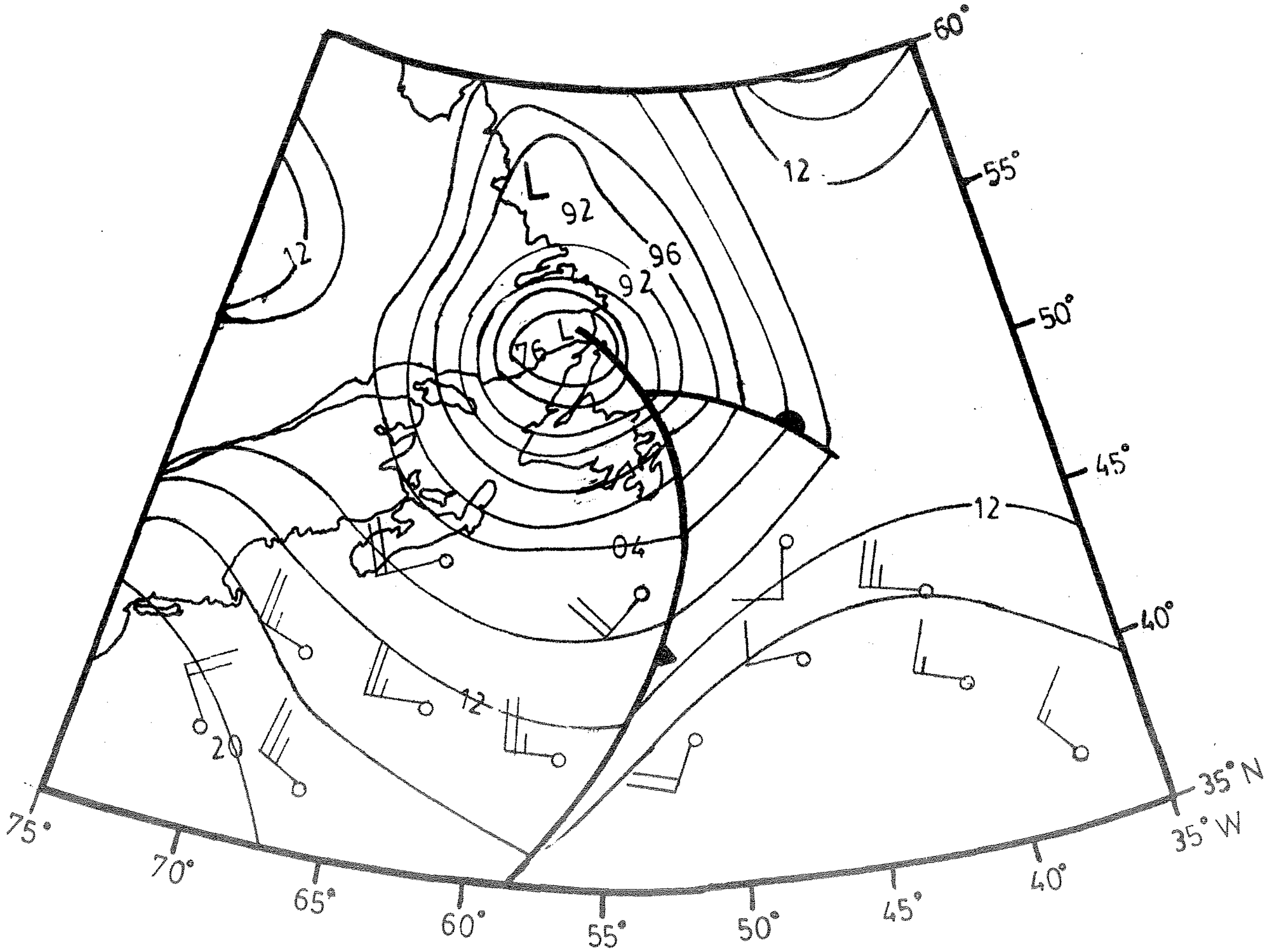
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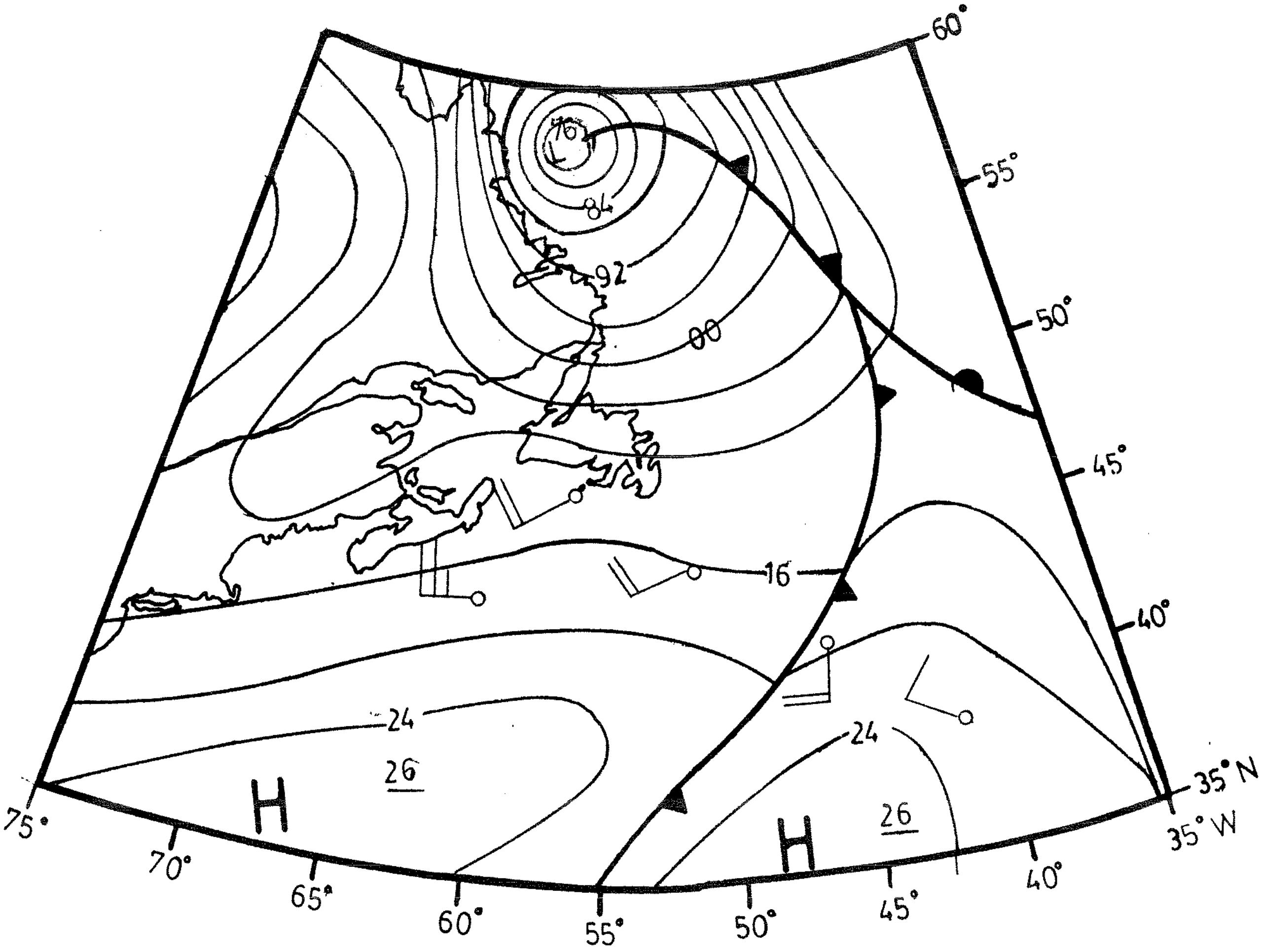

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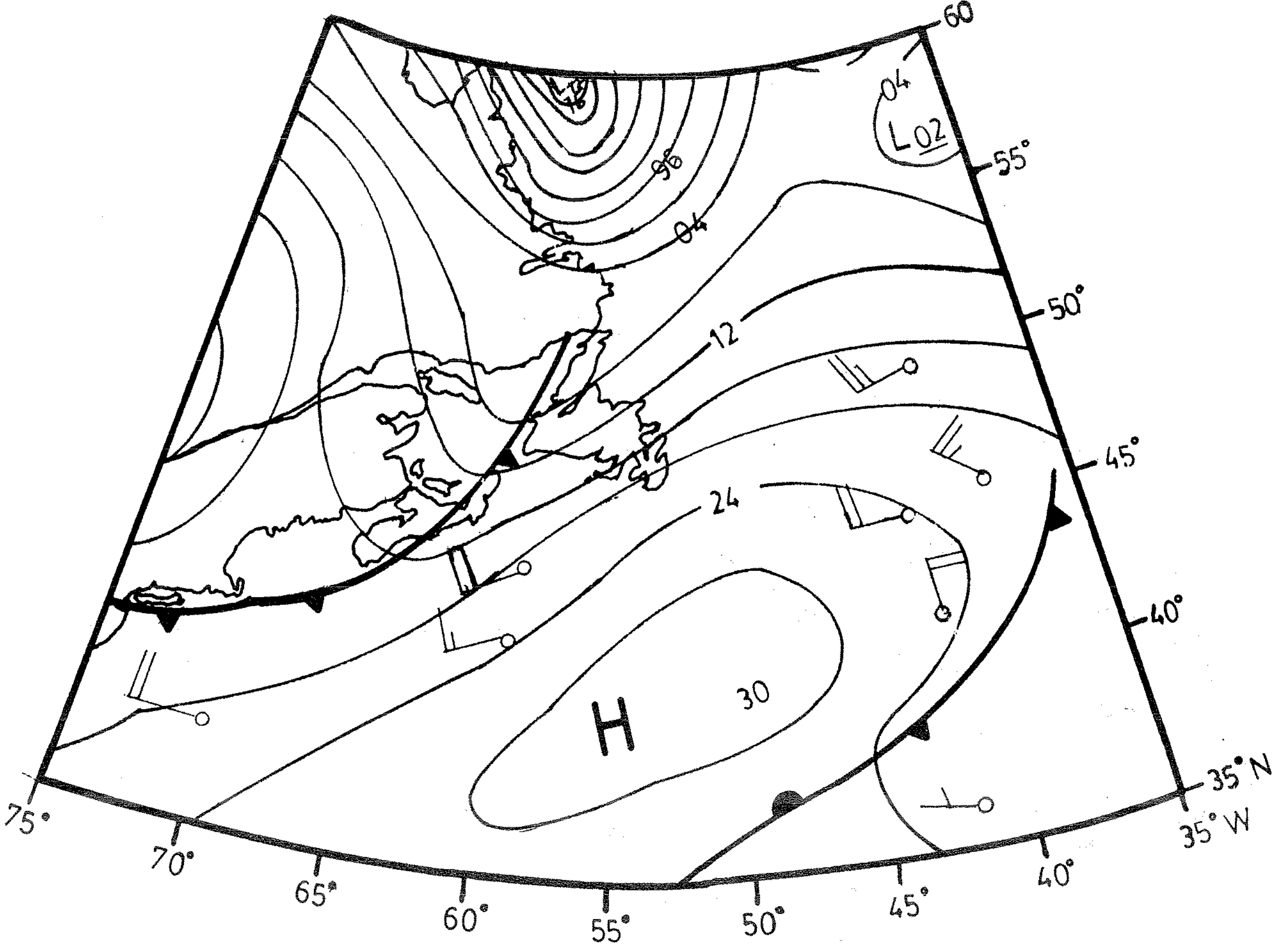

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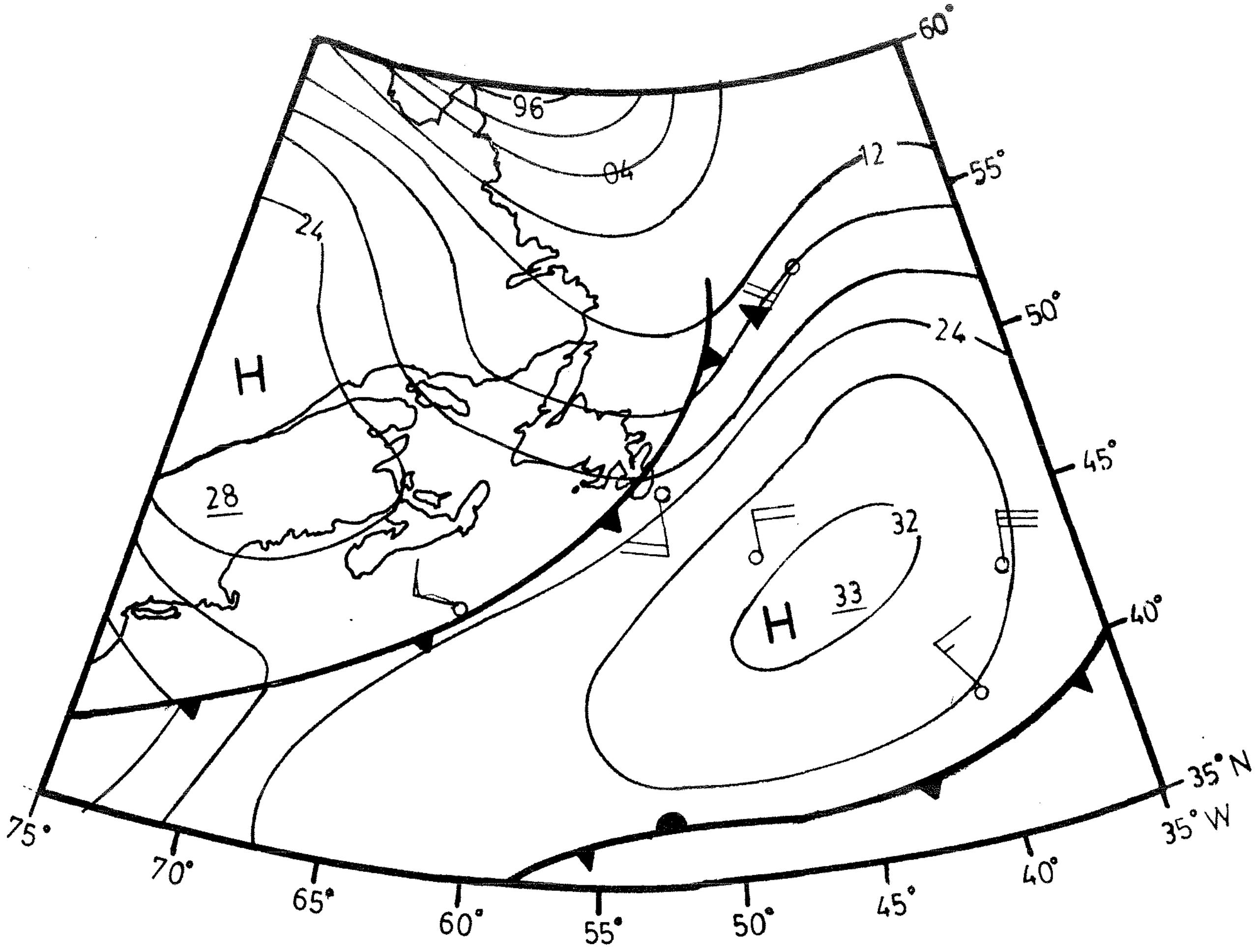
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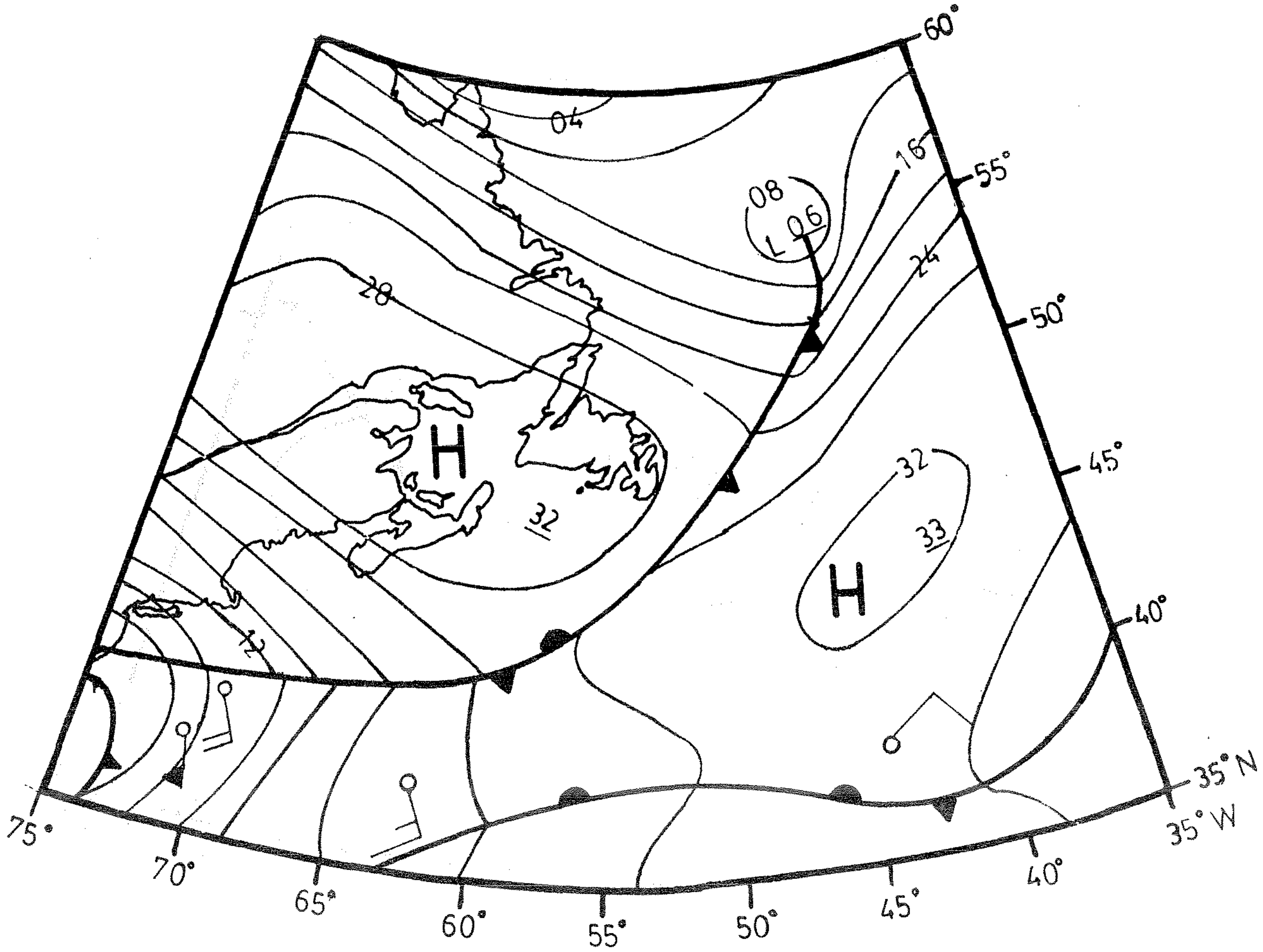
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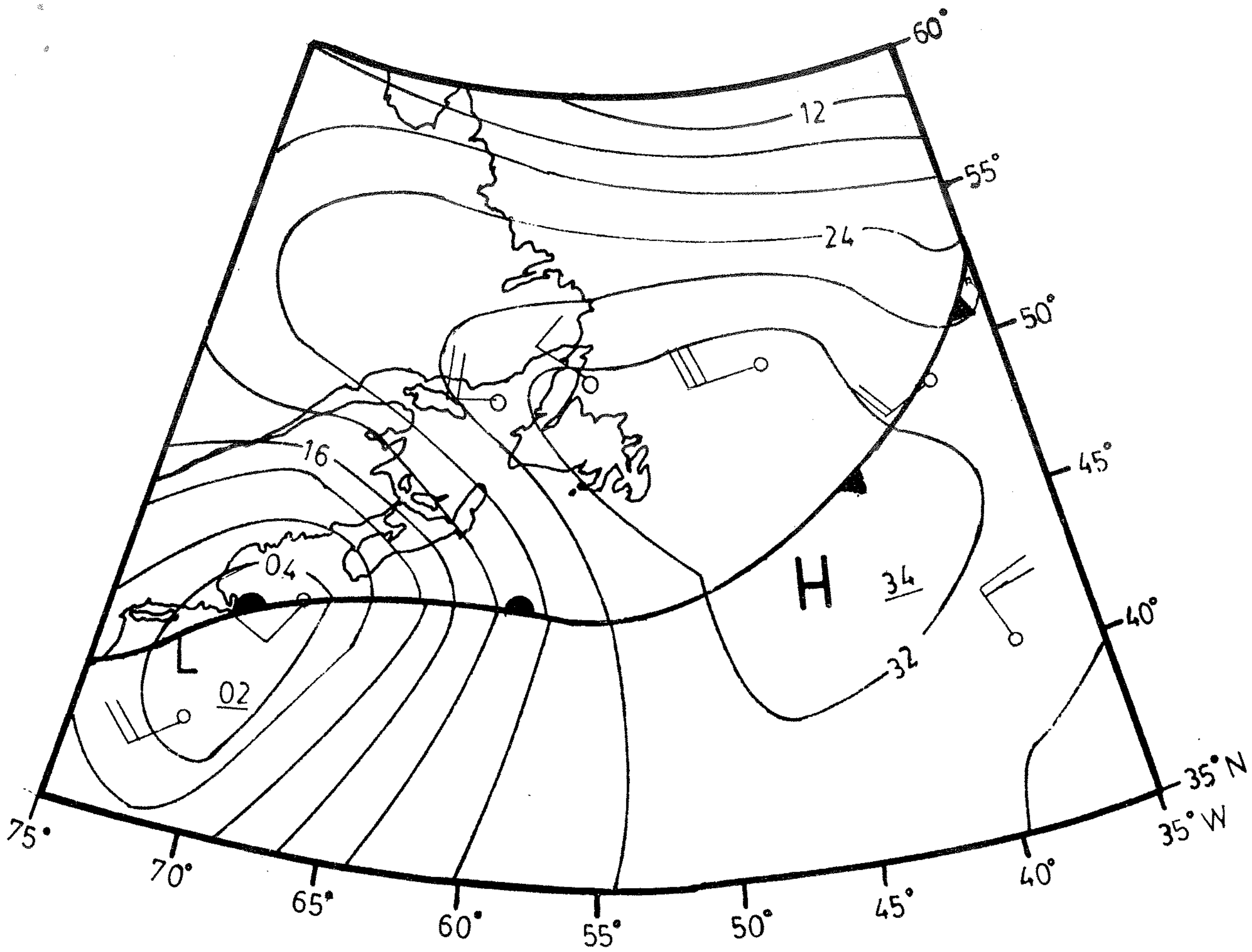

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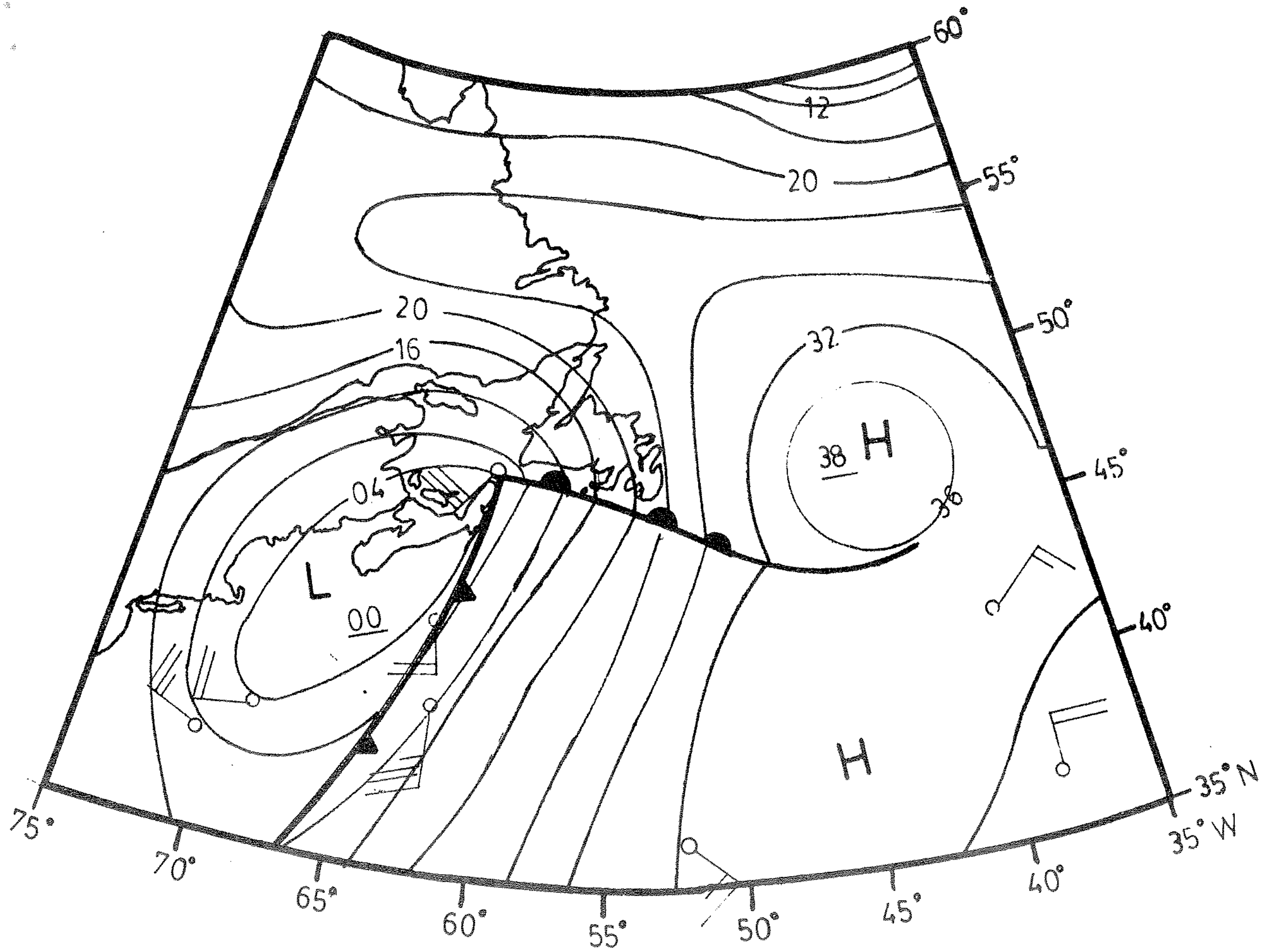
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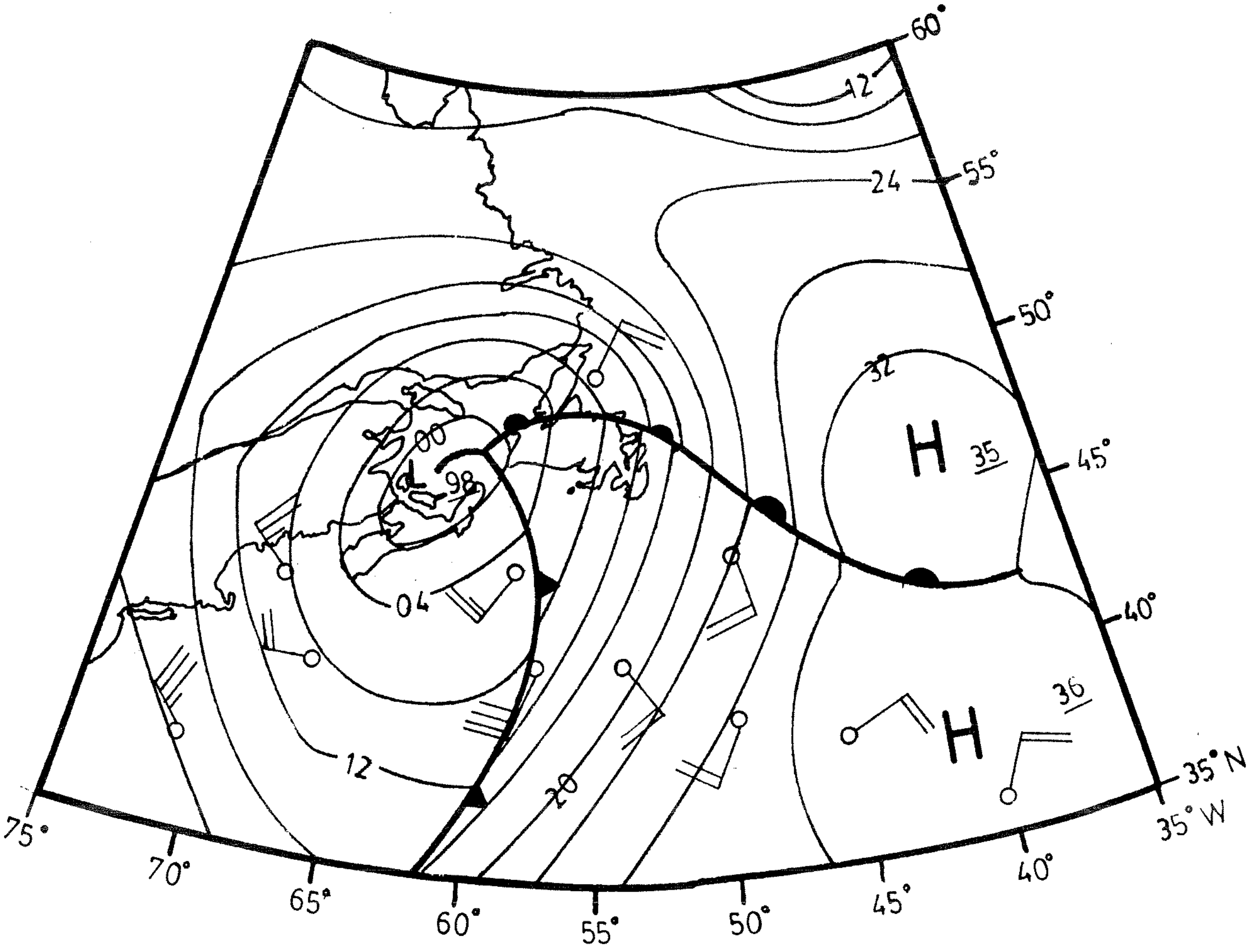
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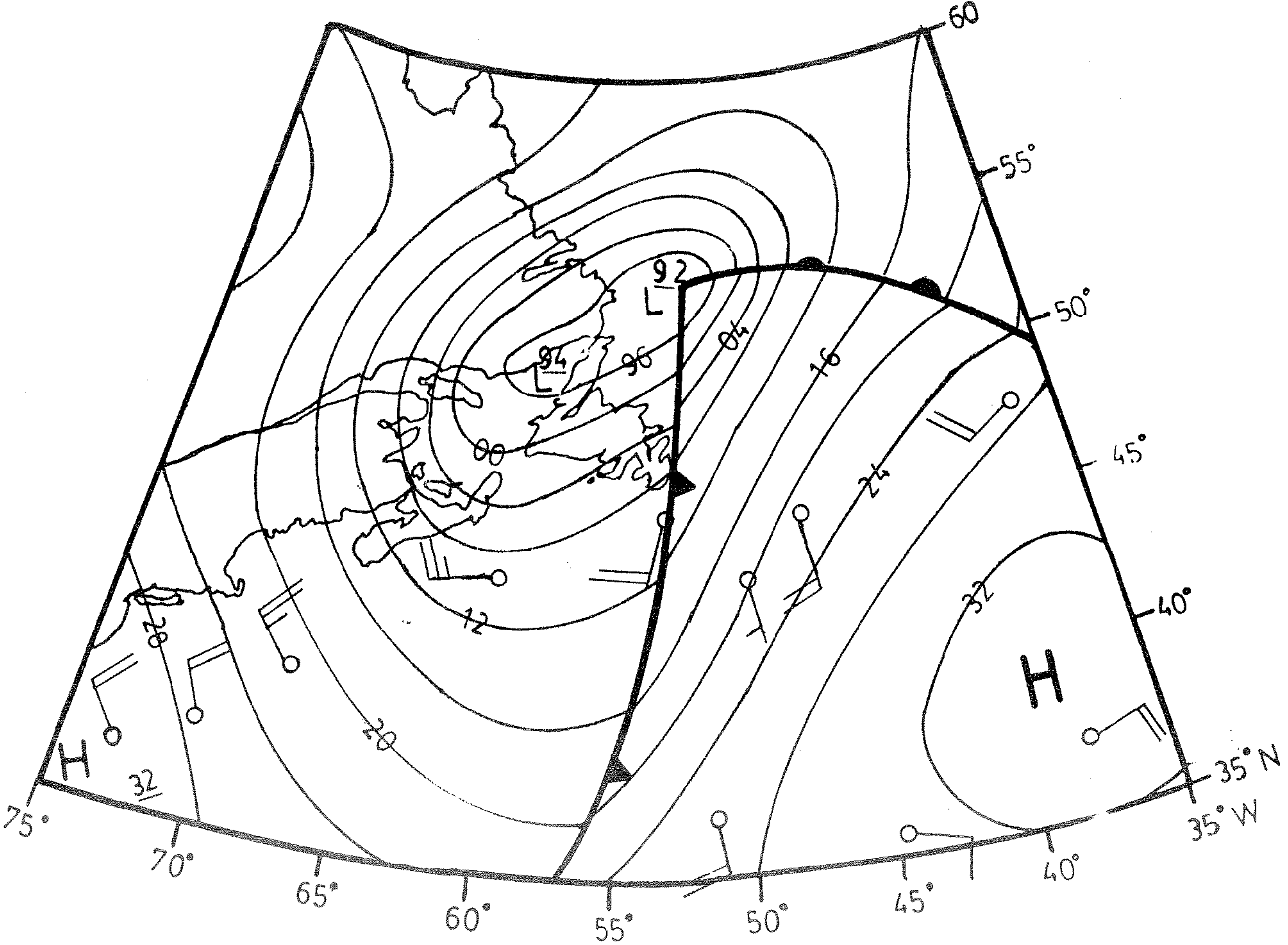
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