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020 Climatology of Severe Storms Affecting Coastal Areas of Eastern Canada

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CLIMATOLOGY OF SEVERE STORMS AFFECTING COASTAL AREAS OF EASTERN CANADA

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Thanks are also extended to D. McGillivray for his many useful comments during the review of the draft manuscript.

ACRONYMS

The following acronyms are used in this text:

AES	Atmospheric Environment Service (Dept. of the Environment, Canada)
ESRF	Environmental Studies Revolving Funds
FNWC	Fleet Numerical Weather Central (United States Dept. of Navy)
MAST	Marine Statistics (AES software facility)
MEDS	Marine Environmental Data Service (Dept. of Fisheries and Oceans, Canada)
METOC	Meteorological and Oceanographic Centre (Dept. of Defence, Canada)
NEDN	Naval Environmental Data Network (United States Dept. of the Navy)
NOAA	National Oceaographic and Atmospheric Agency (United States)
NWS	National Weather Service (United States)
PM	Pierson-Moskowitz spectrum
SMB	Sverdrup-Munk-Bretschneider
SOWM	Spectral Ocean Wave Model (Canada)
SSI	Storm Severity Index
WES	Waterways Experimental Station

SUMMARY

The Environmental Studies Revolving Funds (ESRF) initiated a study in January, 1984, to identify significant wave-producing storms affecting areas off the Canadian east coast. The specific objectives were to select the 30 to 35 most severe wave-producing storms, characterizing them by season and by meteorological type.

The main study rationale is outlined in a recommendation made by Resio (1982) regarding design wave specifications for the Canadian continental shelf: because of the sensitivity of wave hindcast models to the specification of the wind field (this is particularly critical for extreme events), it was recommended that a set of 20 to 30 of the largest storms be selected so that the wind fields could be re-analysed employing greater forecaster input than had been used in previous wave hindcasts. These storms would then be hindcast, the results forming the basis of design wave information for the Canadian east coast. The other rationale for the study was to provide a synthesis of the spatial, temporal, and meteorological characteristics of large wave-producing storms affecting east coast offshore areas.

The delineation of seven regions selected for severe storm identifications (see Fig. 1) was based on regions prescribed by ESRF and on marine forecast areas of the Atmospheric Environment Service (AES). Following definition of the study areas, a variety of data sources were assembled for each region to allow identification of potentially severe wave events.

The main sources consulted were the spectral ocean wave model (SOWM) and Waterways Experimental Station (WES) wave hindcasts covering the period 1956-75. These were supplemented by Canadian Forces Meteorological and Oceanographic Centre (METOC) wave data from 1972-82, AES geostrophic wind hindcast data from 1946-78, the Fleet Numerical Weather Central (FNWC) Naval Environmental Data Network (NEDN) data set from 1974-82, itinerant ship observations beginning in the late 1800s and measured wave data beginning in the early 1970s. Because of the lack of available data for severe storm identification prior to 1946, the study period was defined to covr the 37 years from 1946-82.

The storm selection methodology involved three main processes:

- selection of potentially severe storms;
- storm verification; and
- storm ranking.

For the SOWM and WES hindcasts, software was developed to provide storm summaries. A storm was defined for this purpose as a wave event exceeding 6.0 m in height (4.0 m in Baffin Bay) for a duration of greater than 6 hours. The interval between "independent" storms was arbitrarily set at 18 hours as severe storm independence was to be assesed at a later stage through consultation of synoptic charts. Storm summaries were carried out at each grid point within a defined region (see Figure 1) and storms ranked separately based on maximum storm wave height and a storm severity index (SSI) calculated from the product of mean storm wave height and storm duration.

The top 30 storms from each hindcast point within a region for each ranking scheme were combined to form regional ranked files of storms based on maximum storm wave height and SSI. The top 30 storms from each of these files usually produced 45 to 50 potentially severe storms for subsequent verification. Potential storms from the other data sources were obtained by extracting extreme value listings above various thresholds using the Marine Statistics (MAST) software facility at AES. A Bretschneider (CERC 1977) nomogram was used with the AES geostrophic wind data to estimate storm wave heights. This initial identification process for severe storms typically yielded around 60 to 70 potentially severe storms per region. Ice cover effects were ignored in all regions except Baffin Bay where an ice-free period from July to November was assumed.

Storm verification was carried out at two levels: first, storms identified as potentially severe were verified with other data sources. Secondly, during the process of obtaining synoptic charts for the initially verified severe storms, forecasters were able to check whether the pressure gradients were sufficient to produce a major wave event.

To determine the 30 worst storms for each region, all the verified storms were hindcast using a Bretschneider nomogram (CERC 1977) with geostrophic winds derived manually from surface pressure charts. This approach has limitations for the accurate hindcasting of storm waves. However, these limitations are not as critical when the methodology is being applied within the same geographical region for the sole purpose of ranking storms.

Tables presenting the final lists of ranked storms for each region are presented in Appendix 4 and the performance of the various data sources used for identifying severe storms is discussed. In general, the SOWM wave hindcast was found to be the most useful. Interestingly, the amount of overlap between severe storms identified by SOWM and WES was very low: taking the top 30 height-ranked storms from both hindcasts, the degree of overlap averaged 9 to 10 storms in Region 2, 3, 4, and 5, which included points from both hindcasts. A comparison of the selected severe storms with the results of other similar studies carried out for east coast oil operators was not made because of the proprietry nature of these studies.

The annual distribution of severe events over the entire study domain revealed exceptionally intense weather and sea conditions in 1972 and 1974. Similar peaks in the number of severe storms were reported by Lewis and Moran (1984). These peaks were shown to be real rather than the by-product of bias in the storm selection process, in agreement with other investigators of secular variability in cyclonic activity in the northern and eastern coastal zones (Zishka and Smith 1980; Saulesleja and Phillips 1982).

The seasonal distribution of storms showed that severe wave producers were primarily cold-season events. This result was consistent with the observation that nearly two-thirds of the storms were explosive cyclones, as defined by Sanders and Gyakum (1980), with the monthly histograms showing striking similarity to those of the above authors. The monthly storm tracks suggested that most of the maritime storms were associated with outbreaks of Arctic air across the baroclinic (thermal contrast) zone of the east coast.

This observation was consistent with the work of Sanders and Gyakum (1980), and that of Dickson and Namias (1976), who demonstrated the importance of enhanced baroclinicity at the Atlantic seaboard with respect to increased cyclonic activity along the coastal areas.

The regional storm classification analyses showed the dominance of the storm track along the Atlantic coast, which included from 60 to 90% of all storms in Regions 1 to 5, tapering off to 55% and 12% in Regions 6 and 7, respectively. Little evidence in this study supports the separation of storm populations on the basis of origin in the analysis of extreme waves as suggested by Readshaw and Baird (1981), with the possible exceptions of Region 6 and 7. The most crucial aspect of a storm in terms of its eventual association with a severe wave event in a particular region did not appear to be the origin of the storm but rather its eventual track across either continental or maritime areas. The evolution and extent of the development of cyclones appeared to be intimately involved with this general classification of storm tracks following the findings of Roebber (1984) and Sanders and Gyakum (1980).

The usual severe wave-producing winds were from the northerly direction, although the channeling of the wind along the NW-SE corridor of the Davis Strait and Baffin Bay was important in Region 6, and was dominant in Region 7. In particular, northwesterly flow was predominant, most probably resulting from enhanced vertical exchange in the unstable airmass following a storm, which produces stronger norhtwesterly winds.

A majority of the severe storms were observed to undergo an explosive development phase which conforms to the finding of Sanders and Gyakum (1980) that rapidly deepening storms account for the vast majority of the most intense cyclones.

To investigate the relationship between storm intensity and wave height a correlation analysis was performed relating storm ranking to storm central pressure at the approximate time of the wave event, based on the expectation that the degree of storm intensity and the strength of the pressure gradient, and consequently the magnitude of the wind-driven waves, are indicated by this variable. In general, a weak positive correlation was found, suggesting that the effects of wind, fetch, and duration also needed to be included in the analysis to account for more of the variance in storm rankings.

RÉSUMÉ

Les Fonds renouvelables pour l'étude de l'environnement (FREE) commença une étude en janvier 1984 pour l'identification des tempêtes créant des vagues majeures qui affectent les régions côtières de l'est canadien. Les objectifs spécifiques étaient de sélectionner les 30 à 35 plus violentes tempêtes créant des vagues extrêmes, et de les caractériser par saison et par type météorologique.

Le rationnel principal de l'étude est souligné dans une recommendation faîte par Resio (1982) concernant des spécifications sur les vagues types pour le plateau continental canadien: à cause de la sensibilité des "arrière-prévisions" de vagues à la spécification des champs de vent (ceci soyant particulièrement critique dans des événements extrêmes), il a été recommandé qu'une série de 20 à 30 des plus violentes tempêtes soient choisies pour que les champs de vent puissent être ré-analysés en employant de façon plus considérable le jugement de la part du prévisionniste qu'était le cas dans les préalables études des "arrière-prévisions" de vagues. Ces tempêtes seraient alors "arrière-prévisionnées", les résultats donc, formant la base d'informations pour les vagues types des régions côtières de l'est canadien. Le second rationnel de l'étude était de produire une synthèse des caractéristiques spéciaux-temporaux et météorologiques des tempêtes créant les vagues extrêmes affectant les régions côtières de l'est.

Le tracé des sept régions sélectionnées pour l'identification des violentes tempêtes (voir figure 1) a été basé sur les régions prescrites de FRÉE et sur les zones de prévision maritimes de SEA. Suivant la définition des régions,

une variété de sources de données a été assemblée pour chacune des régions, afin de pouvoir identifier les événements qui puissent produire des vagues extrêmes.

Les sources principales consultées comprient les "arrière-prévisions" de vagues couvrant la période de 1956 à 1975, de "spectral ocean wave model (SOWM)", et de "Waterways Experimental Station (WES)". A ces renseignements ont été ajoutées: des données de vagues, couvrant la période de 1972 à 1982 de "Meteorological and Oceanographic Centres of the Department of the National Defence"; des données de vents géostrophiques analysées par SEA, couvrant la période de 1946 à 1978; les données couvrant la période de 1974 à 1982 de "Fleet Numerical Weather Central (FNWC)" "Naval Environmental Data Network (NEDN)"; des observations de navire itinérant commençant vers la fin du 19ème siècle; et des données de vagues mesurées dès la décennie de 1970. A cause de manque de données disponibles pour les identifications de violentes tempêtes avant 1946, la période d'étude a été définie pour couvrir les 37 années entre 1946 et 1982 inclusivement.

La méthodologie pour la sélection des tempêtes comprit trois méthodes principales:

- la sélection des tempêtes efficacement violentes;
- la vérification des tempêtes; et
- la classification des tempêtes.

Pour les "arrière-prévisions" de SOWM et WES, un logiciel a été développé pour fournir des sommaires de tempêtes. Or, pour ce but, une tempête a été définie comme un événement de vagues extrêmes dépassant 6,0 m de hauteur

(4,0 m dans la Mer Baffin) pour une durée de plus de 6 heures. Comme l'indépendence des violentes tempêtes devait être évaluée dans une étape suivante par la consultation des cartes synoptiques, l'intervalle entre les tempêtes "indépendantes" a été arbitrairement fixé à 18 heures. Des sommaires de tempêtes ont été exécutés à chaque point de grille à l'intérieur d'une région précise (voir la figure 1.). Ces tempêtes ont été classées séparément, basées sur la hauteur maximum des vagues de tempêtes et sur l'index de gravité de la tempête (IGT) qui a été calculé par le produit de la moyenne de la hauteur des vagues et de la durée de la tempête.

Les 30 premières tempêtes de chaque point "d'arrière-prévision" à l'intérieur d'une région précise, pour chaque système de classification, ont été réunies afin de former des fichiers de tempêtes classés par région, celles-ci étant basées sur la hauteur maximum des vagues de tempêtes et sur l'IGT. Généralement, les 30 premières tempêtes de chacun de ces fichiers produisaient 45 à 50 tempetes efficacement graves pour une vérification subséquente. D'autres tempêtes efficaces ont été obtenues par des renseignements de données où l'on a retiré des listages les valeurs extrêmes au-dessus de divers seuils, en utilisant le logiciel "Marine Statistics" MAST offert à SEA. Un nomogramme de Bretschneider (CERC 1977) a été utilisé avec les données de vent géostrophiques de SEA, afin d'estimer les hauteurs de vagues de tempêtes. Ce processus initial pour l'identification de violentes tempêtes a produit typiquement par région environ 60 à 70 tempêtes efficacement graves. Des effets de concentration de glaces ont été ignorés dans toutes les régions sauf dans la Mer Baffin où une période de libre de glaces a été assumée entre juillet et novembre.

La vérification des tempêtes a été exécutée à deux niveaux: premièrement, les tempêtes identifiées comme efficacement graves ont été vérifiées avec d'autres sources de données. Deuxièmement, pendant le processus d'obtenir les cartes synoptiques pour les violentes tempêtes, préalablement vérifiées, les prévisionnistes avaient pu examiner si les gradients de pression avaient été suffisants pour produire un phénomène majeur de vagues.

Pour déterminer les 30 plus mauvaises tempêtes pour chacune des régions, toutes les tempêtes vérifiées ont été "arrière-prévisionnées" d'après le nomogramme de Breitschneider (CERC 1977) avec l'aide des vents géostrophiques qui avaient été dérivés manuellement des cartes de pression. Cette approche a ses limites sur la précision des "arrière-prévisions" des vagues de tempête. Cependant, ces limites ne sont pas si critiques quand la méthodologie est appliquée à l'intérieur de la même région géographique pour le seul but de classer les tempêtes.

Les tableaux illustrant les listes finales des tempêtes classées pour chaque région sont présentés dans l'appendice 4, et le fonctionnement de diverses sources de données utilisées pour l'identification de violentes tempêtes est discuté. En général, "l'arrière-prévision" de vagues de SOWM a été la méthode la plus pratique. Il serait intéressant de noter que le montant de chevauchement entre les tempêtes "violentes" identifiées par SOWM et par WES était très bas: prenant les 30 premières tempêtes classées par la hauteur des deux prévisions, leur moyenne de degré de chevauchement était environ de 9 à 10 tempêtes dans les régions 2, 3, 4, et 5 comprenant des points des deux "arrière-previsions". Aucune comparaison n'a pu être dérivée entre les violentes tempêtes sélectionnées et les résultats d'autres études semblables réalisées pour les opérateurs du forage de pétrole dans les régions côtières de l'est, à cause de la nature propriétaire de ces études.

Dans le domaine entier de l'étude la répartition annuelle des violentes tempêtes a révélé des conditions du temps et de la mer exceptionnellement intenses en 1972 et 1974. De semblables maximums parmi le nombre de violentes tempêtes ont été rapportés par Lewis et Moran (1984). En accord avec d'autres investigateurs pour la variabilité séculaire dans l'activité des zones littorales du nord et de l'est (Zishka et Smith 1980; Saulesleja et Phillips 1982) cette méthode de sélectionnement de tempêtes a prouvé être plûtot réèlle que d'être une fabrication partiellement préjugée.

La répartition saisonnière des tempêtes a révélé que les tempêtes produisant des vagues extrêmes étaient principalement associées avec les phénomènes de saisons froides. Ce résultat est compatible avec l'observation que presque deux-tiers des tempêtes étaient des cyclones détonants, tel que défini par Sanders et Gyakum (1980) et d'après les histogrammes révélant des similitudes éclatantes à celles des auteurs susmentionnés. Les trajectoires mensuelles des tempêtes ont suggéré que la plupart des tempêtes maritimes étaient reliées aux invasions de l'air arctique à travers la zone barocline (contraste thermique) du littoral de l'est. Cette observation était compatible avec l'œuvre de Sanders et Gyakum (1980), et avec celle de Dickson et Namias (1976) qui ont démontré l'importance de la baroclinicité rehaussée dans le littoral atlantique par rapport à l'activité cyclonique qui est augmentée le long du littoral.

Les analyses de la classification des tempêtes régionales ont révélé la dominance de la trajectoire côtière de l'atlantique, qui variait entre 60 et 90% de toutes les régions 1 à 5, et se reduisait à 55 et à 12% dans les régions 6 et 7 respectivement. Sauf pour les régions 6 et 7, il y avait peu de preuves dans la présente étude qui puissent indiquer que la séparation des populations de tempêtes par rapport à l'analyse des vagues extrêmes pourrait être expliquée par leur point d'origine, comme recommandé par Readshaw et Baird (1981). L'aspect le plus critique de la tempête par rapport à son association éventuelle avec le phénomène des vagues extrêmes dans une région particulière n'avait pas paru d'être l'origine de la tempête mais plûtot sa trajectoire éventuelle à travers le continental ou les régions maritimes. Suivant les découvertes de Roebber (1984) et de Sanders et Gyakum (1980), le déroulement et l'étendue du développement des cyclones paraissaient prochement impliqués dans cette classification générale de trajectoires de tempêtes. Toutefois, ceci ne prévient pas la stratification plus détaillée à l'intérieur de la zone maritime comme avait proposé Resio (1978).

Bien que la voie du vent le long du corridor du NO-SE du détroit de Davis et de la mer de Baffin fût importante dans la région 6, et dominante dans la région 7, les vents habituels produisant les vagues extrêmes venaient du nord. Le flux du vent du nord-ouest, en particulier, était prévalent, sans doute à cause de la force relative de ces vents à la suite d'un passage de tempête, et devenus plus forts par l'augmentation de l'échange vertical dans une masse d'air instable.

Une majorité de violentes tempêtes a été observée à subir une phase de développement explosive, conformément aux épreuves de Sanders et Gyakum (1980) à l'effet que les tempêtes qui s'intensifient rapidemment, comprennent la vaste majorité des plus intenses cyclones.

Pour examiner la relation entre l'intensité de la tempête et la hauteur des vagues, une analyse de correlation a été réalisée en reliant la classification de la tempête à la pression centrale de celle-ci, à l'heure approximative du phénomène de vagues, ceci étant basée sur l'attente que le gradient de pression et conséquemment, la grandeur de vagues poussées par le vent, soient indiqués par ce variable. En général, une faible relation positive a été découverte suggérant que les effets du vent, ainsi que le fetch et la durée, devaient être inclus dans l'analyse afin d'expliquer encore plus de variance dans les classifications des tempêtes.

INTRODUCTION

The MEP Company was contracted by the Environmental Studies Revolving Funds (ESRF) to undertake a study to identify the 30 to 35 most severe wave-producing storms off the Canadian east coast and in the Gulf of St. Lawrence. The specific aims of the study were:

- to provide a set of worst storms for East Coast regions ranked by severity; and
- to classify the identified storms by type and season.

In addition to providing a climatology of severe wave-producing storms, the main rationale behind the study was to identify the meteorological conditions associated with severe wave development for subsequent application of hindcast procedures and extreme value analysis to provide estimates of design wave parameters. By pre-selecting the meteorology, it is possible to perform much more detailed hindcasts (e.g. ice cover can be included and input from meteorologists can be included in the specification of the wind fields) than is the case where long-period hindcasts are carried out.

Similar studies have been carried out on the Canadian east coast by oil operators, namely Mobil Oil Canada Ltd., for the Grand Banks and Total Eastcan for the Labrador Sea[1]. However, this study is particularly important for wave

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[1] See "Bibliography of environmental studies by industry in the Canadian offshore 1964-82." Department of Energy Mines and Resources, Ottawa, July 1983.

climate studies in that it is the first of its kind to consider the entire Canadian east coast from the Gulf of St. Lawrence to Baffin Bay, and because its circulation will not be limited by any proprietary classification.

This study is also significant in that a considerable time period (37 years from 1946-82) was investigated, which represents almost double the period associated with the two 20-year spectral wave model hindcasts frequently used in studies of this nature.

The severe storm climatology presented is unique for the Canadian east coast in that all the storms were selected based on their ability to generate extreme wave events. Previous studies such as Archibald (1969) used storm central pressure as an index for selecting severe storms whereas others such as Maxwell (1982) and Bursey et al. (1977) present summaries based on _all_ cyclones identified during a defined study period.

SPATIAL CONTEXT

The study area covered the entire Canadian east coast from the Scotian Shelf to Baffin Bay, and included the Gulf of St. Lawrence. This area was subdivided into seven separate regions for storm selection purposes: Gulf of St. Lawrence, Scotian Shelf, Grand Banks, northeast Newfoundland Shelf, Labrador Sea, Davis Strait, and Baffin Bay (Figure 1). The division of the east coast area into separate regions was based on:

(1) ESRF prescribed regions (Figure 2)
(2) Marine forecast areas (Figure 3).

Except for well-defined physiographic regions such as the Gulf of St. Lawrence, some degree of subjectivity was involved in defining the offshore regions. The defined regions have important ramifications for the severe storms selected, in that they affect the number and type of storms crossing a region. The only way around this problem is to ignore the regional approach and perform severe storm identification on a grid basis throughout the entire east coast area. Unfortunately, the amount of work required to do this would be prohibitive. The rationalization for the regional approach is that the extreme storms selected are likely to cover a significant area. However, it should be noted that the 30 worst storms defined for a region may not necessarily be the 30 largest storms for any given point within a region.

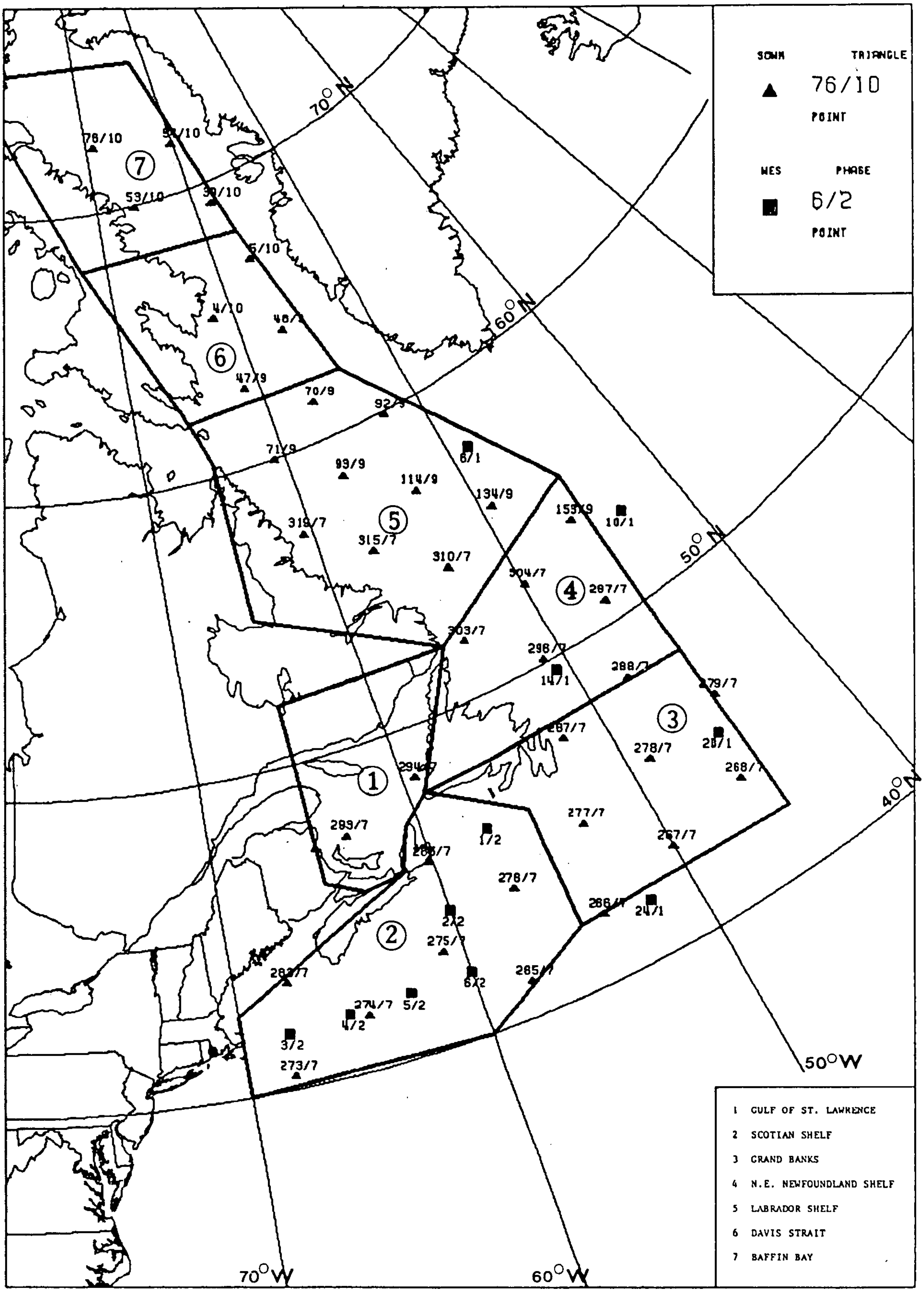


Figure 1. Location of study regions and SOWM and WES wave hindcast points.

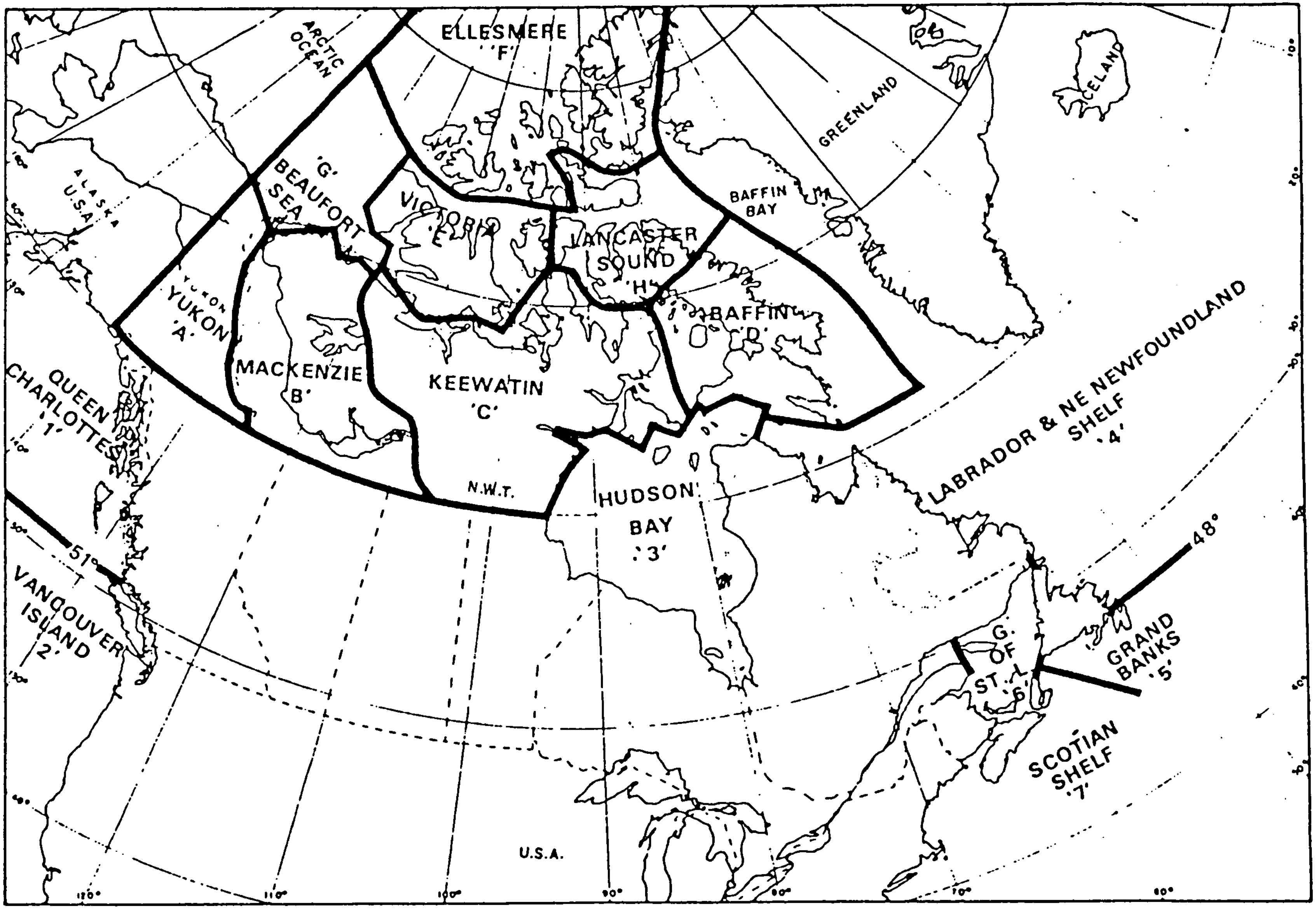


Figure 2. ESRF prescribed regions.

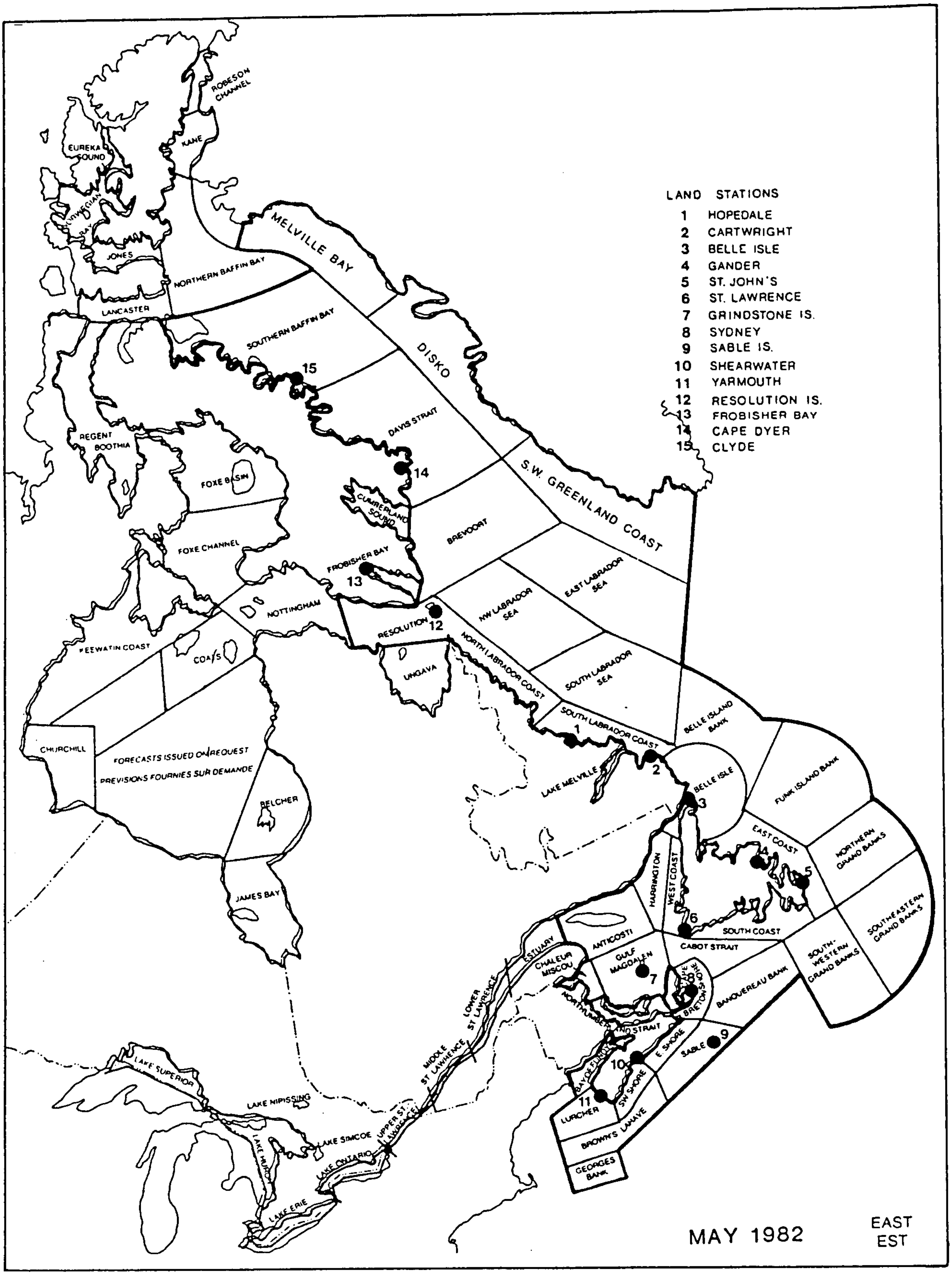


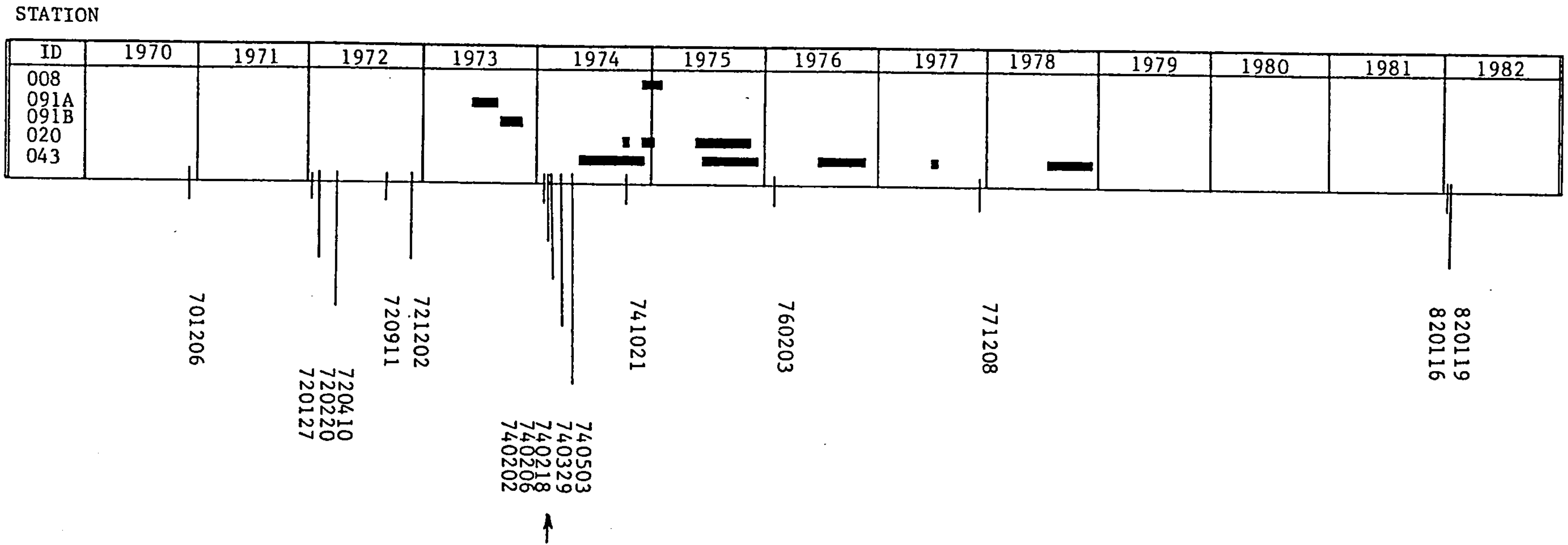
Figure 3. From Atmospheric Environment Service Marine Forecast Regions.

DATA SOURCES FOR SELECTION OF SEVERE STORMS

A variety of data sources are available for the identification of significant wave-producing storms. These can be generalized into two basic categories: first, explicit sources that provide wave information directly (e.g., observed, measured, and hindcast wave data); and secondly, implicit sources, such as wind data, from which wave information can be inferred. The data sources consulted by the authors are summarized in Appendix 1 and are described here in more detail.

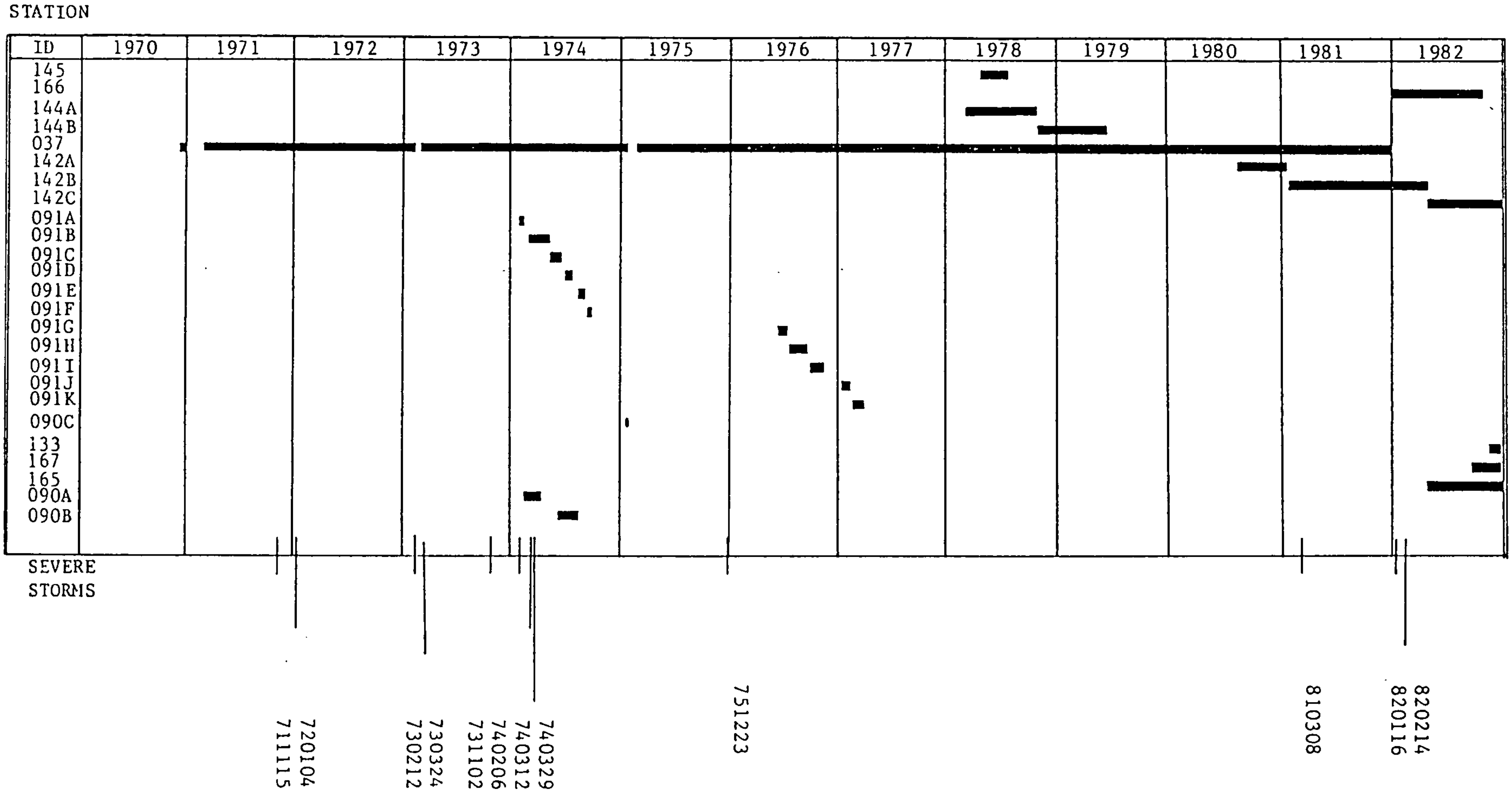
MEASURED WAVE DATA

A continuous record of measured wave data in each study area would simplify the task of selecting extreme wave-producing meteorological events. Unfortunately, the spatial and temporal coverage of measured wave data off the Canadian east coast is such that it severely restricts its use for this purpose. Waverider buoy measurement programs in deeper-water regions off the east coast have usually been related to offshore oil exploration activities which results in highly variable coverage in both spatial and temporal terms, except in more recent years for the Scotian Shelf and Grand Banks areas. A summary of available waverider buoy data in each of the study regions is provided in Figures 4 to 10 and in Appendix 1. These summaries were developed from summaries of wave data received from the Marine Environmental Data Service (MEDS), in response to a request for information on deep water waves over the entire study domain. In some instances shallow water measurement sites were included where significant temporal coverage was a feature (e.g., Osborne Head and Logy Bay).



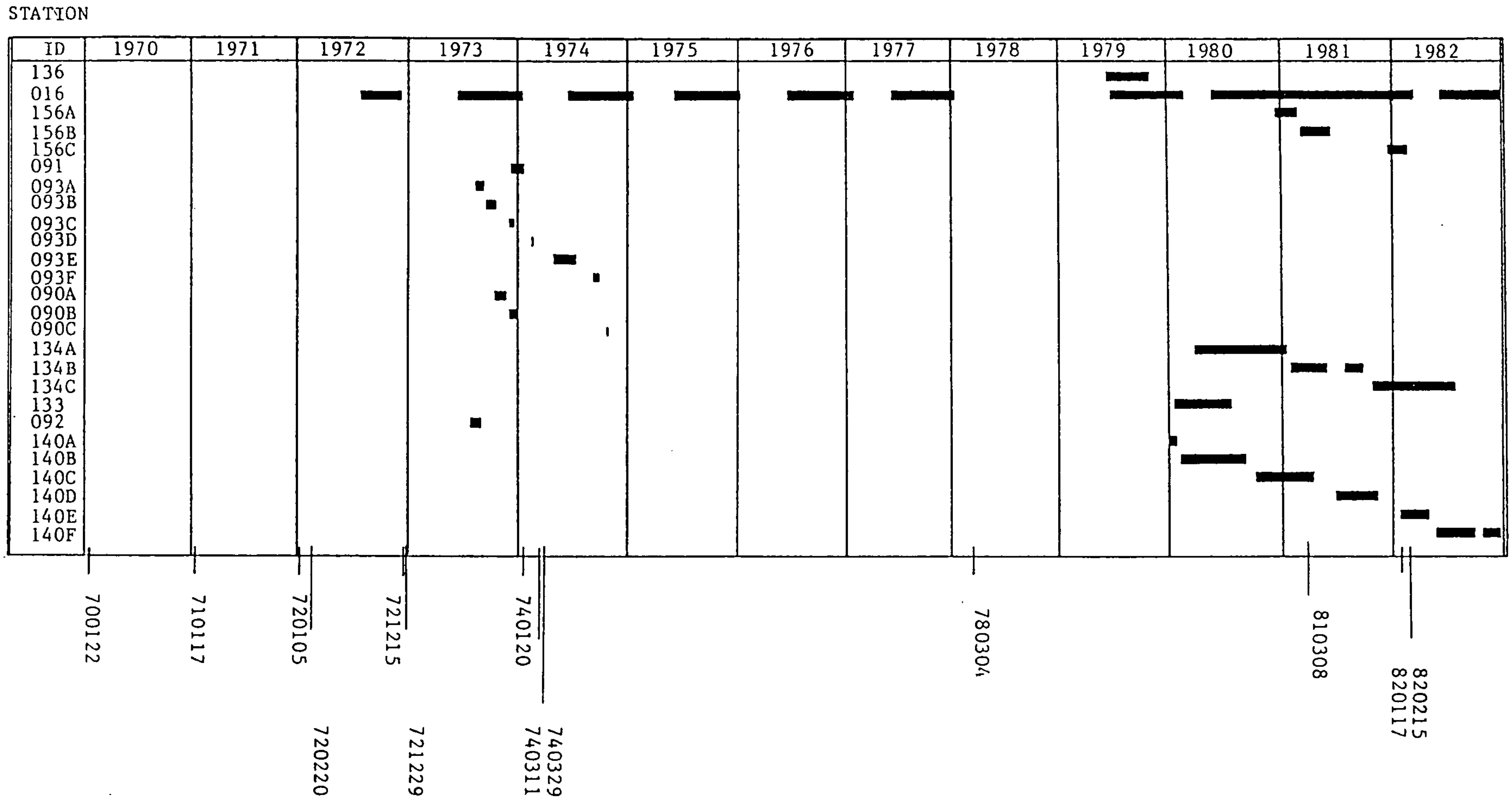
Dates of severe storms identified from study.

Figure 4. Temporal distribution of waverider buoy data, for the Gulf of St. Lawrence.



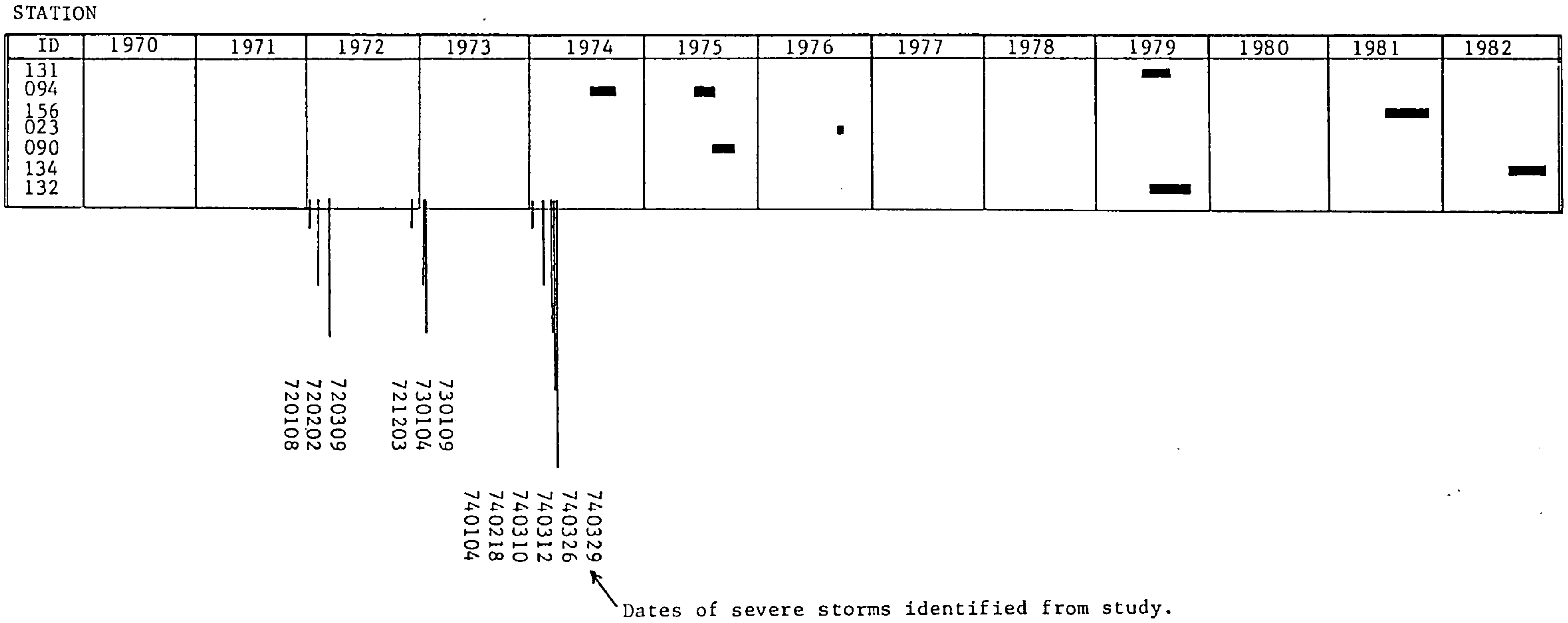
Dates of severe storms identified from study.

Figure 5. Temporal distribution of waverider buoy data for the Scotian Shelf.



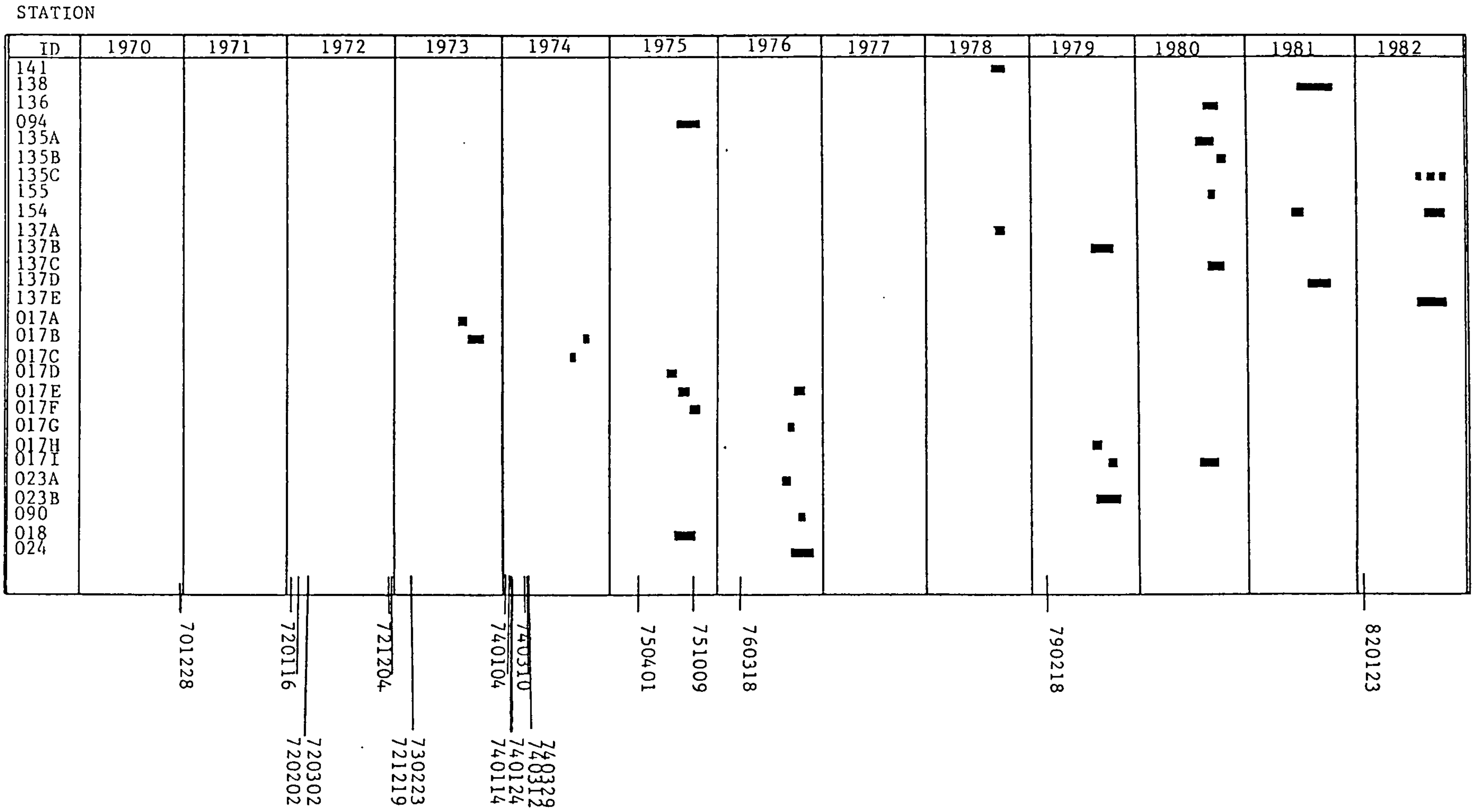
Dates of severe storms identified from study.

Figure 6. Temporal distribution of waverider buoy data for the Grand Banks.



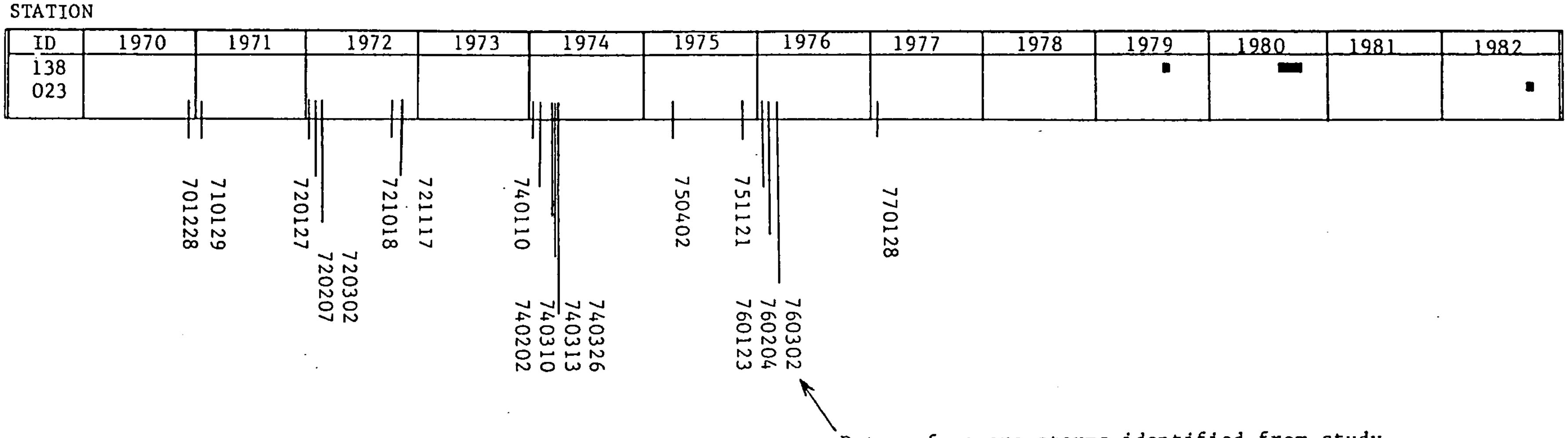
Dates of severe storms identified from study.

Figure 7. Temporal distribution of waverider buoy data for the northeast Newfoundland Shelf.



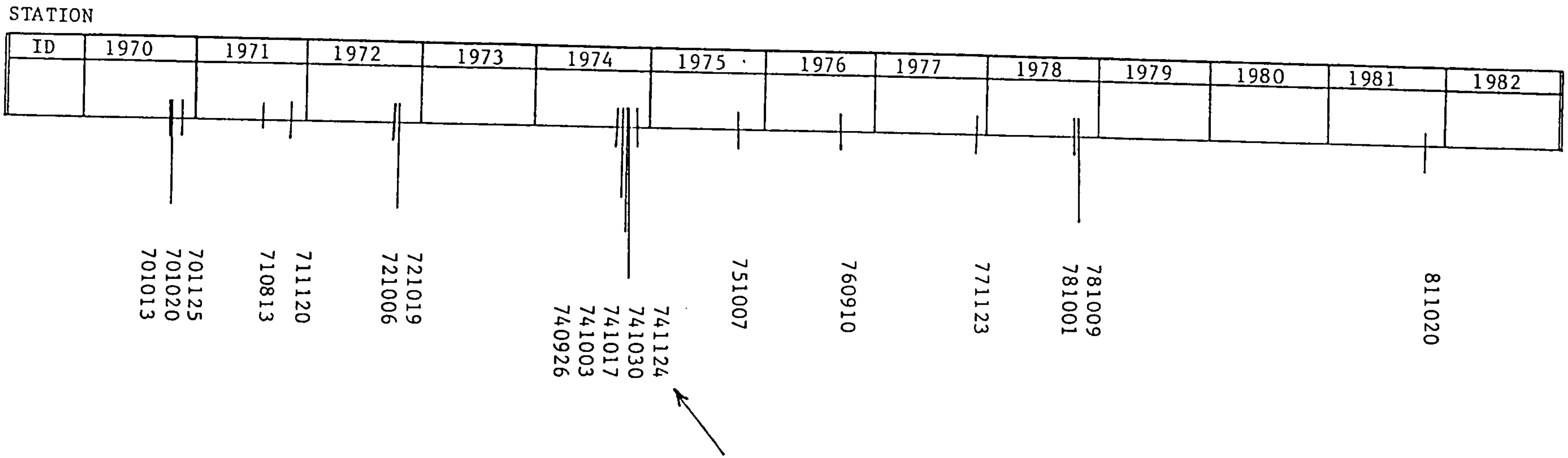
Dates of severe storms identified from study.

Figure 8. Temporal distribution of waverider buoy data for the Labrador Shelf.



Dates of severe storms identified from study.

Figure 9. Temporal distribution of waverider buoy data for Davis Strait.



Dates of severe storms identified from study.

Figure 10. Distribution of waverider buoy data for Baffin Bay.[1]

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[1] No available waverider data for this region.

The chronology of the severe storms for the years 1970 to 1982 (see Figures 4 to 10) gives an indication of the availability of measured wave data during these events. It should be noted, however, that even though a severe storm may coincide with a wave measurement program, the waverider buoy will not necessarily be located in the area of maximum wave energy. Thus, measured wave heights during the identified severe events may be considerably less than extreme wave heights occurring at other locations within a region. Another problem with waverider buoy data is that data recovery is sometimes less than 100%. Thus, data gaps can exist in the period of record.

Only one National Oceanographic and Atmospheric Agency (NOAA) buoy (#11005) was located in the study area. However, its position close to Cape Cod meant that it did not experience waves of a magnitude greater than about 6.0 m.

WAVE HINDCAST DATA

Two 25-year wave hindcast data sets, the Spectral Ocean Wave Model (SOWM) and the Waterways Experiment Station (WES), were the main sources used for identification of severe wave events from 1956 to 1975.

Spectral Ocean Wave Model

The SOWM is designed to operate in three basic modes: wave growth, wave propagation, and dissipation.

Wave growth. The wave-generation mechanism is based upon the work of Phillips and Miles as explained by Inoue (1967). Phillips (1957) found that wave growth occurs initially through resonant fluctuations caused by turbulent fluctuations of the atmosphere. Waves develop by means of this resonance mechanism which occurs when a component of the surface pressure distribution moves at the same speed as the free-surface waves with the same wave number ($\frac{2\pi}{L}$, where L is the wave-length). Miles (1957, 1959 a and b, 1962) considered a wind shear with a simple logarithmic velocity profile over a water surface on which waves are present. Pressure variations on the water surface, resulting from the perturbation of the airflow because of the presence of waves, causes an air pressure distribution which is greatest over the troughs and least over the crests. This distribution in turn causes the air flow over the crest to turn back, as it is flowing toward the higher pressure in the next trough.

The rate at which energy is transferred from the air shear flow to the water waves is proportional to the curvature of the air velocity profile at the elevation where the air velocity is equivalent to the phase velocity of the waves. Miles (1960) combined the theories of wave generation by turbulent pressure fluctuations (Phillips 1957) and by shear flow instability (Miles 1957) and the SOWM uses this Phillips-Miles growth mechanism.

The waves grow according to their individual frequencies, and the spectral frequency bands fill until dissipation occurs or the fully developed state of the Pierson-Moskowitz (PM) (1964) spectrum is attained for the given wind speed. The PM spectrum defines the energy distribution or limiting frequency distribution of waves for a given wind speed over unlimited fetch and duration. Wave energy is allowed to grow until saturation occurs or until the spectrum has reached 95% of the PM spectrum. All other energy is discarded from wave growth at a particular wind speed after saturation is reached. Cardone[1] modified the Phillips-Miles growth mechanism such that for wind speeds $\leq$ 30 knots, wave energy grows faster than the Phillips-Miles growth mechanism during the initial six hours. The reverse is true for wind speeds > 30 knots. After six hours, the wave growth is slower in each case.

Wave propagation. The propagation scheme moves the wave energy according to the frequency-dependent group velocity between grid points described within the triangular icosahedral-gnomonic grid used by the SOWM. A velocity gradient technique is used with a time step of three hours. Six primary and six secondary geometrical directions are defined and wave energy is propagated directly from grid point to grid point along the six primary directions and by a zig-zag method along the secondary directions. No energy is propagated in from the coastlines. The coast also acts as a perfect absorber for incident waves.

Dissipation. Dissipation also is included in the model. If the waves enter $\pm 90^{\circ}$ of the wind direction, a weighted decay is attached to the energy spectrum. Strongest dissipation occurs at 180° to the wind at the highest frequencies. The model does not include any wave-wave interaction terms; nor does it account for the effects of shallow water.

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[1] Cardone, personal communication, cited in Lazanoff and Stevenson (1975).

Wind Input. The accuracy of the SOWM model output, as with all other wave model output, is limited by the accuracy of the wind input data. An accurate marine wind analysis, in turn, requires good observational data. In 1976 the U.S. Navy began the derivation of an historical climatological data file of SOWM wave spectra covering 20 years (1956-75) of Atlantic and Pacific Ocean weather. This data set provides directional wave spectra, wind speeds, and directions at six hour intervals for the 1,530 grid points in the Northern Hemisphere oceans, of which over 500 represent the Atlantic Ocean. Grid points used in this study are shown in Figure 1. The model uses archived and well-refined wind fields from historical synoptic observations from ships and the derived surface pressure analysis and wind fields. The analysis technique (field by information blending, Holl and Mendenhall 1971) included a consideration of upper air steering of surface systems, air-sea temperature differences, island reports, and actual wind observations; accuracy was checked through machine quality control, including logical controlled error analysis and bench-mark defaults.

Limitations. The consensus in the oceanographic community appears to be leaning towards a non-linear, wave-wave interaction type of mechanism as the method of wave growth in the forward face of spectrum rather than a Phillips-Miles type of process. The wave-wave mechanism is linked integrally to the location of the spectral peak, whereas the Phillips-Miles growth terms are not linked directly to the spectral peak. An irreconcilable difference arises between the two approaches in terms of equivalence of growth in time and space. Resio and Vincent (1979) have suggested a rescaling of the source terms for application to different situations with different time and space scales of wave generation. The model seriously underestimates fetch-limited growth rates for all lengths of fetch, although it agrees more closely with wave-wave interaction models for duration-limited growth. However, the model differences all tend towards zero for fully developed conditions. Nevertheless, Resio and Vincent (1979) advise the use of wave-wave models in any future hindcast study.

Lazanoff and Stevenson (1975) evaluated the SOWM and reported that comparisons of SOWM and wave data measured by NOAA buoys showed that significant wave heights computed from the SOWM were generally higher than buoy-derived significant wave heights. The comparison study concluded that SOWM wave spectra had 20% excess energy and suggested that the cause was lack of strong decay coefficients in the low frequency range. Following a comparison of SOWM and significant wave heights from waverider buoys on the Grand Banks and Scotian Shelf, MEP (1982) found that the SOWM tended to over-predict higher waves.

The coarse resolution of the SOWM land and sea boundaries severely restricts the performance of the model in enclosed areas such as the Gulf of St. Lawrence and Baffin Bay. As noted previously, the SOWM also does not incorporate shallow water effects on wave growth and decay which limits its performance in the vicinity of the Magdalen Islands in the Gulf of St. Lawrence. The effects of ice cover on wave development and decay are similarly not taken into account in the SOWM, which has important consequences for the identification of severe events. This is discussed in the section on methodology for selection.

Waterways Experiment Station

The WES wind-wave hindcast model was developed by Dr. D.T. Resio and Dr. C.L. Vincent of the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksberg, during 1978-79. The WES model is a discrete spectral model that approximates the similarity-based fetch and duration growth characteristics of the Hasselmann et al. (1976) parametric model. The fundamental physics of the model consists of three parts: a new parameterization of the wave-wave interaction source term, an exponential atmospheric input term, and a variable energy density level in the range of frequencies above the spectral peak. The dominant source term is the non-linear wave-wave interaction, unlike the SOWM model, which relies on atmospheric input as the wave growth mechanism.

Wave-wave interaction. The parameterization of the wave-wave interaction source term by Barnett (1968) was seen to be too low by a factor of three for a Joint North Sea Wave Project (JONSWAP) spectrum; the WES parameterization was formulated to correct this problem by parameterizing , the Phillips equilibrium value, as a function of dimensionless wave height rather than as a constant. This parameterization can also account for certain aspects of spectral shape variation and leads to a simple $\alpha^3 f_m^{-4}$ scaling relationship for the non-linear source term in a self-similar spectrum with an f^{-5} high frequency tail. Here, f is defined as spectral frequency whereas f_m refers to the frequency corresponding to peak spectral energy density. This type of representation has been found to depict both wave growth and wave decay rates in accordance with observational evidence, while maintaining spectral shapes consistent with observed spectra.

The dominant energy input on the forward face of the spectrum is related to a convergence of energy flux resulting from non-linear, resonant wave-wave interactions of the form described by Hasselmann (1962).

Atmospheric input. The atmospheric input source terms are based on essentially the same mechanisms as with the SOWM model; the resonance and instability mechanisms of Phillips and Miles. In the non-linear wave-wave interaction source terms, the atmospheric input can be identified in terms of the non-dimensional Phillips equilibrium coefficient α, which can be parameterized in terms of a non-dimensional peak frequency as a function of wind speed. In this way, a wave-wave interaction source term can behave as an apparent wind source term (Resio 1981).

Variable energy density levels above the spectral peak. Whereas in parametric models, a fully developed sea is achieved by placing a site condition on the value of a parameter (e.g. wave growth is halted automoatically when the non-dimensional peak frequency attains a particular value), in the WES model an asymptotic approach to a fully developed sea is achieved. The saturation range is attained when the atmospheric input places more energy into the central frequency bands than is transferred out of this range by the wave-wave interactions. The subsequent balance of energy fluxes leads to an f^{-5} distribution of energy. Dimensional considerations indicate that a fully developed energy state depends on wind speed to the fourth power, i.e., $E_{sat} \alpha u^4$, in agreement with empirical evidence which suggests a squared wind-speed relationship for fully developed wave height.

Data input. The wind fields used in the production of the hindcast waves were derived from pressure fields defined by Fleet Numerical Weather Central (FNWC) on a 63 x 63 point grid (222-km spacing) over the northern hemisphere. The raw data, obtained from the millions of land and ship observations archived on magnetic tape, was augmented in the area near storm centres along the U.S. Atlantic coast by pressure data derived from the National Weather Service (NWS) surface analyses for the 25-year period, 1952-77. These additional pressure data were interpolated on an approximately 50-mile grid and blended with the 63 x 63 point grid data in such a way as to preserve the NWS analysed pressure gradient in the 200-mile square around the storm centre and maintain a smooth transition into the FNWC pressure field away from the storm centre. The hindcast waves were archived at the 222-km spacing off the U.S. coast and the Scotian Shelf. However, north of this, only selected points were archived (see Figure 1).

A planetary boundary-layer model was used to derive wind velocity at the 19.5 m level. This model relating the geostrophic (pressure derived) and lower level winds provides an opportunity to incorporate both the stability and baroclinicity of the lower atmosphere into the wind estimates, and has been shown to produce a root-mean-square (rms) error of less than 2 m/sec (Resio and Vincent 1979) for geostrophically derived winds. Air-sea temperatures were derived from ship-board observations, and constructed at sites that lacked data by an algorithm which accounted for spatial and temporal gradients. Observed winds were then blended into the derived wind fields in such a way as to restrict smoothing to only the nearby grid points (on the order of 100 to 200 miles).

Limitations. The study of Resio (1982) indicated that, given accurate wind fields, the WES model will produce reasonably reliable wave heights.

The WES data, however, appear to be reasonably reliable only in the U.S. Atlantic regions where the 63 x 63 grid of pressure data was adjusted (for major storms) to preserve NWS-analysed gradients. The Resio (1982) study recommended not using the WES hindcasts in the Scotian Shelf area because of the problems with the pressure (and, therefore, wind) field gridding. However, in other areas off the Canadian east coast, the WES study appeared to be acceptable in providing a general discription of the wave climate.

Baird and Readshaw (1981) concluded that the WES study does not provide an accurate description of the sea state on the Grand Banks and Scotian Shelf at any given hour. However, they suggested that the hindcast data might provide an accurate representation of the wave climate of the grid point locations to the south and east of these areas. They also urged a re-hindcast of the Canadian Atlantic regions with an improved wind analysis during storms, and consideration of the effects of shallow water which the WES did not include. Like the SOWM, the WES does not include ice cover effects on wave growth and decay.

FORECAST WAVE DATA

Forecast wave data from the FNWC spectral model (SOWM) are contained in the NEDN data set archived at AES. The model output is archived at a six-hourly interval based on model runs at 0000Z and 1200Z. Values of significant wave height, period, and direction are available for analysis using the gridded area statistics package (GASP) facility developed by AES.

The data covers the period of June 1974 to June 1982 but has some missing months and some incomplete months. In the latter case, these vary with the area under consideration. The missing months are September and October 1974, April 1977, February 1978, and November 1981.

OBSERVED WAVE DATA

A large volume of ship-based observations on wave height is contained in the marine weather reports archived at AES. Although marine weather observations go back to the late 1800s in all of the east coast regions, sea wave observations were not reported regularly until 1949 and swell wave observations did not begin until 1959. Observed wave data have two main disadvantages for the identification of severe wave events. First, the spatial and temporal coverage of the ship observations is highly variable and will include a fair weather bias. Secondly, ship observations are inconsistent in terms of data quality. Jardine (1979) showed good agreement between observed and measured wave data at Ocean Weather Station 'I' in the North Atlantic. However, these observations were made by trained observers who, no doubt, had access to data from the shipborne wave recorder in operation at OWS "I" over the same period that Jardine's comparison was carried out. An example of an inconsistency in observed wave data was particularly visible at OWS *Bravo* in the Labrador Sea where the reported wave heights exhibited a well-defined upper limit of 9.5 m: during 24 years of wave observations, only 37 observations of greater than 9.5 were reported, whereas over 260 observations of waves equal to 9.5 were reported. (The maximum reported wave height was 12.5 m.)

METOC WAVE DATA

Every 12 hours, METOC issues a significant wave height analysis and prognosis fields for the Canadian east coast area and northwestern Atlantic. The area of coverage includes all the regions in the study domain with the exception of the Davis Strait and Baffin Bay regions. The analysed fields are based on available wave data (including ship observations and oil rig data) together with Sverdrup-Munk-Bretschneider (SMB) derived wave information from analysed pressure fields and wind speed observations. METOC employ quality control procedures for screening vessel observations and this, combined with the experience of their forecasters, makes their wave analysis fields one of the more useful products for identifying severe wave events. The analysis charts, containing significant wave height isopleths at 1-m intervals, have been digitized by METOC for the period 1972-82 to give the highest significant wave height, period, and direction occurring in a five degree latitude-longitude tessera. These data are archived at AES in coded format (TDF11) and can be accessed and summarized using the MAST software package developed by AES. The Bedford Institute of Oceanography has also digitized the METOC wave charts (significant wave height at the mid-point of a five degree latitude-longitude tessera). These data are available in TDF11 format for the period 1972-80. For this study, the METOC digitized data were used. Unlike the two wave hindcasts, the METOC charts include seasonal ice cover effects: areas of ice cover greater than six-tenths concentration are assumed to be equivalent to land surfaces with respect to wave growth, propagation, and decay.

AES GEOSTROPHIC WINDS

The Atmospheric Environment Service has derived a 33-year geostrophic wind climatology (1946-78) for Canada and adjacent marine areas. The winds are derived from FNWC surface pressure data for a 381 km grid, using only the geostrophic assumption that Coriolis acceleration exactly balances the horizontal pressure force. This results in a wind blowing parallel to the isobars with a speed inversely proportional to the isobar spacing and the Coriolis parameter (Swail and Saulesleja 1981). In reality, the relationship between the theoretical geostrophic wind and the actual surface wind is complex, depending on a large number of factors including atmospheric stability, horizontal temperature gradients, baroclinicity, and latitude. According to Swail and Saulesleja (1981), the ratio of typical anemometer level winds to geostrophic winds can range from 40 to 90% over typical ranges of wind speed and air-sea temperature difference. However, this general statement does not apply to the AES data set as it has been shown that the geostrophic winds are low compared with true geostrophic winds (a result of smoothed pressure gradients): Swail et al. (1984) found that wind speeds from OSV _BRAVO_ were, on average, about 90% of the geostrophic wind data set values.

Although, the geostrophic assumption may reduce the value of this data set for applications requiring accurate surface level winds, the data are very useful for climatological analyses, particularly for severity studies in which relative magnitudes are more important than actual values.

The AES hindcast winds were used in conjunction with the SMB nomogram to determine severe wave events.

WIND OBSERVATIONS FROM SHIPS

Ship observations of wind speed and direction are available from the late 1800s in all of the regions in the study domain. These may be more reliable than wave observations, as many ships were and equipped with wind measuring devices. However, according to Shearman, quoted in Swail and Mortsch (1984), more than 90% of wind observations are estimates. Even for the Hibernia location in recent years, the percentage is about 75%. These data suffer from the same problems of variable spatial and temporal coverage and fair weather bias. Extreme-value listings of ship winds were used to identify potentially severe storms for later verification, and for verification of potential storms from the AES geostrophic wind data set.

WIND OBSERVATIONS FROM LAND STATIONS

Measured wind data from island and coastal stations throughout the East Coast area (see Figure 3) are potentially useful for severe storm identification in that the data form a complete time series. Many of these stations have digitized wind records going back to 1953. One problem with using these stations, however, is that local influences can have a significant impact on observed winds. For this reason, only data from the three island stations (Grindstone, Sable, and Belle Isle) were used in this study.

METHODOLOGY FOR SELECTION OF SEVERE STORMS

The methodology for selection of the worst storms in each region was divided into three main tasks: identification of potentially severe storms, storm verification, and ranking of severe storms for selection of the 30 to 35 worst cases.

IDENTIFICATION OF POTENTIALLY SEVERE STORMS

Wave Hindcasts

The SOWM and WES hindcasts were the main data sets used for this task. To summarize the hindcast data into storm events, a suitable definition of a storm had to be determined. According to Readshaw and Baird (1981) the usual practice is to define a storm as an independent event producing waves above a predetermined threshold condition. The main problem with such storm definitions is how to ensure independence. In some cases, arbitrary spacings of 24 or 36 hours are specified to ensure independence. However, Readshaw and Baird (1981) pointed out that this procedure is unsatisfactory over the Canadian Atlantic continental shelf as storms can stall there for several days. They indicated that the only satisfactory procedure was to refer to synoptic charts to determine the independence of sequential storms. Bearing these points in mind it was decided to use 18 hours as the time period separating "independent events." Eighteen hours corresponds to two hindcast values below the storm threshold wave height and was selected instead of 12 hours (the minimum separation possible) to take into account the possibility of spurious values or "spikes" in the wave hindcast record. In the above context, the word independent refers to the meteorological independence of the severe storms. However, for extreme value analysis, the statistical independence of the storms also must be determined.

The choice of a particular threshold value is important in that it will affect the number of storms identified in a particular region. In this study, a threshold value for significant wave height of 6.0 m was employed over all regions except Region 7, where a threshold value of 4.0 m had to be used to identify a sufficient number of storms.

Ice Cover Effects

All the regions included in the study domain experienced seasonal ice coverage to a greater or lesser extent. However, neither the SOWM nor the WES hindcasts included ice cover effects; the models assumed open water conditions all year round. One solution to this problem would have been to determine 'average' ice cover periods at each hindcast grid point, and to consider only extreme wave events which occurred during the defined open water period. However, this methodology has two main weaknesses: first, even though one location is ice free, ice cover remaining within a region may affect wave development and propagation considerably; secondly, the annual variability displayed by seasonal ice cover, particularly in the more southern regions, is significant enough that major wave-producing events could be screened out by using averaged ice cover information.

It was, therefore, decided to ignore ice cover in the selection of potential severe storms in Regions 1 to 6, as all these regions (see Figure 1) could experience significant areas of open water throughout the winter. However, Region 7, Baffin Bay, exhibited a high probability of complete ice cover in the period December to June (Markham 1981). Severe storms from this region were, therefore, restricted to the period from July to November.

It should be noted that ice cover effects will have to be taken into account when determining the return periods associated with large wave heights. This problem is complicated by the fact that the spatial distribution of ice concentration is not independent of the storms producing larger waves. Thus, the application of joint probability statistics is more difficult and requires further investigation.

The above storm and ice-free season definitions were incorporated into a FORTRAN program "STORMSCAN" which was run for every wave hindcast point within the study domain. STORMSCAN compiled output information on all storms identified including a storm severity index (SSI). The SSI for each storm was calculated by the product of mean storm significant wave height and storm duration. The idea behind the SSI was to generate an additional indicator of potentially severe storms other than maximum height of storm waves. An example of STORMSCAN output for SOWM point 153/9 in Region 4 is given in Appendix 2.

Once a storm file had been generated for every SOWM and WES point within a region, files were sorted based on maximum wave height and SSI. The top 30 storms from each sorted file were then merged and sorted to form regional files of potentially severe storms, ranked by maximum wave height and SSI. An example of a regional file ranked by maximum height of storm waves is given in Appendix 2 which illustrates that a considerable amount of overlap exists in the identified storms when several points picked up the same storm. This overlap was eliminated manually and a final set of potentially severe storms was obtained from combining storms ranked 30 or above with respect to maximum wave height or to SSI. This yielded about 45-50 potential storms per region. During this final selection process, an additional criterion was imposed: storms with durations of less than, or equal to, six hours were rejected to take into account possible "spikes" in wave model output.

Other Sources

The other sources used for identification of potentially severe storms in order of importance were:

- METOC maximum significant wave data
- AES geostrophic winds
- NEDN data set
- wind and wave observations from ships
- historical records.

METOC maximum significant wave data and the NEDN data set were the main sources used to extend the hindcast identified storms up to 1982, the end date for the study period. Ranked listings of the METOC wave data by month and by region were obtained using the MAST facility developed by

AES, whereas listings of wave height values above various thresholds were obtained from the NEDN data set using GASP. These were scanned manually and storms selected that exceeded a determined threshold height. The selection of this height was based on the region under consideration and the range of storm wave height values exhibited in the METOC and NEDN data. Several of the NEDN-identified storms were found to be spurious, with no corresponding wind speeds greater than 20 knots. In regions 2, 3, and 4, the NEDN-selected storms compared reasonably well with METOC-derived storms. However, it did not seem to perform as well in the Gulf of St. Lawrence or the Labrador Shelf regions.

The main source for identification of severe storms prior to 1956 was the AES geostrophic wind data set. Ranked listings of wind speeds above 48 knots were obtained for each region using MAST, and extreme events were selected manually. These winds were then used with the Bretschneider deepwater wave nomogram (CERC 1977) to hindcast storm wave heights. Storms with hindcast wave heights falling within the range exhibited by the SOWM and WES identified potential storms which were then selected for inclusion in the final set of potential severe storms.

Wind and wave observations from ships were less useful for identification of severe events because of their variable spatial and temporal coverage. However, data from OWS Bravo (Region 5) and OWS Delta (Region 3) were found to be of more use. Ranked listings of ship wind speeds (> 48 knots) and wave observations (> 8.0 m) were generated for all regions using MAST. A lower wave threshold of 4.0 m was used for Regions 1, 6, and 7. These listings were then scanned manually for extreme wind speeds and wave heights. Quality control procedures had to be applied during this process as many of the extreme observations were the result of coding errors. The quality control method used involved simple intercomparisons between wind speed, wave height, and air pressure. Extreme events passing these quality control procedures were noted for further verification.

Copies of the Marine Observer (1924 to date) and the Mariner's Weather Log (1957 to date) were scanned for reports of severe storms and vessel sinkings. Early reports of severe weather events in these sources were found to be of limited value because of highly subjective reporting of wind and wave conditions: storms reported prior to 1946 could not to be verified by other available sources and for this reason, the study period was defined to start in 1946.

STORM VERIFICATION

Storm verification was carried out at two levels: first, intercomparisons were carried out between all available data sources to establish the validity of a potentially severe storm; secondly, during the process of obtaining the surface pressure charts for potential storms, the meteorologists involved were able to judge whether the meteorology was sufficient for generating an extreme wave event.

At the first level, tables were constructed to allow cross comparisons between data sources for each significant storm identified. All available data sources were used and storms were rejected if they were unable to be confirmed by more than one source. This procedure had to be relaxed for pre-1956 storms as the AES wind hindcast was often the only regularly available data source. Following initial verification, surface pressure charts were obtained for each potentially severe storm. For the period 1957 to 1982, Canadian Meteorological Centre surface pressure charts were copied from microfilm archived at AES, Downsview. These charts are available at six-hourly intervals. Prior to 1957, daily surface pressure charts were copied from the Daily Series of Synoptic Weather Maps[1] archived in book format at AES, Downsview. Severe wave events were confirmed during the copying process by investigation of the pressure gradients. In most cases, the identified potential severe storms were associated with significant low pressure systems. However, there were a few potential events where the analysed pressure fields showed little or no evidence of the pressure gradients and fetch-duration requirements needed to produce major wave events. These storms were subsequently deleted from the list of severe events. The independence of the various storms was also established at this time.

RANKING SEVERE STORMS

It had been proposed originally to use a multiple ranking system based on SOWM and WES storm wave heights and SSI rankings to determine final ranked sets of the 30-35 worst storms in each region. However, this approach later proved to be impractical as many of the storms identified did

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[1] Daily Series Synoptic Weather Maps, Part I, Northern Hemisphere Sea Level and 500 mb Charts, U.S. Department of Commerce, Washington, D.C.

not have corresponding hindcast information and because of a low correlation between SOWM and WES-identified severe storms. The solution to this problem was to hindcast maximum storm wave heights for each storm.

Hindcasting was performed using the Bretschneider nomogram (CERC 1977) with geostrophic winds derived manually from the surface pressure charts collected during the verification phase. The resulting wave hindcast values should not be considered accurate representations of actual wave conditions for several reasons: first, surface winds can differ significantly from assumed geostrophic flow; secondly, hindcasting with the daily series pressure charts (pre-1957) involved considerable subjective interpolation of wind speed, duration, and fetch information; thirdly, the hindcasting technique does not consider swell which can have a considerable effect on storm wave heights. However, it should be noted that the main aim of the hindcasting was to provide values for ranking purposes. Here, relative magnitudes are more important than accuracy: provided the hindcast procedures are applied consistently, the results should provide reasonable indications of the relative severities of the various storms.

The results of the ranking are summarized and discussed by region in the following section.

SUMMARY AND DISCUSSION OF STORM SELECTION BY REGION

REGION 1 GULF OF ST. LAWRENCE

The ranked storms for Region 1 are presented in Table 1. Region 1 was one of the more difficult regions for identifiying potentially severe storms as the SOWM hindcast results were not found to be reliable in the Gulf. This point is demonstrated in Table 2 which shows that 20 of the top 30 storms height-ranked by SOWM were not chosen in the severe storm selection process. Because of the problems with the SOWM-identified storms, greater reliance had to be placed on the AES geostrophic wind climatology and Grindstone Island winds for storm identification. A breakdown of the total number of verified potentially severe storms by selection criteria is shown in Table 3.

Part of the SOWM's problem is related to the coarse resolution used in the specification of land and sea boundaries which has a significant effect on fetch definitions within the Gulf. However, there also appeared to be a problem with the SOWM surface winds in this region: over 60% of the SOWM identified severe storms did not have corresponding observed wind speeds of 48 knots or greater at Grindstone Island, and 20% of the storms were not confirmed by AES geostrophic winds $\geq$48 knots. This contrasts with Regions 2 to 5 where nearly all SOWM-identified severe storms had corresponding AES geostrophic wind speeds of 48 knots or greater.

Table 1

Selected severe storms for the Gulf of St. Lawrence

Storm Date	Rank	SMB (m)	SOWM (m)	SOWM (rank)	WES (m)	WES (rank)	Measured (m)	METOC (m)	Ship (m)
02 Mar.49	22	10.0							
20 Feb.52	23	9.8							
03 Mar.52	11	10.7							
13 Nov.52	11	10.7							
19 Nov.52	18	10.4							
29 Jan.54	30	8.5							
05 Jan.55	3	12.2							
21 Sep.55	11	10.7							
08 Jan.56	11	10.7	14.6	(1)					
26 Nov.59	30	8.5	8.9	(29)					
17 Dec.61	9	11.3	8.5						
28 Jan.62	23	9.8	9.9	(13)					
10 Feb.63	2	12.8	10.1	(11)					
09 Apr.63	10	11.0	8.8						
28 Jan.66	11	10.7	9.5	(20)					
06 Jan.68	3	12.2	7.5						
06 Dec.70	25	9.1	6.4						
27 Jan.72	19	10.1	9.2	(24)				< 4.0	10.5
20 Feb.72	25	9.1	10.7	(7)				< 4.0	
10 Apr.72	25	9.1	6.8					< 4.0	
11 Sep.72	25	9.1	*					4.0	5.0
02 Dec.72	3	12.2	11.8	(2)				8.0	8.8
02 Feb.74	3	12.2	11.2	(4)				< 4.0	
06 Feb.74	3	12.2	10.8	(6)				< 4.0	
18 Feb.74	19	10.1	8.9	(29)				< 4.0	5.0
29 Mar.74	11	10.7	8.9	(29)				< 4.0	5.0
03 May.74	25	9.1	*					< 4.0	6.5
21 Oct.74	3	12.2	*				020/4.9	6.0	9.0
03 Feb.76	11	10.7						< 4.0	5.0
08 Dec.77	30	8.5						5.0	8.5
16 Jan.82	19	10.1						9.0	
19 Jan.82	1	13.4						8.0	

* No corresponding storm identified

Table 2

Comparison of 30 highest SOWM and WES storms for Region 1

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	293/7	90156	14.6	No WES points in this region		
2	294/7	21272	11.8			
3	293/7	40475*	11.3			
4	294/7	20274	11.2			
5	293/7	281269*	10.9			
6	293/7	60274	10.8			
7	293/7	200272	10.7			
8	293/7	251270*	10.6			
9	293/7	100269*	10.5			
10	294/7	80259*	10.4			
11	294/7	100263	10.1			
12	294/7	40273*	10.0			
13	294/7	280162	9.9			
14	293/7	30458*	9.9			
15	293/7	290467*	9.9			
16	293/7	260269*	9.7			
17	294/7	281172*	9.7			
18	293/7	120273*	9.6			
19	294/7	70272*	9.6			
20	293/7	91163*	9.5			
21	293/7	280166	9.5			
22	293/7	290372*	9.4			
23	293/7	240372*	9.4			
24	294/7	311256*	9.2			
25	293/7	60575*	9.2			
26	294/7	270172	9.2			
27	293/7	170158*	9.1			
28	294/7	270256*	9.0			
29	294/7	191275*	8.9			
30	293/7	310374	8.9			

* Storms not making final selection

Table 3

Breakdown of Verified Severe Storms by Selection Criteria for Region 1, Gulf of St. Lawrence

Selection criteria	No. of verified[a] potential storms
AES Geostrophic Wind Climatology	9
Grindstone Island	16
METOC	6
SOWM	32
NEDN	3
Total (1946-82)	66

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[a] Initial verification from other data sources.

The two SOWM points in the Gulf of St. Lawrence showed little evidence of a marked bias in the spatial variation of storms. Taking the top 30 height-ranked SOWM storms, 60% were identified at point 293/7 and the remainder at point 294/7.

Very few ship wave height observations of ≥ 4.0 m were found for the final set of selected storms. This is a reflection of the fact that 10 of the 32 selected severe storms occurred during the months of February and March when the mean sea ice concentration in the Gulf is about six-tenths or greater (Markham 1980, p. 11). If the ice cover season is extended to include January and April (mean ice concentration < 6/10 but > 0), then 21 of the 32 severe storms have a high probability that ice cover affected wave development. Verification of ice cover conditions for individual storms was not included in the work scope of this study. However, this will have to be addressed if these storms are to be hindcast accurately at some later date. This process may well show a need to include additional severe storms in the set provided for this region.

A comment should be made about the rather excessive hindcast wave height values produced in the Gulf by both the SOWM and the Bretschneider nomogram. According to METOC staff,[1] significant wave heights in the Gulf rarely exceed values of around 6.0 m. The maximum METOC wave height over the period 1972-82 was 9.0 m on 16 January 1982. However, both hindcasts produced storm maximum significant wave heights well in excess of 9.0 m. These are most likely

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[1] Personal Communication

overestimates and are reflections primarily of the problem of fetch definition in the Gulf, and secondly, of the effect of shallow water on wave growth in the area of the Magdalen Islands. The NEDN forecast wave heights did not appear to exhibit the same degree of overprediction which is a little unusual given that the NEDN wave data consists of operational runs of the SOWM model.

REGION 2 SCOTIAN SHELF

The ranked storms for the Scotian Shelf are presented in Table 4. This region included six WES hindcast points in addition to seven SOWM points and is the only region where the regional storm selection capabilities of each hindcast can be fairly assessed: in regions 3, 4, and 5, WES points are too few to adequately represent the extreme storm climate of the large areas included in the regions. Surprisingly, the degree of overlap between severe storms identified by each hindcast was very low: Table 5 demonstrates that of the top 30 height ranked storms from each hindcast, only 10 cases overlapped. According to Resio (1982), there were problems with the pressure field specification over the Scotian Shelf area which produced spurious overpredictions (the December 1973 and March 1974 storm cases were cited by Resio as examples of this problem). Problems with the pressure field may explain the low number of WES-identified storms which made it into the final set of severe storms: only nine of the WES-identified storms made the final list compared with 15 from the SOWM.

<u>Table 4</u>

Selected severe storms for the Scotian Shelf

Storm Date	Rank	BRET. (m)	SOWM (m)	SOWM (rank)	WES (m)	WES (rank)	Measured (m)	METOC (m)	Ship (m)
05 Apr. 49	22	12.2							9.5
03 Mar. 51	15	13.7							9.5
18 Feb. 52	22	12.2							9.5
01 Dec. 52	21	12.5							9.0
03 Dec. 53	15	13.7							9.5
04 Jan. 55	5	16.8							8.5
14 Jan. 55	15	16.8							8.0
21 Sep. 55	22	12.2							9.5
09 Jan. 56	10	16.2	14.8	(3)	10.3	(18)			8.0
29 Mar. 58	11	15.2	9.8		7.7				9.5
02 Apr. 58	1	18.3	10.4	(29)	6.7				
08 Mar. 62	4	17.4	15.5	(2)	10.5	(15)			10.0
23 Mar. 62	1	18.3	9.7		9.1				8.0
24 Mar. 64	11	15.2	12.7	(5)	8.7				12.7
29 Jan. 66	15	13.7	12.0	(6)	13.0	(5)			11.0
23 Feb. 67	22	12.2	11.7	(8)	10.6	(14)			10.0
29 Apr. 67	5	16.8	11.2	(12)	9.5				12.5
06 Jan. 68	11	15.2	10.3	(30)	11.2	(12)			9.0
19 Feb. 69	30	11.9	10.5	(24)	12.2	(8)			
15 Nov. 71	22	12.2	7.5		8.5		037/1.7		10.7
04 Jan. 72	22	12.2	10.8	(18)	7.9		037/2.3	< 8.0	14.1
12 Feb. 73	15	13.7	13.7	(4)	7.6		037/ND	10.0	14.0
24 Mar. 73	5	16.8	16.2	(1)	12.3	(7)	037/4.5	11.0	14.1
02 Nov. 73	30	11.9	9.8		13.5	(2)	037/3.8	13.0	14.6
06 Feb. 74	15	13.7	11.4	(11)	9.9	(26)	091A/6.9	12.0	18.4
12 Mar. 74	5	16.8	10.7	(20)	8.1		090/6.4	12.0	12.0
29 Mar. 74	3	17.7	9.9		8.3		091B/6.0	9.0	15.6
23 Dec. 75	22	12.2	11.9	(7)	9.4		037/ND	< 8.0	8.0
08 Mar. 81	22	12.2					142B/6.6	12.0	10.6
16 Jan. 82	11	15.2					166/11.4	12.0	14.4
14 Feb. 82	20	13.4					166/9.8	11.0	10.0

ND: No data available for the storm period.

Table 5

Comparison of 30 highest SOWM and WES storms for Region 2

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	273/7	230373	16.2	5/2	70173*	13.7
2	273/7	70362	15.5	2/2	21173	13.5
3	275/7	90156	14.8	4/2	50371*	13.3
4	273/7	120273	13.7	6/2	160170*	13.1
5	265/7	240364	12.7	6/2	290166	13.0
6	265/7	290166	12.0	6/2	90168*	12.5
7	276/7	231275	11.9	6/2	240373	12.3
8	276/7	220267	11.7	3/2	200269	12.2
9	275/7	200272*	11.6	3/2	221273*	11.7
10	265/7	180274*	11.5	3/2	181273*	11.5
11	265/7	60274	11.4	6/2	180166*	11.3
12	273/7	290467	11.2	6/2	281073*	11.2
13	275/7	100269*	11.1	2/2	60168	11.2
14	276/7	170171*	11.0	6/2	220267	10.6
15	265/7	20368*	10.9	3/2	70362	10.5
16	275/7	301256*	10.9	6/2	160375*	10.5
17	276/7	21272*	10.9	6/2	210161*	10.4
18	276/7	40172	10.8	4/2	90156	10.3
19	276/7	271270*	10.8	5/2	110164*	10.2
20	276/7	120374	10.7	5/2	20368*	10.2
21	275/7	310367	10.6	6/2	10167*	10.2
22	185/7	70369*	10.6	4/2	171272*	10.1
23	276/7	210263*	10.6	5/2	50374*	10.0
24	265/7	160459*	10.5	1/2	210173*	10.0
25	265/7	200269	10.5	1/2	281073*	10.0
26	276/7	210161*	10.5	6/2	60274	9.9
27	273/7	170475*	10.5	6/2	100166*	9.9
28	285/7	101163*	10.5	6/2	71172*	9.9
29	275/7	20458	10.4	6/2	140373*	9.9
30	276/7	50374*	10.3	6/2	30366*	9.8

* Storms not making final selection
_ Storms identified by both SOWM and WES
No. of overlapping storms = 10

A total of 56 storms were verified as being potentially severe events in the Scotian Shelf. A breakdown of these by selection criteria is given in Table 6. No additional NEDN storms were obtained for this region as these storms all coincided with METOC-selected storms.

The hindcast-identified, potentially severe storms exhibited some degree of spatial preference: for the SOWM, 33% of the 30 top height-ranked storms were associated with point 276/7, whereas 50% of the WES top 30 storms were associated with point 6/2.

REGION 3 GRAND BANKS

The final set of ranked storms for the Grand Banks region is presented in Table 7. The SOWM was found to perform well at identifying severe storms in this region with 19 of the top 30 height-ranked SOWM storms making final selection. The WES, although not performing as well as the SOWM, was most successful in this region with 14 of the top 30 storms making the final severe storm set. The degree of overlap between the two hindcasts was only marginally better than in the Scotian Shelf with 11 storms common to both out of the top 30 height-ranked storms (see Table 8).

A total of 69 potentially severe storms were obtained for this region: a breakdown of these by selection criteria is given in Table 9.

The SOWM storm results for this region exhibited a strong bias toward point 279/7 where 70% of the 30 top height-ranked storms were found. WES results were more or

Table 6

Breakdown of Verified Severe Storms by Selection Criteria for Region 2, Scotian Shelf

Selection criteria	No. of verified[a] potential storms
AES Geostrophic Wind Climatology	12
SOWM	21
WES	9
METOC	14
Total (1946-82)	56

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[a] Initial verification from other data sources.

Table 7

Selected severe storms for the Grand Banks

Storm Date	Rank	BRET. (m)	SOWM		WES		Measured (m)	METOC (m)	Ship (m)
			(m)	(rank)	(m)	(rank)			
14 Dec. 51	15	13.7							
16 Mar. 56	15	13.7	15.2	(5)	10.1				8.0
24 Jan. 57	22	12.2	12.8	(20)	9.2				9.5
09 Feb. 57	22	12.2	10.8		7.7				8.0
06 Dec. 57	11	15.2	12.5	(24)	8.0				
08 Feb. 59	5	18.3	16.1	(2)	9.9				9.5
16 Apr. 59	1	21.3	12.3	(25)	10.1				9.5
21 Jan. 61	21	12.8	15.7	(4)	11.0	(25)			9.5
09 Dec. 61	22	12.2	9.3		12.6	(11)			8.5
17 Dec. 61	1	21.3	14.9	(10)	13.2	(9)			9.0
27 Feb. 62	22	12.2	9.2		12.7	(10)			14.0
11 Jan. 64	22	12.2	13.7	(15)	13.5	(8)			12.5
01 Mar. 64	15	13.7	10.9		13.8	(6)			10.0
15 Mar. 64	22	12.2	15.1	(7)	14.2	(3)			13.4
26 Jan. 65	22	12.2	11.5		10.2				8.0
19 Feb. 65	15	13.7	12.6	(23)	11.5	(22)			13.8
10 Jan. 66	22	12.2	11.9		13.6	(7)			10.3
17 Feb. 66	3	20.4	15.9	(3)	16.6	(1)			12.8
17 Feb. 67	5	18.3	13.0	(19)	10.3				10.5
23 Feb. 67	7	16.8	16.5	(11)	12.6	(11)			13.4
05 Jan. 68	15	13.7	10.8		12.1	(17)			11.3
22 Jan. 70	7	16.8	12.1		12.6	(11)			12.5
17 Jan. 71	13	14.3	13.6	(16)	10.4				14.1
05 Jan. 72	22	12.2	13.5	(18)	11.1	(24)		< 8.0	13.1
20 Feb. 72	22	12.2	12.2	(29)	*			< 8.0	
15 Dec. 72	22	12.2	14.1	(12)	7.4			12.0	12.0
29 Dec. 72	22	12.2	12.8	(20)	6.8			9.0	
20 Jan. 74	10	15.9	11.3		6.3		091/6.5	< 8.0	9.5
11 Mar. 74	20	13.4	12.2	(29)	6.1			11.0	18.4
29 Mar. 74	11	15.2	15.2	(5)	*			10.0	16.4
04 Mar. 78	13	14.3						16.0	13.9
08 Mar. 81	22	12.2					140/6.3	12.0	
17 Jan. 82	4	19.2					140/10.7	14.0	11.0
15 Feb. 82	7	16.8					140/12.7	15.0	10.0

* No corresponding storm identified.

NB: 13.0 m significant wave height event measured on 22 December 1983 at Hibernia. This was not included as 1982 had been defined as the end date for the study period.

Table 8

Comparison of 30 highest SOWM and WES storms for Region 3

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	279/7	230267	16.5	20/1	160266	16.6
2	279/7	80259	16.1	24/1	220169*	14.5
3	279/7	170266	15.9	20/1	180364	14.2
4	279/7	220161	15.7	20/1	240266*	14.1
5	279/7	290374	15.2	24/1	190264*	13.9
6	279/7	160356	15.2	24/1	10364	13.8
7	279/7	120374	15.1	24/1	100166	13.6
8	268/7	180364	15.1	20/1	140164*	13.5
9	279/7	40174*	15.0	20/1	171261	13.2
10	279/7	171261	14.9	24/1	260262	12.7
11	287/7	280166*	14.2	24/1	90369*	12.6
12	279/7	240266*	14.1	24/1	101261	12.6
13	279/7	161272	14.1	20/1	230170	12.6
14	279/7	210360*	14.0	20/1	230267	12.6
15	279/7	160164*	13.7	24/1	120363*	12.5
16	279/7	170171	13.6	24/1	50166*	12.3
17	268/7	200472*	13.6	20/1	60168	12.1
18	279/7	20172	13.5	20/1	260167*	12.0
19	277/7	170267	13.0	20/1	290357*	11.9
20	266/7	80156*	12.8	24/1	160170*	11.6
21	279/7	291272	12.8	24/1	300166*	11.6
22	279/7	260157	12.8	20/1	180375*	11.5
23	278/7	190265	12.6	20/1	190265	11.5
24	268/7	61257	12.5	20/1	20172	11.1
25	268/7	170459	12.3	20/1	220161	11.0
26	279/7	260167*	12.3	20/1	281261*	11.0
27	279/7	30272*	12.3	20/1	190165*	10.9
28	267/7	60274*	12.3	20/1	311256*	10.9
29	279/7	150372*	12.2	20/1	140173*	10.6
30	279/7	210272	12.2	24/1	200256*	10.6

* Storms not making final selection
_ Storms identified by both SOWM and WES
No. of overlapping storms = 11

Table 9

Breakdown of Verified Potential Severe Storms by Selection Procedure for Region 3, Grand Banks

Selection criteria	No. of verified[a] potential storms
AES Geostrophic Wind Climatology	7
SOWM	43
WES	14
METOC	3
NEDN	2
Total (1946-82)	69

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[a] Initially verified by other data sources.

less evenly divided between the two points in the region with point 20/1 being associated with a greater number of storm events.

The storm producing the 11-year (1970-80) highest wave height on the Grand Banks as identified by Neu (1982) was included in the list of severe storms. This storm occurred on 4 March 1978, not 4 March 1980 as indicated by Neu.

REGION 4 NORTHEAST NEWFOUNDLAND SHELF

The severe storms for Region 4 are presented in Table 10. This region included six SOWM points and two WES points (note that even though WES point 10/1 lay outside the defined region, it was included for the purposes of severe storm identification). The SOWM performed well at identifying severe storms, with 19 of the top 30 height-ranked SOWM storms making it into the final ranking (Table 11). Only seven WES storms made it into the final set and the degree of overlap (eight storms) between the SOWM and WES was the lowest of those regions containing WES data.

An interesting observation about this region is that the top-ranked SOWM storm (22.8 m for 25 January 1957), also ranked sixth by the WES, did not make it into the final set. This storm produced 60-knot winds from the northwest over the region on 25 January, but these were not maintained for long as the system moved rapidly eastward. However, it is likely that strong (75 knot) winds to the south of this region during 24 January generated a significant swell which propagated into Region 4. These more complex situations could not be dealt with adequately using the Bretschneider

Table 10

Selected severe storms for the northeast Newfoundland Shelf

Storm	Rank	BRET.	SOWM		WES		Measured	METOC	Ship
Date		(m)	(m)	(rank)	(m)	(rank)	(m)	(m)	(m)
15 Jan. 46	17	13.7							
23 Oct. 47	10	15.2							
01 Feb. 50	17	13.7							
23 Jan. 55	10	15.2							
16 Mar. 56	10	15.2	15.3	(13)	14.4	(2)			
10 Feb. 57	5	18.3	10.3		8.1				
05 Mar. 58	26	12.8	13.2		7.7				
08 Feb. 59	4	19.8	19.2	(2)	9.3				9.5
12 Jan. 60	26	12.8	15.7	(10)	10.0				8.0
21 Mar. 60	17	13.7	14.4	(20)	7.0				9.0
21 Jan. 61	2	21.3	16.7	(8)	11.4	(23)			9.0
17 Dec. 61	2	21.3	13.8	(28)	9.4				9.5
03 Mar. 62	16	14.6	17.2	(6)	10.6				
16 Feb. 64	10	15.2	14.2	(23)	13.9	(4)			14.0
22 Feb. 65	9	15.8	14.7	(17)	10.0				
20 Jan. 66	17	13.7	12.8		8.6				12.0
17 Feb. 66	1	22.9	14.4	(20)	9.5				13.0
23 Feb. 67	10	15.2	14.0	(27)	9.5				8.0
08 Jan. 72	8	15.9	12.6		14.3	(3)		< 8.0	8.5
02 Feb. 72	10	15.2	15.8	(9)	*			< 8.0	
09 Mar. 72	17	13.7	12.0		13.1	(7)		< 8.0	
03 Dec. 72	7	16.2	17.4	(4)	8.2			13.0	13.9
14 Jan. 73	17	13.7	17.0	(7)	15.6	(1)		8.0	6.0
19 Jan. 73	26	12.8	12.9		9.6			8.0	
04 Jan. 74	26	12.8	14.5	(18)	6.8			13.0	21.2
18 Feb. 74	17	13.7	11.3		6.9			8.0	15.0
10 Mar. 74	17	13.7	15.7	(10)	*			8.0	9.5
12 Mar. 74	17	13.7	18.0	(3)	*			12.0	
26 Mar. 74	26	12.8	11.6		*			8.0	
29 Mar. 74	5	18.3	17.4	(4)	*			8.0	8.0

NOTE: It may be advisable to also consider the following storm in any future hindcast analysis.

25 Jan. 57	-	10.7	22.8	(1)	13.5	(6)			9.0

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* No corresponding storm identified

Table 11

Comparison of 30 highest SOWM and WES storms for Region 4

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	153/9	250157*	22.8	10/1	140173	15.6
2	297/7	80259	19.2	10/1	170356	14.4
3	304/7	120374	18.0	10/1	80172	14.3
4	304/7	31272	17.4	10/1	180264	13.9
5	303/7	290374	17.4	10/1	150172*	13.7
6	303/7	30362	17.2	10/1	250157*	13.5
7	153/9	140173	17.0	10/1	100372	13.1
8	288/7	220161	16.7	10/1	30372*	12.9
9	297/7	30272	15.8	14/1	271274	12.9
10	153/9	270174*	15.7	10/1	250261*	12.9
11	304/7	120160	15.7	10/1	110356*	12.5
12	153/9	130164*	15.4	10/1	300157*	12.3
13	297/7	170356	15.3	14/1	290357*	12.2
14	304/7	290162*	15.1	10/1	150368*	11.9
15	153/9	200167*	15.0	10/1	250275*	11.9
16	153/9	150172*	14.8	10/1	151256*	11.9
17	153/9	210265	14.7	10/1	81156*	11.8
18	288/7	40174	14.5	10/1	160164*	11.8
19	304/7	240165*	14.5	10/1	91168*	11.7
20	288/7	210360	14.4	10/1	221168*	11.7
21	297/7	161272*	14.4	10/1	291163*	11.5
22	288/7	170266	14.4	10/1	41168*	11.4
23	153/9	81272	14.2	10/1	220161	11.4
24	153/9	190264	14.2	14/1	240266*	11.3
25	304/7	20372*	14.2	14/1	71271*	11.2
26	153/9	71261*	14.1	10/1	91260*	11.2
27	288/7	230267*	14.0	10/1	241061*	11.1
28	297/7	50172	13.8	10/1	100271*	11.1
29	288/7	171261	13.8	10/1	40257*	11.0
30	304/7	250162*	13.7	10/1	271168*	11.0

* Storms not making final selection
_ Storms identified by both SOWM and WES
No. of overlapping storms = 8

nomogram, which may explain partly why this storm did not make final selection. This particular case was noted for discussion as it represented the greatest storm wave height hindcast by SOWM for the entire study domain.

A total of 60 potentially severe storms were identified in this region for further verification. A breakdown of these storms by selection criteria is given in Table 12.

The low number of METOC storms reflects a high degree of overlap between hindcast identified and METOC-identified storms in this region.

In terms of the spatial distribution of severe storms, the top 30 height-ranked SOWM storms did not show as marked a bias toward a single point as in Region 3. Severe storms were most frequently associated with point 153/9 (33%) followed by points 304/7 (23%), 288/7 (20%), and 297/7 (17%). Only two of the top 30 SOWM storms were associated with point 303/7 and no storms with point 296/7 . The severe storms identified by WES were dominated by point 10/1.

REGION 5 LABRADOR SHELF

The ranked severe storms for Region 5 are presented in Table 13. A total of 72 verified potentially severe storms were identified for this region. A breakdown of these by selection criteria is given in Table 14.

Table 15 compares the storm identification abilities of the SOWM and WES. As in the other regions, the degree of overlap between the hindcasts was low (nine storms

Table 12

Breakdown of Verified Potential Severe Storms by Selection Criteria for Region 4, Northeast Newfoundland Shelf

Selection criteria	No. of verified[a] potential storms
AES Geostrophic Wind Climatology	11
SOWM	42
WES	5
METOC	1
NEDN	1
Total (1946-82)	60

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[a] Initial verification by other data sources.

Table 13

Selected severe storms for the Labrador Shelf

Storm Date	Rank	BRET. (m)	SOWM		WES		Measured (m)	METOC (m)	Ship (m)
			(m)	(rank)	(m)	(rank)			
25 Jan. 48	29	14.3							9.5
07 Oct. 54	17	16.5							
10 Feb. 57	7	18.3	10.4		8.3				
06 Mar. 58	19	15.8	15.0	(13)	8.2				
06 Jan. 59	5	19.8	14.1	(22)	11.8	(4)			9.5
09 Feb. 59	1	21.3	13.6	(28)	*				9.5
14 Jan. 60	28	14.6	18.5	(3)	9.6	(27)			9.5
18 Dec. 61	29	14.3	14.4	(20)	7.3				9.5
22 Feb. 65	20	15.2	16.4	(15)	9.5	(28)			8.0
19 Jan. 66	20	15.2	13.6	(28)	10.0	(19)			11.0
17 Feb. 66	7	18.3	12.6		6.7				8.0
06 Mar. 69	20	15.2	15.6	(8)	8.6				
28 Dec. 70	12	16.8	14.1	(22)	8.0				9.5
17 Jan. 72	20	15.2	14.9	(15)	9.3			< 8.0	10.0
02 Feb. 72	20	15.2	12.1		*			< 8.0	
02 Mar. 72	12	16.8	15.1	(12)	10.6	(13)		< 8.0	8.5
04 Dec. 72	10	17.7	15.9	(6)	*			10.0	
19 Dec. 72	12	16.8	14.1	(22)	*			< 8.0	8.1
23 Feb. 73	12	16.8	11.9		*			8.0	8.3
04 Jan. 74	20	15.2	11.4		*			8.0	9.3
14 Jan. 74	12	16.8	12.7		*			< 8.0	
27 Jan. 74	20	15.2	14.5	(19)	8.1			< 8.0	5.5
10 Mar. 74	5	19.8	13.3		*			9.0	
12 Mar. 74	2	20.4	19.3	(2)	*			11.0	10.0
29 Mar. 74	2	20.4	15.7	(7)	*			< 8.0	
01 Apr. 75	17	16.5	13.8	(26)	11.4	(7)		< 8.0	
09 Oct. 75	2	20.4	14.6	(17)	6.9		017F/8.1	10.0	12.7
18 Mar. 76	20	15.2						10.0	8.3
18 Feb. 79	11	17.1						12.0	
23 Jan. 82	7	18.3						12.0	

NOTE: It may be adveiseable to also consider the following storm in any future hindcast analysis.

25 Jan. 57 - 19.9 (1) 9.3 (39)

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* No corresponding storm identified

Table 14

Breakdown of Verified Potential Severe Storms by Selection Criteria for Region 5, Labrador Shelf

Selection criteria	No. of verified[a] potential storms
OSV Bravo	7
AES Geostrophic Wind Climatology	7
SOWM	44
WES	1
METOC	10
NEDN	3
Total (1946-82)	72

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[a] Initial verification from other data sources.

Table 15

Comparison of 30 highest SOWM and WES storms for Region 5

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	134/9	250157*	19.9	6/1	81274*	14.9
2	310/7	120374	19.3	6/1	281274*	12.2
3	114/9	120160	18.5	6/1	301264*	12.1
4	134/9	20362*	18.5	6/1	30266*	11.8
5	114/9	220265	16.4	6/1	60159	11.8
6	310/7	41272	15.9	6/1	220175*	11.6
7	310/7	290374	15.7	6/1	10475	11.4
8	319/7	70369	15.6	6/1	20262*	11.3
9	134/9	140173*	15.4	6/1	270172*	11.2
10	134/9	81261*	15.3	6/1	20464*	11.2
11	134/9	81272	15.2	6/1	130364*	11.1
12	134/9	20372	15.1	6/1	50372*	11.0
13	319/7	171172*	15.0	6/1	20372	10.6
14	315/7	60358	15.0	6/1	251175*	10.5
15	134/9	140164*	14.9	6/1	250163*	10.5
16	134/9	150172	14.9	6/1	240266*	10.5
17	315/7	91075	14.6	6/1	190261*	10.2
18	071/9	220256*	14.6	6/1	70473*	10.1
19	134/9	271074	14.5	6/1	201271*	10.0
20	134/9	171261	14.4	6/1	241269*	10.0
21	071/9	60272	14.2	6/1	180166	10.0
22	092/9	281159*	14.1	6/1	41168*	9.9
23	114/9	30159	14.1	6/1	90172*	9.9
24	310/7	191272	14.1	6/1	140362*	9.8
25	071/9	281270	14.1	6/1	71156*	9.7
26	134/9	190264*	13.8	6/1	140164*	9.7
27	134/9	10475	13.8	6/1	120160	9.6
28	310/7	80259	13.6	6/1	240265	9.5
29	310/7	180166	13.6	6/1	81261*	9.5
30	134/9	170364*	13.6	6/1	110369*	9.5

* Storms not making final selection
_ Storms identified by both SOWM and WES
No. of overlapping storms = 9

common to both hindcasts for the top 30 height-ranked storms). In terms of performance, the SOWM worked well in this region with 20 out of the top 30 height-ranked storms making the final severe storm set.

The storm of 12 March 1974, identified by Neu (1982) as producing the highest wave height in the Labrador Sea over the period 1970-80, was ranked second by the SOWM but did not appear in the top 30 height-ranked WES storms. This storm was also ranked second in the regional ranking based on the SMB hindcasting method. A storm with higher METOC waves than the 12 March, storm identified by Neu, occurred on 18 February 1979. This storm was also included in the final list but only ranked 11th based on the SMB hindcast. As in Region 4, the storm of 25 January 1957 was identified as having the highest waves by the SOWM. Because of certain inadequacies of the Bretschneider hindcast methodology outlined earlier, this storm did not make final selection. However, it may be advisable to consider this case for more detailed hindcasting.

Spatially, SOWM point 134/9 dominated the severe storms (43%) followed by point 310/7 (20%). This is indicative of an increase in storm wave heights toward the south and east of the region.

REGION 6 DAVIS STRAIT

The final set of severe storms for Region 6 is presented in Table 16. Selection of severe storms in this region was more biased toward the SOWM in that the WES and METOC data sources were not available. Prior to 1956, AES hindcast winds were the main source for storm identification.

Table 16

Selected severe storms for Davis Strait

Storm Date	Rank	BRET. (m)	SOWM (m)	SOWM (rank)	WES (m)	WES (rank)	Measured (m)	METOC (m)	Ship (m)
26 Nov. 47	29	10.0							
07 Jan. 49	29	10.0							
28 Nov. 55	17	11.0							
22 Feb. 56	5	13.7	14.4	(1)					
02 Jan. 57	19	10.7	10.0	(24)					
18 Jan. 59	5	13.7	13.1	(2)					
25 Jan. 63	1	16.5	11.3	(14)					
01 Dec. 63	31	9.8	9.7	(28)					
13 Jan. 64	31	9.8	8.1						
06 Jan. 65	14	11.6	8.7						
23 Feb. 65	12	12.2	12.8	(3)					
16 Nov. 65	14	11.6	9.6	(29)					
06 Feb. 69	5	13.7	11.1	(16)					
06 Mar. 69	12	12.2	9.4						
28 Dec. 70	3	15.2	12.4	(6)					
29 Jan. 71	2	15.8	10.7	(20)					
27 Jan. 72	9	12.8	12.2	(9)					
07 Feb. 72	19	10.7	12.3	(8)					
02 Mar. 72	5	14.3	11.6	(13)					
18 Oct. 72	24	10.1	10.9	(18)					
17 Nov. 72	9	12.8	11.6	(11)					
10 Jan. 74	9	12.8	8.5						
02 Feb. 74	16	11.3	12.4	(6)					
10 Mar. 74	24	10.1	12.7	(5)					
13 Mar. 74	24	10.1	12.7	(5)					
26 Mar. 74	19	10.7	11.0	(17)					
02 Apr. 75	24	10.1	12.8	(3)					
21 Nov. 75	24	10.1	8.9						9.0
23 Jan. 76	19	10.7							
04 Feb. 76	19	10.7							
02 Mar. 76	17	11.0							
28 Jan. 77	5	13.7							

Very few ship observations were found for this period. From 1976 to 1982, AES hindcast winds, NEDN wave forecast data, ship wave observations, and available waverider buoy data were used to identify significant storms. Of these data sources, the AES wind hindcast used in conjunction with the Bretschneider nomogram was found to be the most successful at identifying severe wave events. A total of 64 potentially severe storms were identified in the region. These are summarized in Table 17 by selection criteria.

Table 18 provides an indication of the SOWM's performance at severe storm identification in this region: 19 of the top 30 height-ranked storms made it into the final set of ranked storms. As can be seen in Table 27, the SOWM-identified storms exhibited a marked bias toward point 47/9 (83%), located in the southern portion of the region.

REGION 7 BAFFIN BAY

The final set of severe storms for Region 7 is presented in Table 19. The Baffin Bay region was the most difficult for selection of severe events as much of the data used in other regions was not available. The SOWM-hindcast and AES-hindcast wind data sets were the main sources used, supplemented by NEDN wave-forecast data, ship observations and a catalogue of significant storms (1974-78) in the Baffin Bay region provided by Maxwell et al. (1980). The latter storms had been identified based on geostrophic winds derived from Arctic Weather Centre pressure analyses. A total of 53 potentially severe storms were identified for this region. These are categorized in Table 20 by selection criteria.

Table 17

Breakdown of Verified Potential Severe Storms by Selection Criteria for Region 6, Davis Strait

Selection criteria	No. of verified[a] potential storms
SOWM	41
AES Geostrophic Wind Climatology	12
Ship Observations	9
Waverider Buoy	1
NEDN	1
Total (1946-82)	64

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[a] Initially verified by other data sources where possible.

Table 18

Comparison of 30 highest SOWM and WES storms for Region 6

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	047/9	220256	14.4			
2	047/9	180159	13.1			
3	047/9	10475	12.8			
4	047/9	220265	12.8			
5	047/9	130374	12.7			
6	047/9	281270	12.4			
7	047/9	20274	12.4			
8	047/9	60272	12.3			
9	047/9	270172	12.2			
10	047/9	130160*	11.7			
11	047/9	20372	11.6			
12	046/9	301261*	11.6			
13	047/9	171172	11.6			
14	004/10	250163	11.3			
15	047/9	311256*	11.2	No WES points in this region		
16	047/9	50269	11.1			
17	047/9	260374	11.0			
18	046/9	181072	10.9			
19	047/9	251268*	10.8			
20	047/9	280171	10.7			
21	047/9	60159*	10.7			
22	047/9	210472*	10.3			
23	047/9	51173*	10.2			
24	047/9	21257*	10.0			
25	047/9	10157	10.0			
26	046/9	21074*	9.9			
27	047/9	70473*	9.9			
28	046/9	21263	9.7			
29	047/9	161165	9.6			
30	047/9	261173*	9.6			

* Storms not making final selection

Table 19

Selected severe storms for Baffin Bay

Storm Date	Rank	BRET.	SOWM		WES		Measured	METOC	Ship
		(m)	(m)	(rank)	(m)	(rank)	(m)	(m)	(m)
11 Oct. 50	5		5.1	(15)					
15 Oct. 56	9		5.4	(11)					
03 Nov. 59	31		4.4	(29)					
27 Oct. 60	12		6.4	(4)					
05 Sep. 62	2		4.6	(25)					
25 Nov. 62	2		*						
02 Oct. 63	1		4.5	(26)					4.3
19 Nov. 65	9		4.3	(30)					
07 Oct. 66	24		6.1	(5)					
01 Nov. 66	12		4.8	(20)					
06 Nov. 66	31		4.8	(20)					
22 Sep. 67	12		5.1	(15)					
07 Nov. 67	27		4.3	(30)					
15 Jul. 68	21		5.7	(7)					
05 Oct. 68	12		5.5	(10)					
17 Nov. 69	24		5.7	(7)					
13 Oct. 70	12		5.1	(15)					
20 Oct. 70	8		8.8	(1)					5.5
25 Nov. 70	4		5.2	(13)					4.6
23 Aug. 71	18		5.1	(15)					6.9
20 Nov. 71	27		5.3	(12)					
06 Oct. 72	27		6.6	(3)					
19 Oct. 72	9		5.8	(6)					4.3
26 Sep. 74	12		5.2	(13)					
03 Oct. 74	6		*						
17 Oct. 74	18		*						
30 Oct. 74	21		4.7	(22)					
24 Nov. 74	31		4.4	(29)					
07 Oct. 75	20								
10 Sep. 76	27								
23 Nov. 77	6								
01 Oct. 78	31								
09 Oct. 78	24								
20 Oct. 81	19								
18 Jan. 59			9.9						
31 Dec. 61	5 worst SOWM -		9.2						
25 Jan. 63	identified		8.8						
06 Feb. 69	storms during		8.8						
05 Feb. 70	ice-cover period		8.4						

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* No corresponding storm identified
Storm selection restricted to July-November "ice-free" period

Table 20

Breakdown of Verified Potential Severe Storms by Selection Criteria for Region 7, Baffin Bay

Selection criteria	No. of verified[a] potential storms
SOWM	34
AES Geostrophic Wind Climatology	4
Maxwell et al. (1980)	13
Ship Observations	1
NEDN	1
Total (1946-82)	53

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[a] Initially verified by other data sources.

This region differed from the others in that an "ice-free" period was specified from July to November in the storm selection process. However, the five worst SOWM storms occurring during the ice-cover period are also included in Table 19 as additional information.

Table 21 provides an indication of the SOWM's performance in identifying severe storms in this region: 23 of the top 30 SOWM height-ranked storms made it into the final set of ranked storms for Region 7. As can be seen in Table 21, there was no marked spatial bias in the SOWM-identified storms. However, the greatest numbers of the top 30 height-ranked storms were associated with points 30/10 (37%) and 53/10 (30%).

Table 21

Comparison of 30 highest SOWM and WES storms for Region 7

Rank	Point No.	SOWM Storm (date)	Max. Height (m)	Point No.	WES Storm (date)	Max. Height (m)
1	030/10	251170	8.8			
2	053/10	211169*	7.0			
3	030/10	191072	6.6			
4	054/10	50962	6.4			
5	053/10	11166	6.1			
6	076/10	260974	5.8			
7	054/10	210967	5.7			
8	030/10	121070	5.7			
9	053/10	51068	5.7			
10	053/10	171169	5.5			
11	054/10	31159	5.4			
12	076/10	51072	5.3			
13	030/10	130871	5.2			
14	030/10	21074	5.2			
15	030/10	201070	5.1	No WES points in this region		
16	030/10	151056	5.1			
17	053/10	201171	5.1			
18	053/10	71167	5.1			
19	076/10	240967	5.0			
20	030/10	151167*	4.8			
21	030/10	51166	4.8			
22	030/0	231174	4.7			
23	054/10	31165*	4.7			
24	076/10	201071*	4.7			
25	030/10	271162	4.6			
26	053/10	250964*	4.5			
27	076/10	80970*	4.5			
28	053/10	161165*	4.5			
29	076/10	261060	4.4			
30	053/10	150768	4.3			

* Storms not making final selection

Note: Storm Selection restricted to July-November "ice-free period".

CLIMATOLOGY OF SEVERE STORMS AFFECTING THE EAST COAST OF CANADA

Most climatological studies of cyclones have focused on storm tracks (Archibald 1969; Keliher et al. 1978), cyclone frequency counts (Maxwell 1982; Colucci 1976), or both (Whittaker and Horn 1982; Reitan 1974) following the earlier work of Klein (1957) and Petterssen (1956). Considerable effort also has been expended on the problem of secular variability in extratropical cyclonic activity (Reitan 1979; Hayden 1981; Zishka and Smith 1980; Kutzbach 1970), mainly in the long-term sense rather than with respect to interannual variability. Much of that work dealt with representative months such as January and July (Maxwell 1982; Kutzbach 1970; Zishka and Smith 1980), although some introduced intermediate months (Reitan 1974). The studies of Klein (1957) and Whittaker and Horn (1982) were the most comprehensive in this respect, covering the entire twelve-month period.

The present study was undertaken with the objective of developing a complete and detailed climatology of severe storms affecting the east coast of Canada. To accomplish this objective, the analysis was carried out on several fronts. The annual distribution of severe events was compiled both by region and for the entire study area, to determine any trends and most importantly, to point out any deficiencies in the process of storm selection related to discontinuities in the data set.

The seasonal distribution of storms also was compiled to indicate any physically meaningful pattern in the occurrence of severe events. The analysis was extended to include monthly storm tracks for the entire study domain, which were then related to the seasonal normals.

Lastly, the regional storm classification was completed, detailing the observed patterns of severe storm tracks as well as the "idealized" preferred storm pattern. These were related to prevailing wind directions at the time of the event, and to the evolution of the storm, including such factors as the rate of storm intensification and patterns of its decay. A simple correlation analysis was performed relating storm ranking to central pressure.

ANNUAL DISTRIBUTION OF SEVERE STORMS

The annual distribution of independent storms for all regions is given in Figure 11. The outstanding characteristic of this histogram is the large number of storms in the years 1972 and 1974. In a similar severe storm study for the Canadian east coast by Lewis and Moran (1984) based on maximum wind speeds, the results also showed peaks in the number of severe storms for 1972 and 1974. However, they showed peaks in 1963 and 1964 which were not replicated in this study. A review of recent literature pertaining to secular variations in east coast cyclones suggests that these anomalies are real rather than the by-product of bias in the process of storm selection.

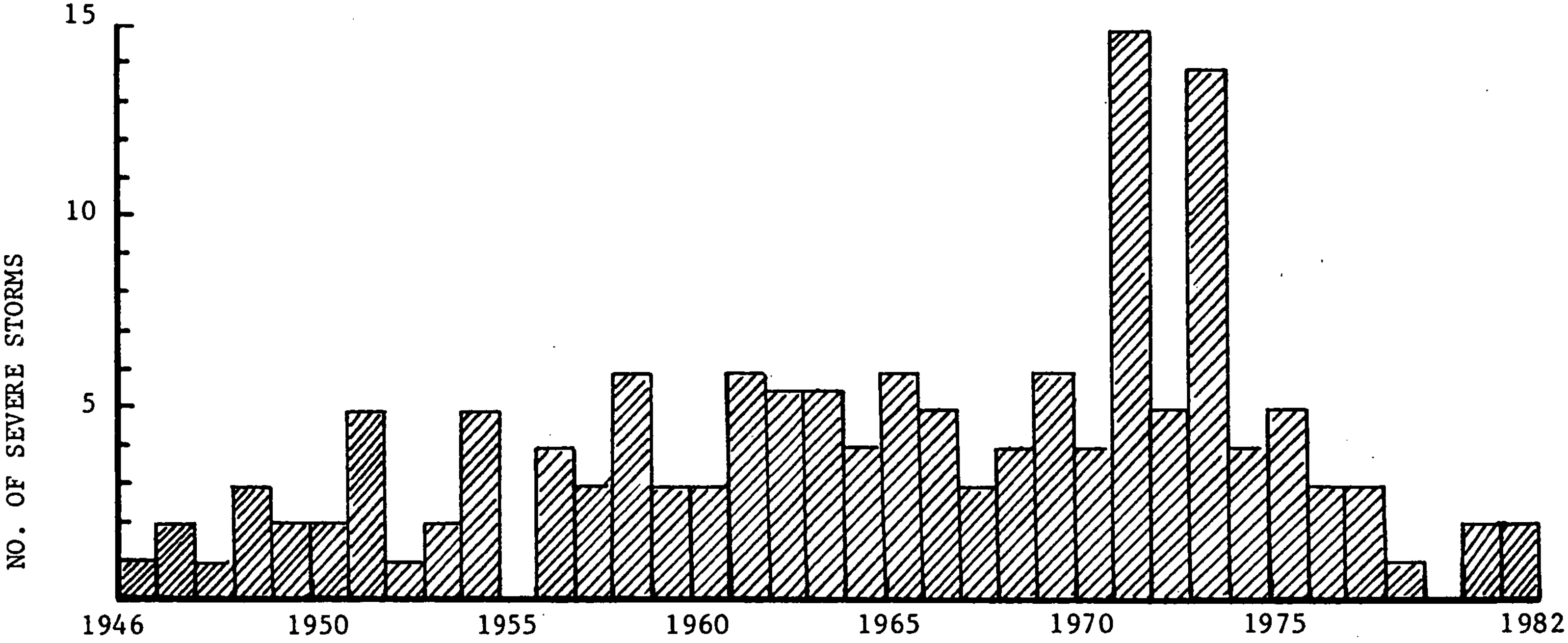

Figure 11. Annual distribution of severe storms for all regions.

During the last two decades, evidence has been collected by various researchers investigating different aspects of climatic variability to suggest that climatic change can occur on time scales much less than that of the glacial periods (as was previously believed). Short-term climatic fluctuations, on time scales which significantly affect the activities of man, are now recognized and accepted. Much of the research work has centred upon decadal and long-period fluctuations rather than interannual variability (Zishka and Smith 1980; Reitan 1979; Resio and Hayden 1975). However, Zishka and Smith discovered a striking trend in their data on frequency and minimum pressure of January and July cyclones from 1950-77, which indicated a 45% decrease in the number of cyclones over the 28 years, combined with a statistically significant trend toward decreasing minimum pressure. If one considers minimum pressure as an indication of cyclone intensity, it appears that cyclones, although less numerous, are increasingly intense. To examine these trends, the period 1970-74 was compared to 1950-54 by Zishka and Smith. The later period showed a greater number of cyclones in the Gulf of Mexico and along the eastern seaboard, but considerably less across all regions of the wave study.

Saulesleja and Phillips (1982) provide additional evidence that the climate was more severe in the early 1970s. The tracks of low-pressure centres of less than 960 mb over eastern Canada and the Northwest Atlantic were contrasted during the month of January for 1959-68 versus 1969-78. In the latter period, the number of cyclones were fewer, and they generally migrated towards the Icelandic low, which intensified during the period. Indeed, the average mean sea-level pressure was lower across the entire northwest

Atlantic: from Baffin Island, south to Labrador and Newfoundland, and east to Europe. The frequency of occurrence of higher wind speeds appears to have been greater in the more recent (1969-78) period throughout all regions of the study, including a record high of 655 hours of gales in 1972 at Sable Island on the Scotian Shelf. This evidence supports the contention that the early 1970s, in general, and 1972, in particular, were exceptionally severe.

The statistics for 1974 were influenced strongly by the weather of the second half of March of that year. In terms of the study, March 1974 was a particularly extreme month, with severe wave events occurring in Regions 2, 3, 4, 5, and 6 (including storms ranked 2 and 5 in Region 5, and ranked 5 in Region 2) from 10-13 March, and in Regions 1, 2, 3, 4, 5, and 6 (including storms ranked 2 again in Region 5, 3 in Region 2, and 5 in Region 4) from 26-29 March. In total there were four severe wave-producing storms, accounting for 15 events in the seven regions during that period. Examination of the synoptic and planetary-scale features of the 700-mb flow pattern helped to illuminate the conditions responsible for this unusually severe weather.

The number of storms and their tracks were near normal for the month but were more intense, with lower pressures in the mean (Mariners Weather Log, September 1974). The Icelandic low was west-southwest of its mean position, and 13 mb deeper for the month. A negative 11 mb pressure anomaly was located over Baffin Bay resulting from a deeper, sharper trough in that area. The average surface temperature across the eastern United States for March was 3°C above normal in some places, as a result of record warmth over the regions during the first one to two weeks of the month, associated with 700-mb ridging aloft. The mean 700-mb height pattern underwent a complete reversal during the following week, coinciding with a basic reversal in the weekly mean temperature anomaly, with troughing across the northwest Atlantic and eastern seaboard and associated colder temperatures in the east.

Explosive cyclonic development[1] in the Pacific helped to establish ridging across western North America in the final two weeks of March, a result consistent with the theoretical work of Gall et al. (1979) and the observation of Sanders and Gyakum (1980) that interactions between cyclone scale instability and larger-scale troughs and ridges can work in both directions. Downstream, the 700-mb trough dominated the circulation over eastern Canada and the United States. Strong northwesterly flow between these features advected very cold air into the United States, with surface temperatures averaging 2-7°C below normal across the east and northeast from the Carolinas to Maine. Dickson and Namias (1976) demonstrated the importance of extreme cold and the associated enhanced baroclinicity at the Atlantic seaboard with respect to cyclonic activity. In their study, the enhanced coastal baroclinicity regimes were associated with increased cyclonic activity to the southwest of the climatological position resulting from a southwestward shift

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[1] Storms at different latitudes with identical pressure gradients do not produce the same maximum geostrophic wind. Sanders and Gyakum (1980) have defined an explosive cyclone as a storm with a 24-hour pressure fall geostrophically equivalent to, or greater than, 24 mb at 60°N (one bergeron).

of the entire storm distribution pattern. In addition, cyclonic activity was increased along a branch extending from the United States coast northward and westward up the Davis Strait.

Although their study did not encompass the rate of development of cyclones, it was suggested that the enhancement of coastal baroclinicity might positively affect the cyclogenetic rate of storms. This explanation seems highly plausible, particularly in the light of the study conducted by Sanders and Gyakum (1980) which associated explosive cyclogenesis with the leading edge of an outbreak of arctic air over the west Atlantic, including an extraordinarily active week in which five explosive storms developed during a cold snap across the eastern United States. These authors and, more recently, Roebber (1984) have shown that the preferred regions of explosive cyclogenesis are baroclinic zones, and that these storms exhibit a relationship to the upper level flow which is qualitatively similar to less intense storms. Sanders and Gyakum further demonstrated that explosive cyclogenesis is a characteristic of the majority of the deepest cyclones, a result which is corroborated by this study where 86 of 135, or 64% of the cyclones (excluding Region 7) exhibited this type of development, including three out of the four severe cyclones in March 1974. Thus, the synoptic flow pattern in the final weeks of March was established in a manner that could only encourage the development of coastal cyclones of a severe nature, which was reflected in the distribution of storms for 1974.

A second prominent feature of the distributions is the fewer number of storms in the years prior to 1955; this is probably related to the data sources, particularly in the northern areas where fewer data were available in the years prior to the SOWM hindcast (1956). This feature is apparent in most of the regions (Figures 12 to 18) and is probably inevitable considering the inherently more systematic nature of the wave hindcast data used to select storms from 1956-75. The lower number of storms after 1975 may also reflect a discontinuity in the storm selection methodology. This problem should have been alleviated somewhat by the availability of both the NEDN data set and METOC data for the period.

However, it should be noted that the METOC data incorporates ice-cover effects whereas the NEDN, SOWM, and WES data did not. This is one possible explanation for a lower number of severe storms in the later period.

SEASONAL DISTRIBUTION OF SEVERE STORMS

The seasonal distribution of severe storms by region is shown in Figures 19 and 20. The distribution of storms in all regions is highly seasonal, with no storms recorded in June, July, or August in Regions 1 to 6. There is a January maximum in all regions except Region 2 where March is dominant, with more storms occurring in the mid-winter and spring months than in the fall and early-winter. The distributions are reminiscent of the monthly frequency of explosive cyclones exhibited in Sanders and Gyakum (1980): this result is not surprising, because, as mentioned earlier, nearly two thirds of all cases were

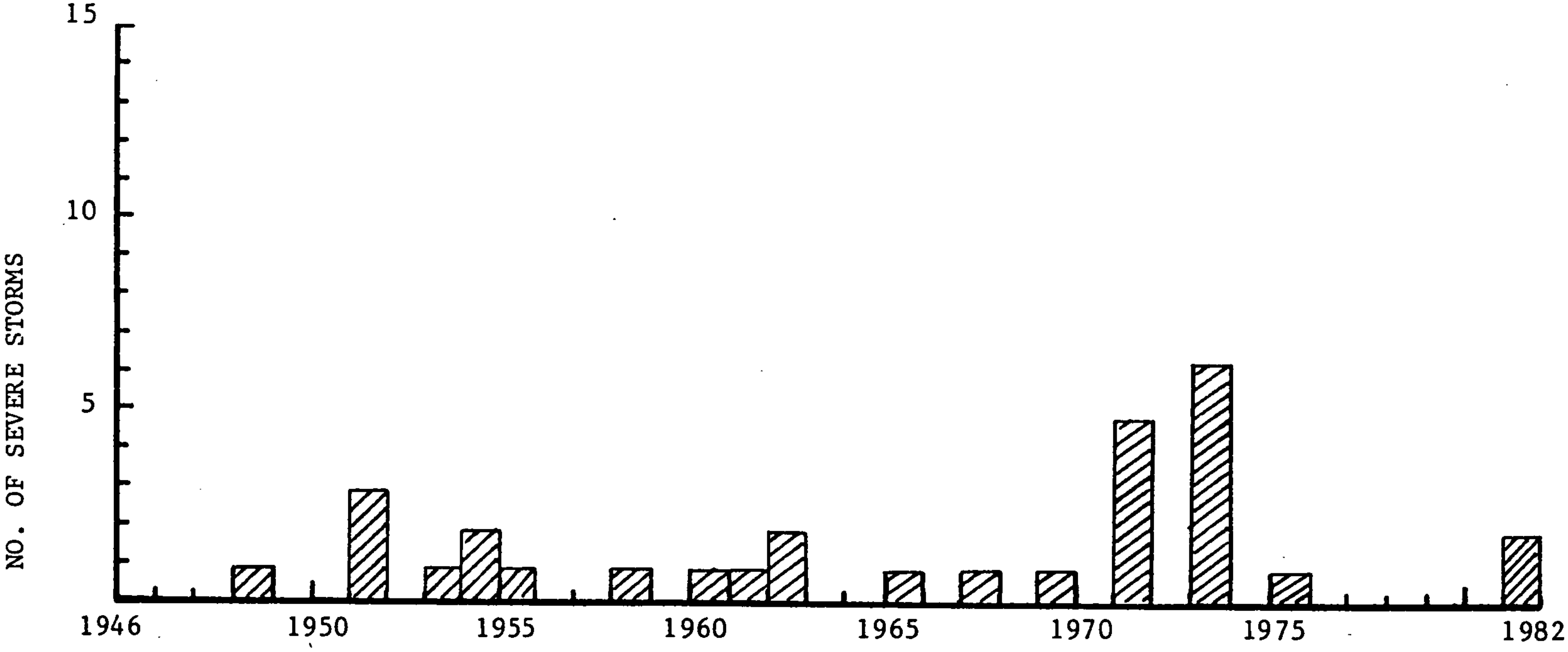


Figure 12. Annual distribution of severe storms for Region 1.

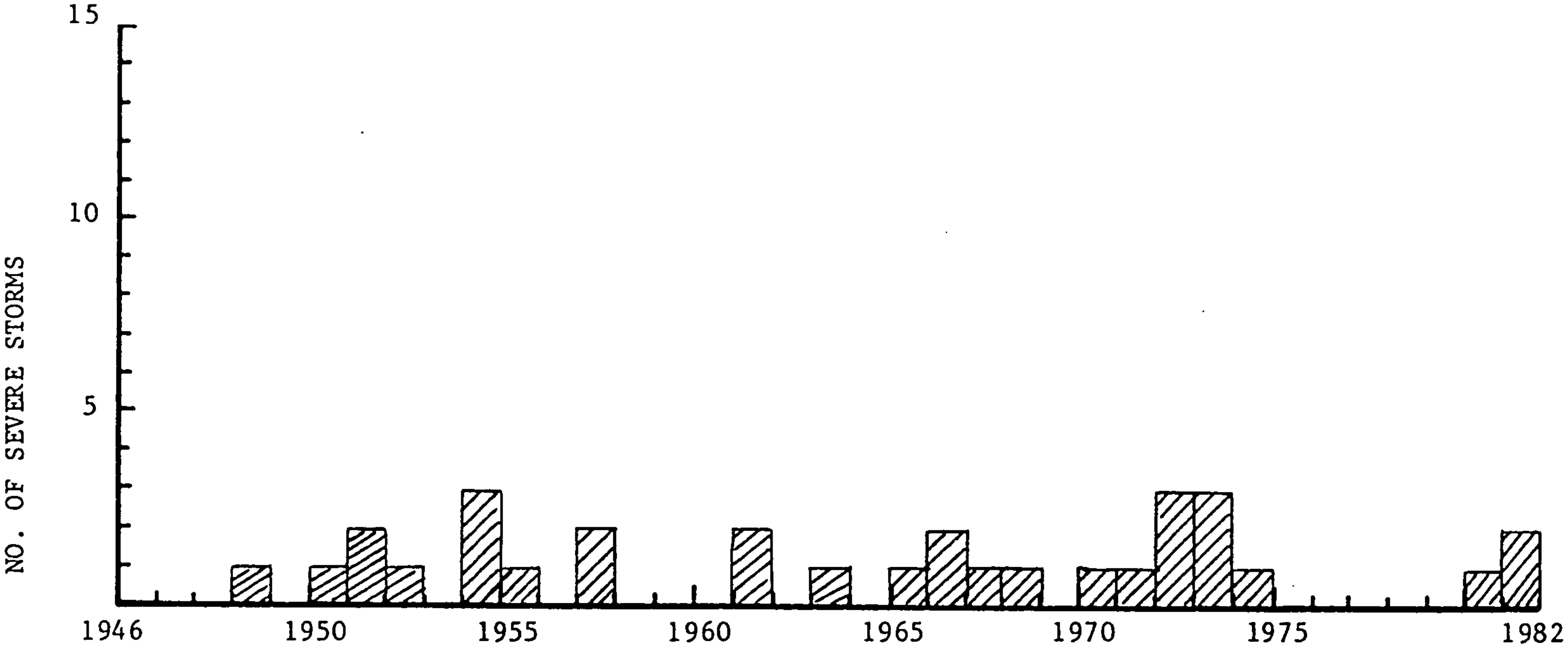


Figure 13. Annual distribution of severe storms for Region 2.

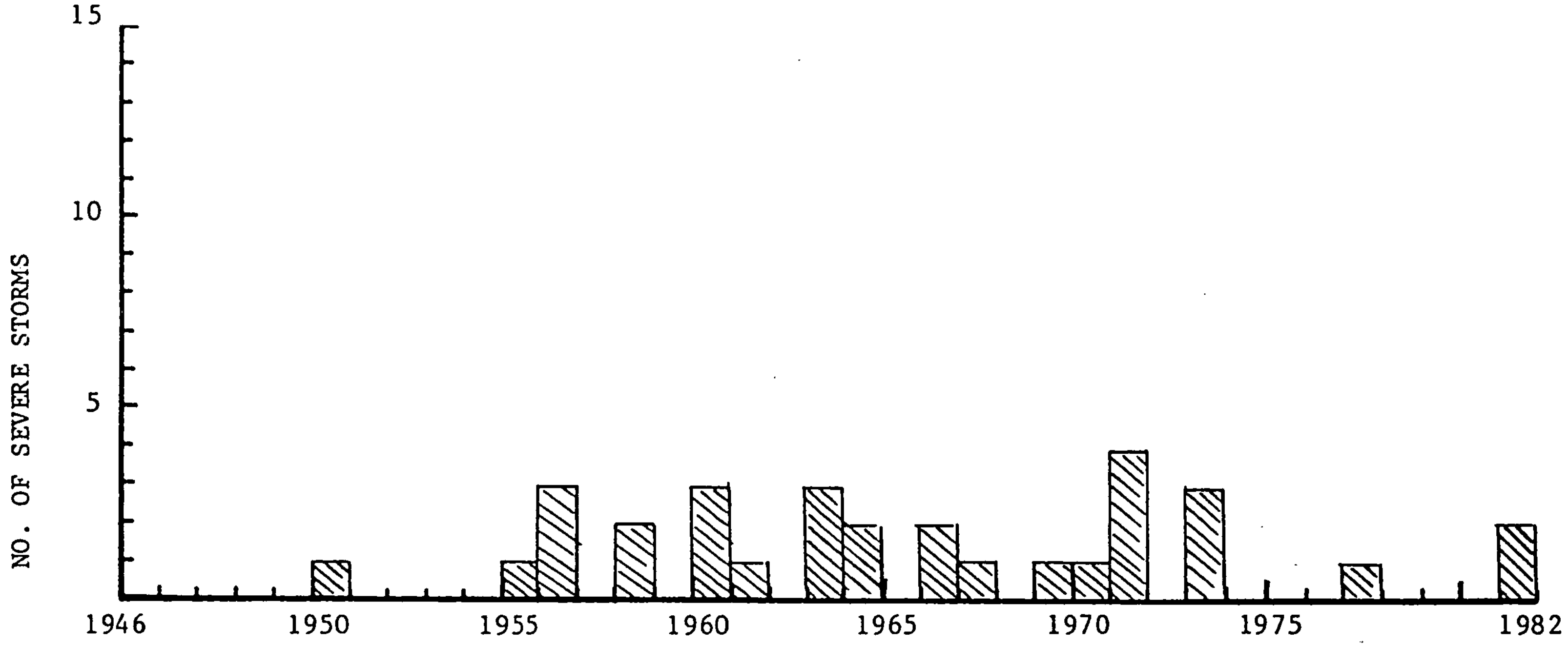


Figure 14. Annual distribution of severe storms for Region 3.

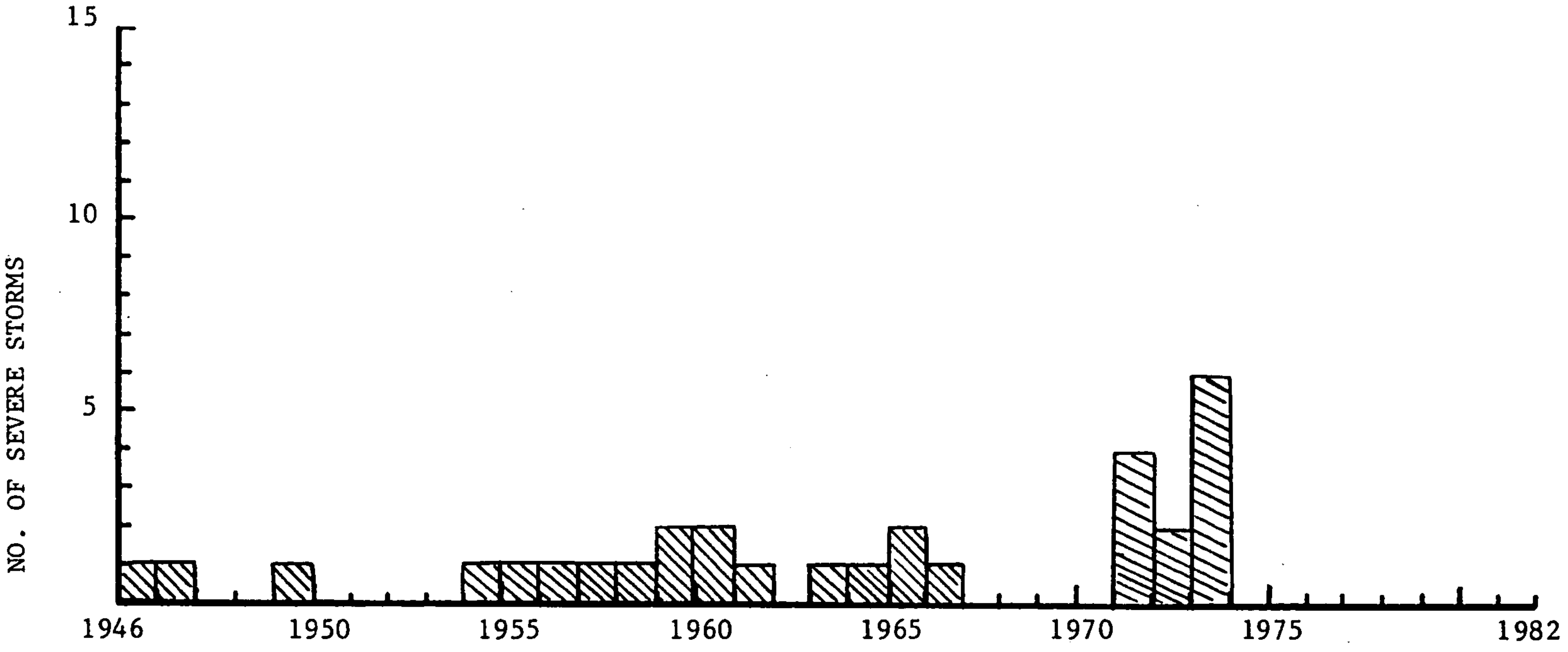


Figure 15. Annual distribution of severe storms for Region 4.

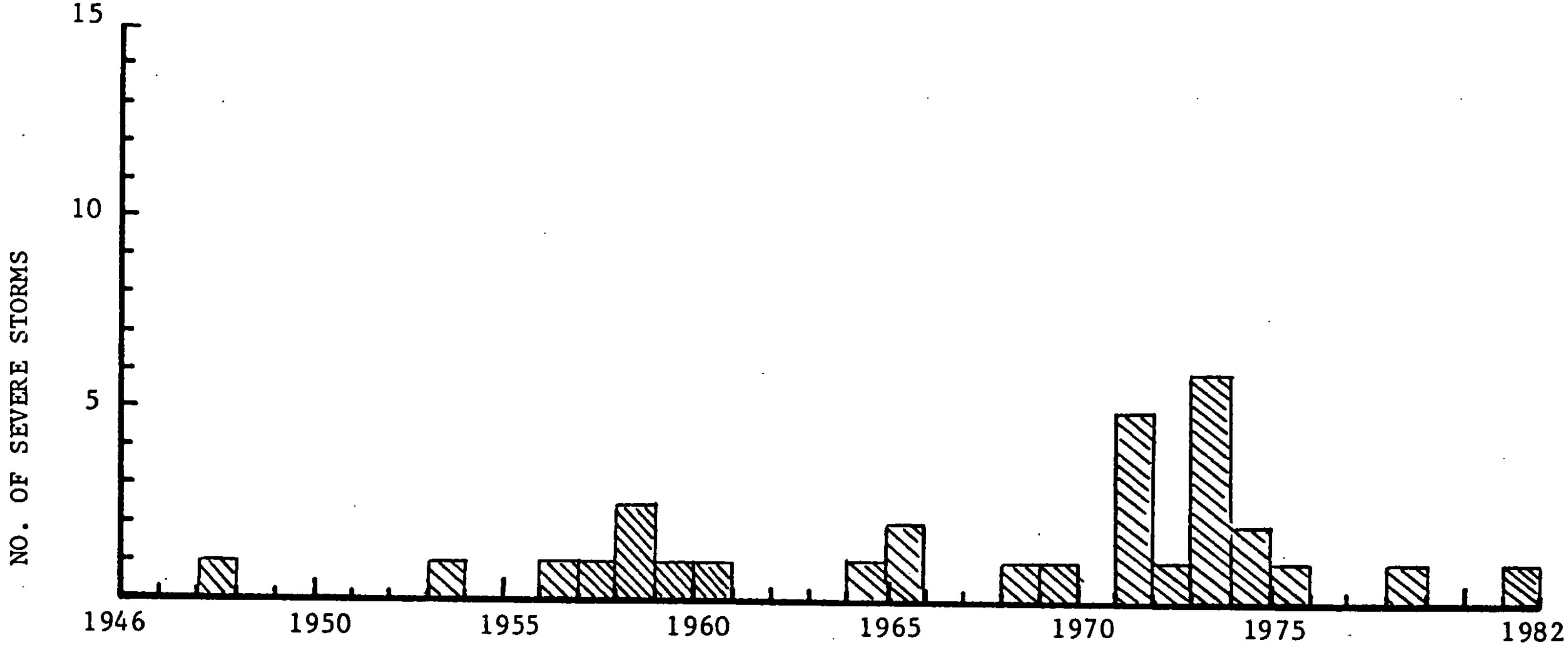


Figure 16. Annual distribution of severe storms for Region 5.

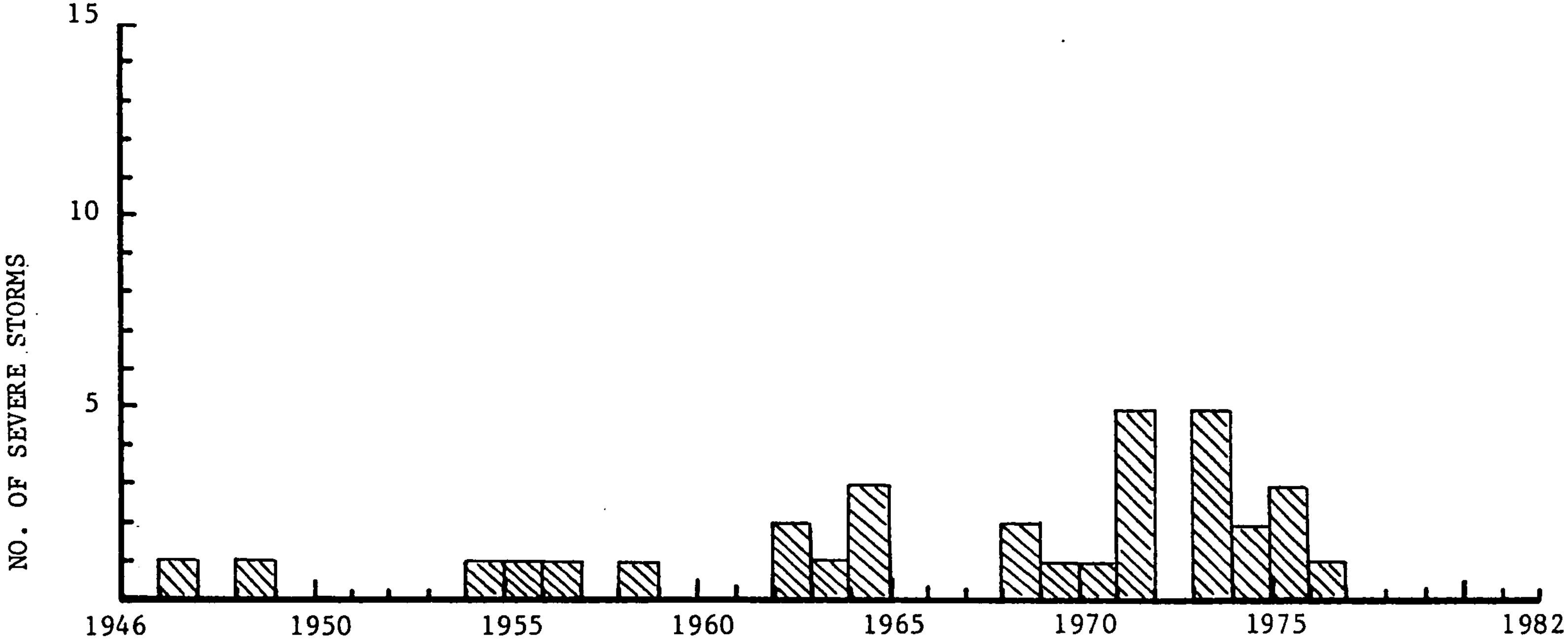


Figure 17. Annual distribution of severe storms for Region 6.

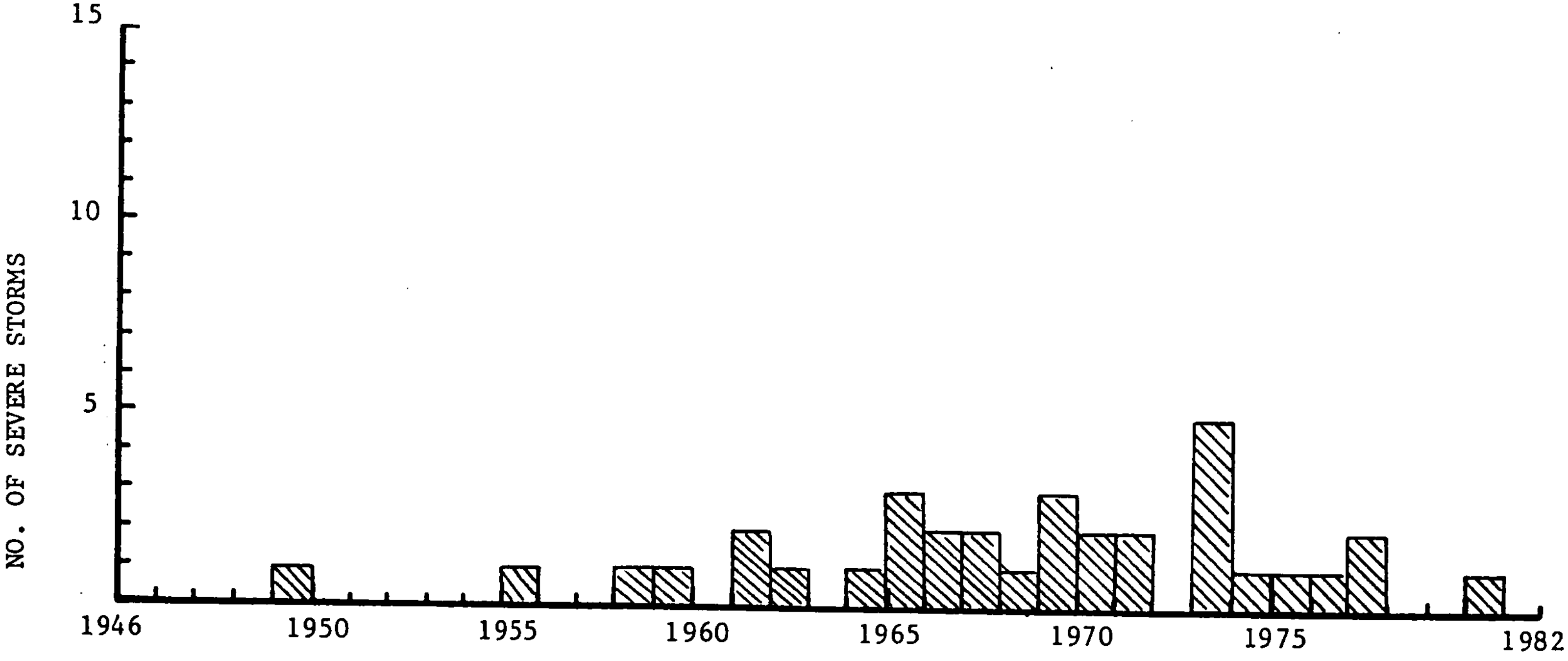


Figure 18. Annual distribution of severe storms for Region 7.

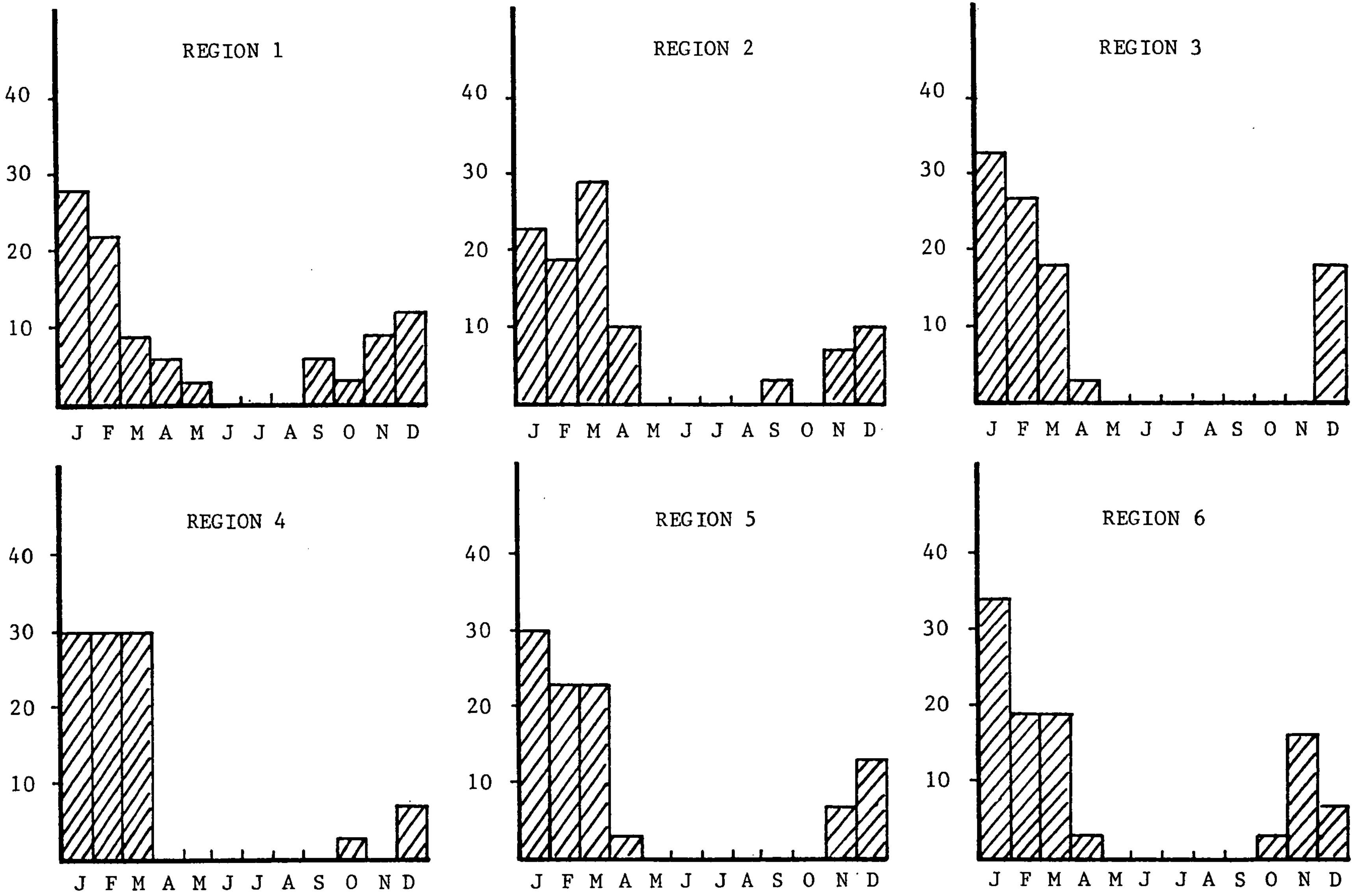
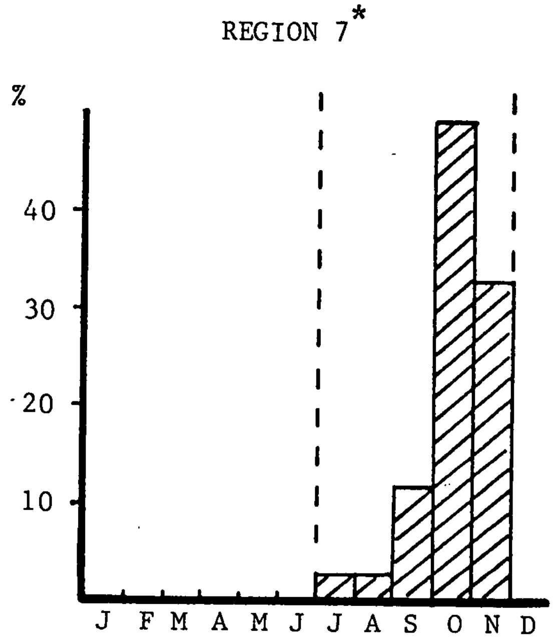


Figure 19. Seasonal distribution of selected severe storms by region.



* Restricted to July - November

Figure 20. Seasonal distribution of severe storms during defined ice-free period in Region 7.

explosive cyclones. The climatology of Whittaker and Horn (1982) shows the decrease in and northward migration of, cyclonic activity as the seasons pass from mid-winter and spring to summer, associated with the weakening of the thermal contrast along the Polar Front and Jet Stream. March represents a transitional month, with insolation increasing strongly, particularly at low latitudes. The thermal contrast is therefore still quite strong along the Polar Front, and storm intensity is maintained along the Jet Stream. This contrast is reflected in the seasonal distributions, with April being the first month of marked decline in severe storm frequency. The seasonal distribution of severe storms in Region 7 cannot be compared directly to the other regions as an "ice-free" period (July-November) was imposed on the storm-selection process. Maxwell et al. (1980) pointed out that the frequency and intensity of cyclonic activity increased in the region beginning in the autumn season (late September-November); significantly, October is the month with the lowest probability of ice cover in Baffin Bay. As the autumn season progresses, pack ice starts to form, eventually eliminating major open water areas within the region. The storm climatologies of Klein (1957), and more recently, Whittaker and Horn (1982) show that the major seasonal development that takes place in the region is the intensification in October of the track that brings storms north from the Labrador and Northern Quebec area through the Davis Strait to Baffin Bay. This region experienced the greatest number of severe events in October.

STORM TRACKS

Plots of storm tracks were generated on a monthly basis to delineate seasonal patterns, and on a regional basis to investigate regional variations in storm track climatology. These plots were derived from a digital storm data base which was created specifically to facilitate analysis of the identified severe storms (see Appendix 3). Finally, the regions were carefully analyzed and preferred tracks were identified for each region. The plots were generated in the following fashion: if the origin of the storm was within the map area, a circle was printed at the location of the first observation of the storm. Otherwise, the tracks were clipped at the edge of the map area. Daily observations are given by solid dots joined by vectors. The storms were not followed to their dissipation, however, unless their dissipation occurred within a day or two of the associated significant wave event. Thus, the last solid dot on a storm track may or may not signify the last position of the storm.

Seasonal Patterns

The graphs of all storm tracks by month are given in Figures 21 to 30. Figure 21 shows all storm tracks for the month of September. There are so few significant storms for this month that it is difficult to say anything meaningful about preferred tracks. There are more storms in the far north than off the Atlantic coast. This situation is a product of the storm selection process in Region 7 where an "ice-free" season was defined from July to November. September storm tracks from the study of Whittaker and Horn (1982), which covered the period 1958-77, exhibit a minor

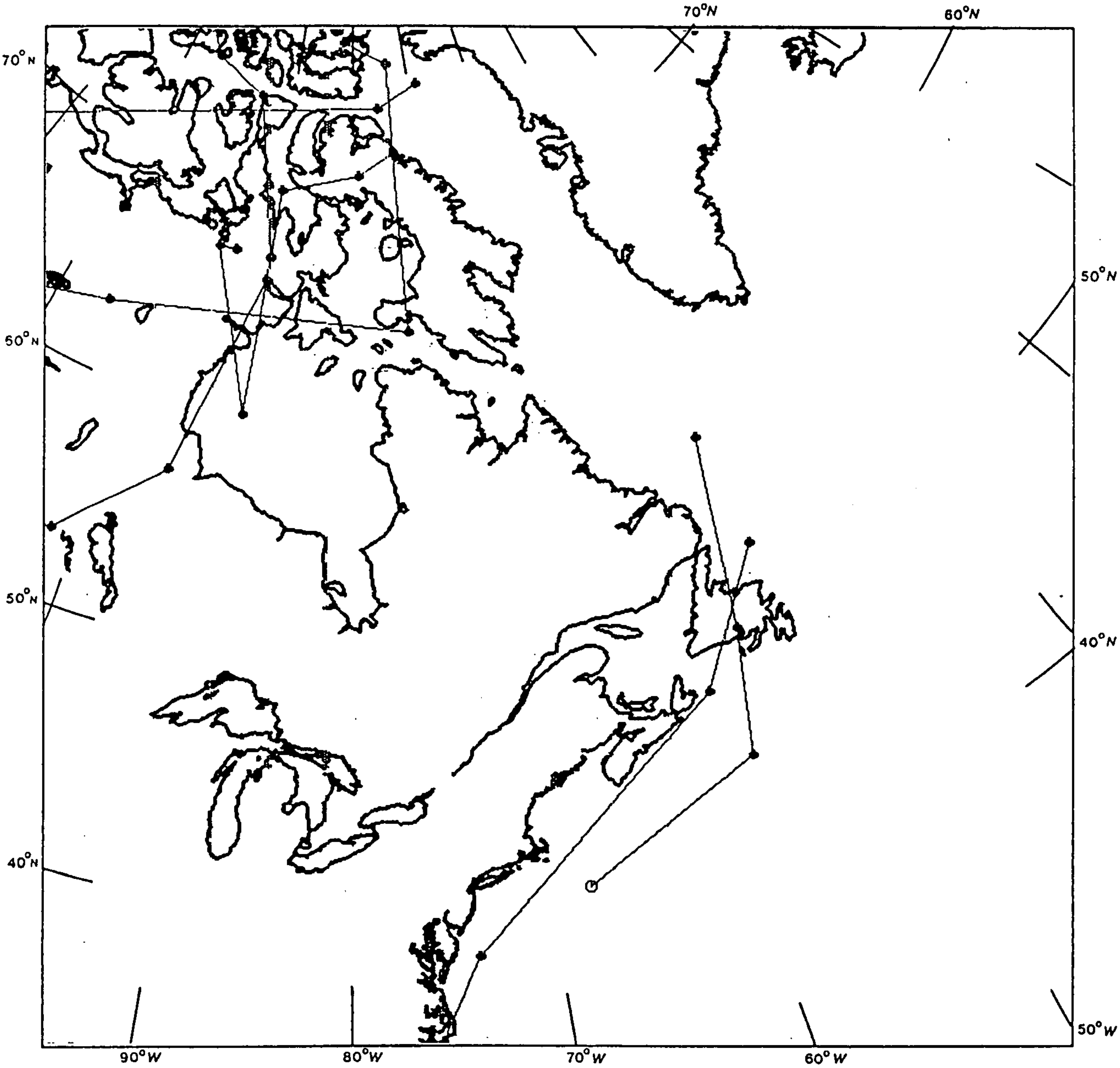


Figure 21. Severe storm tracks for all regions during September.

track across Hudson Bay and northern Quebec, and a major east coast track passing southeast of Nova Scotia and across Newfoundland. The severe tracks show a similar pattern.

In October (Figure 22) the northern regions again dominate, although there is considerable spatial variability. The east coast track passing from Cape Hatteras across Newfoundland to the south of Cape Farewell, Greenland, is clearly indicated, as are the tracks across the Great Lakes to Quebec and Labrador and from across Hudson Bay to northern Quebec and Baffin Island. For November (Figure 23) the main axis of the storm tracks appears to be shifting southward as the Jet Stream migrates towards the equator in response to the expansion of the circumpolar vortex with the approach of winter. The two main tracks appear to be along the eastern seaboard and across Newfoundland to the Labrador Sea-Davis Strait area, and across the Great Lakes to James Bay, northern Quebec and Baffin Island.

December (Figure 24) marks the removal of the influence of Region 7, and the coastal track is clearly established. The storms appear to be following the southern route across the Atlantic to the south of Iceland, with little indication of the northward branch towards Davis Strait.

In January (Figure 25), there are far more storms than in December, with the majority travelling up the Atlantic coast. In the broad view, the cyclone tracks seem to rotate about a point in northern Hudson Bay, which is near the centre of the polar vortex at 500 mb in January.

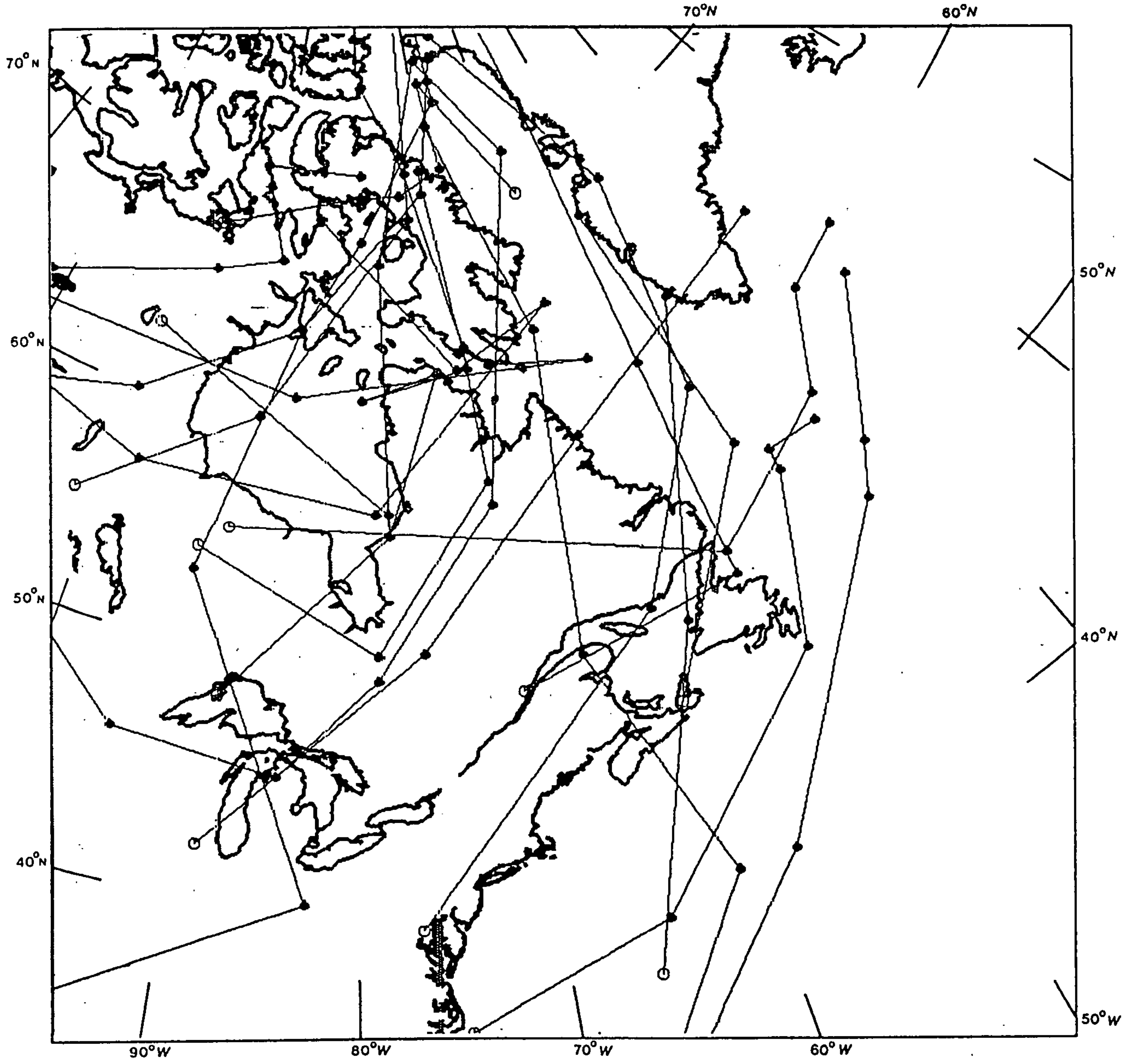


Figure 22. Severe storm tracks for all regions during October.

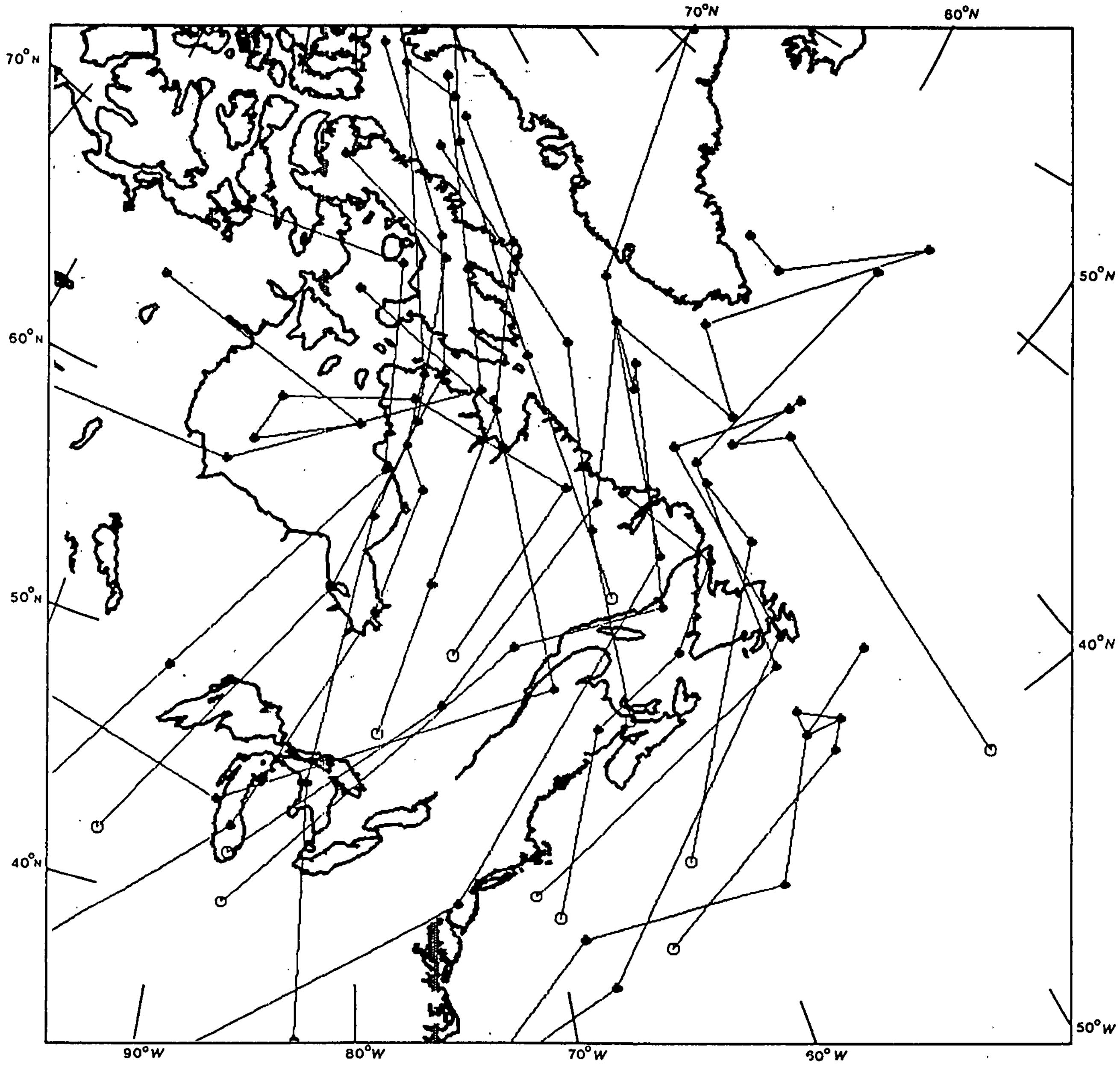


Figure 23. Severe storm tracks for all regions during November.

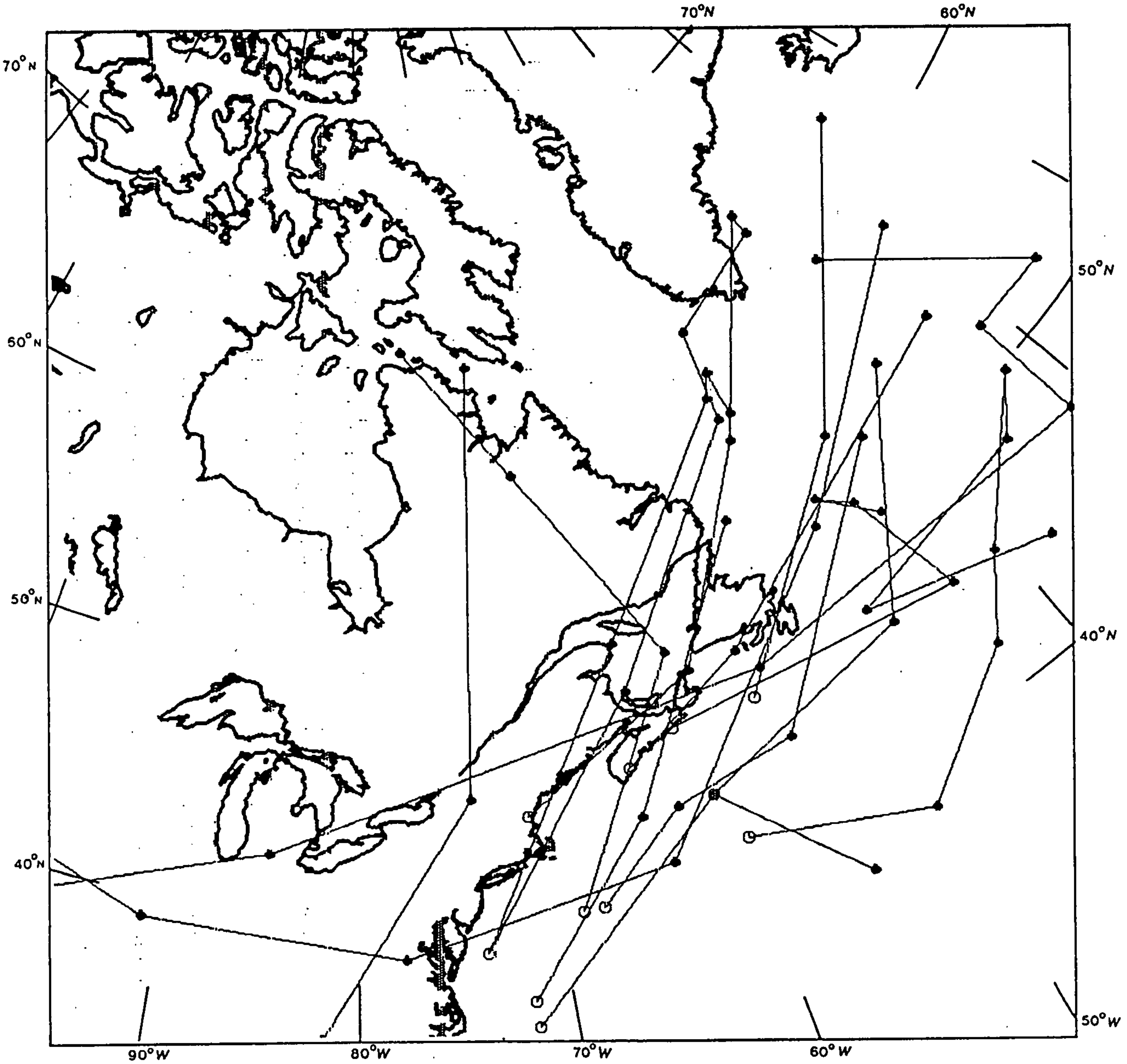


Figure 24. Severe storm tracks for all regions during December.

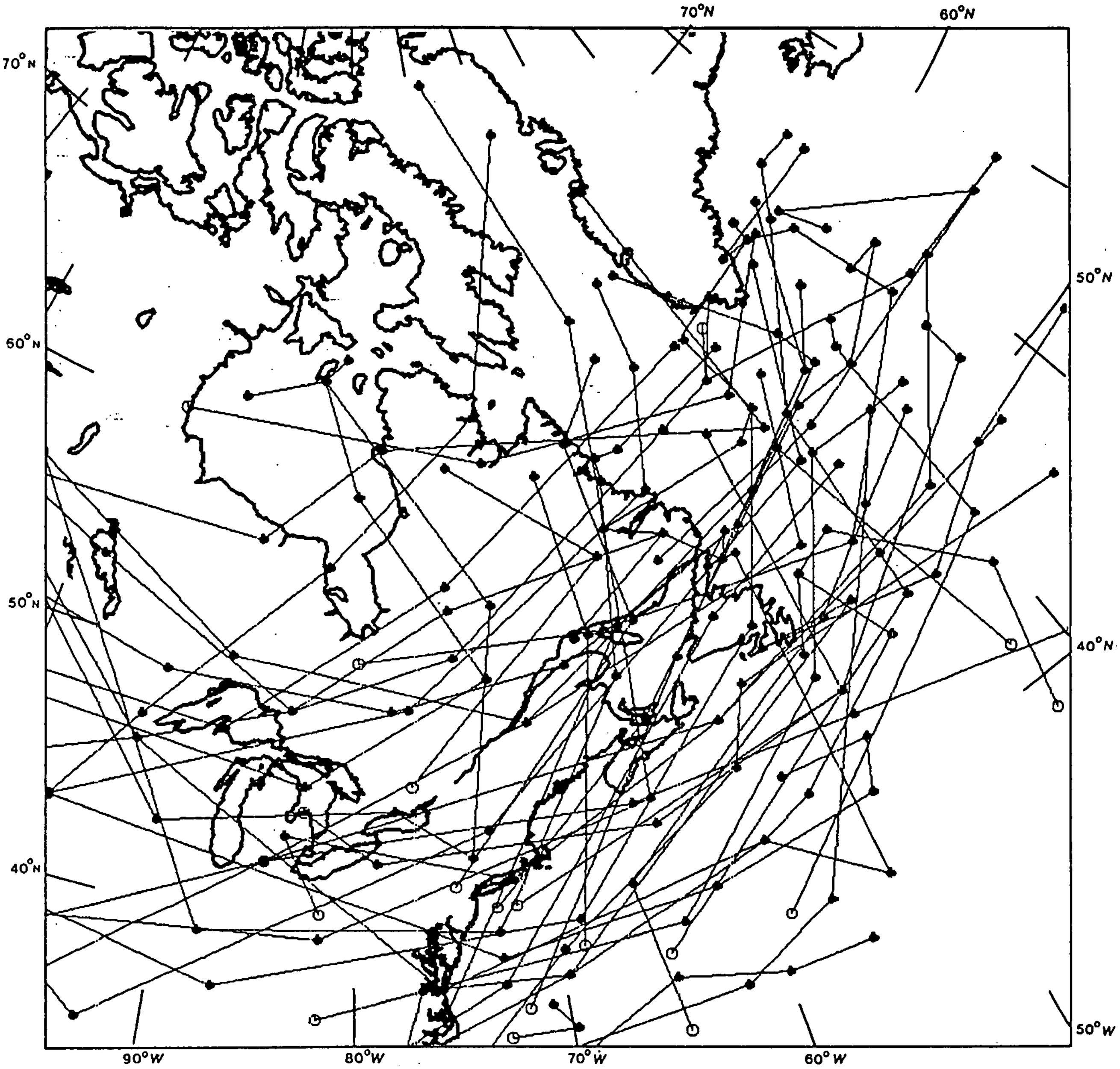


Figure 25. Severe storm tracks for all regions during January.

Figure 26 shows the pattern for February which is qualitatively similar to the results of Whittaker and Horn (1982). Cyclonic activity is diminished across the central and northern reaches of Ontario, Quebec, and Labrador. The main tracks converge across the Great Lakes-St. Lawrence region and the coastal areas near Nova Scotia and Newfoundland. Once again, the path of the cyclones is south of the Labrador Sea-Davis Strait area. There is a hint of the Icelandic low, albeit shifted southwestwards, in the region near Cape Farewell.

March (Figure 27) in many respects resembles the pattern expected for February, with a concentration of storms along the coastal track south of Region 3. This pattern suggests that an outbreak of Arctic air across the east coast maritime regions was involved in many of these cases.

April (Figure 28) displays a drastically reduced level of activity, indicating the onset of spring, and a reduction in thermal contrast along the cyclogenetic coastal regions. Those storms that did occur followed the Atlantic coastal track. Finally, in May (Figure 29), there was only one storm that caused a significant wave event; a low that became cutoff east of Newfoundland. There were so few storms in June, July, and August that it was not thought worthwhile to plot them separately. All of them affect Region 7 (Figure 30).

Regional Storm Classification

Before discussing the storm classification results, it should be noted that the SMB hindcasting of severe storms produced many storms with the same maximum wave heights. As

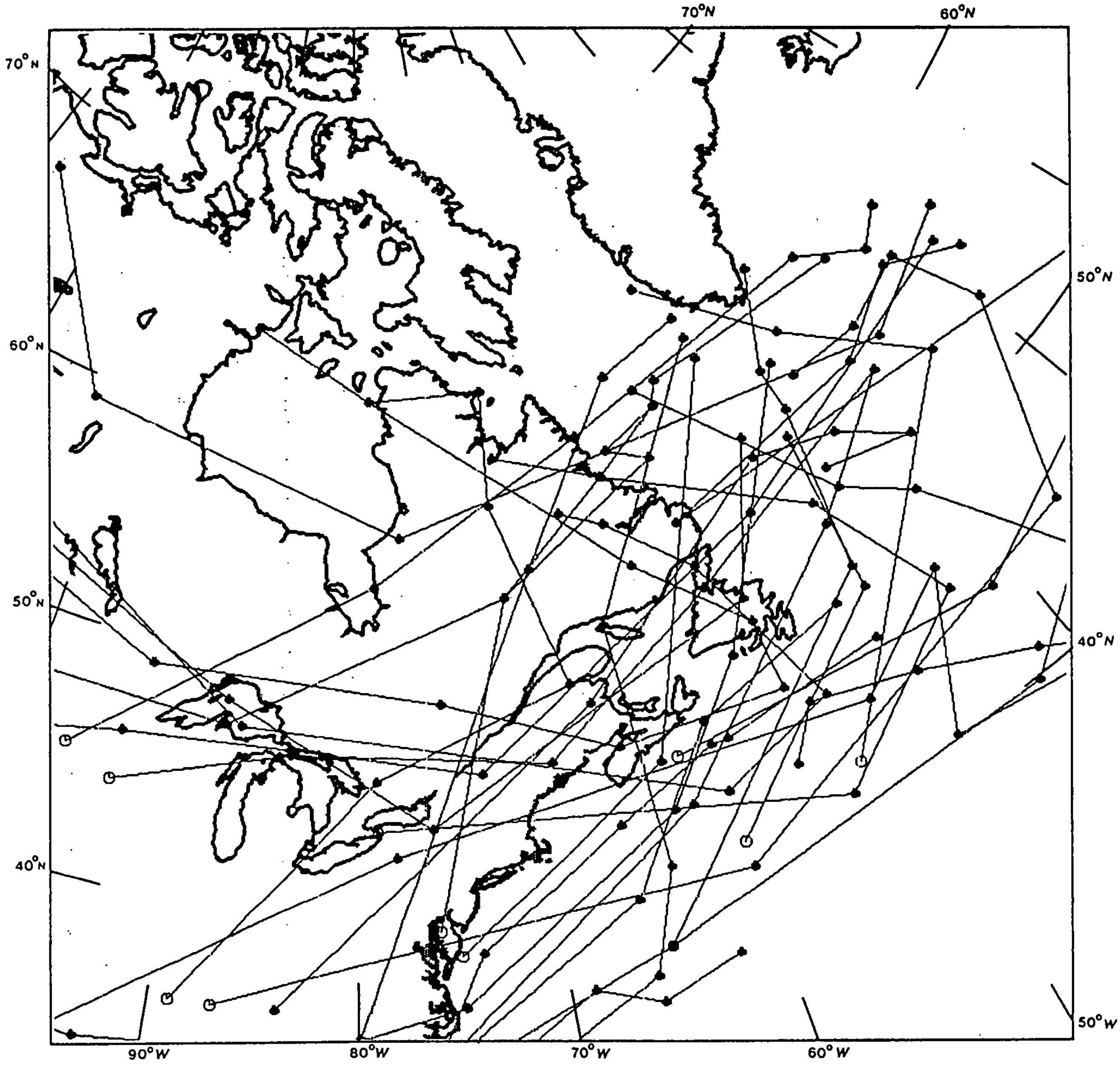


Figure 26. Severe storm tracks for all regions during February.

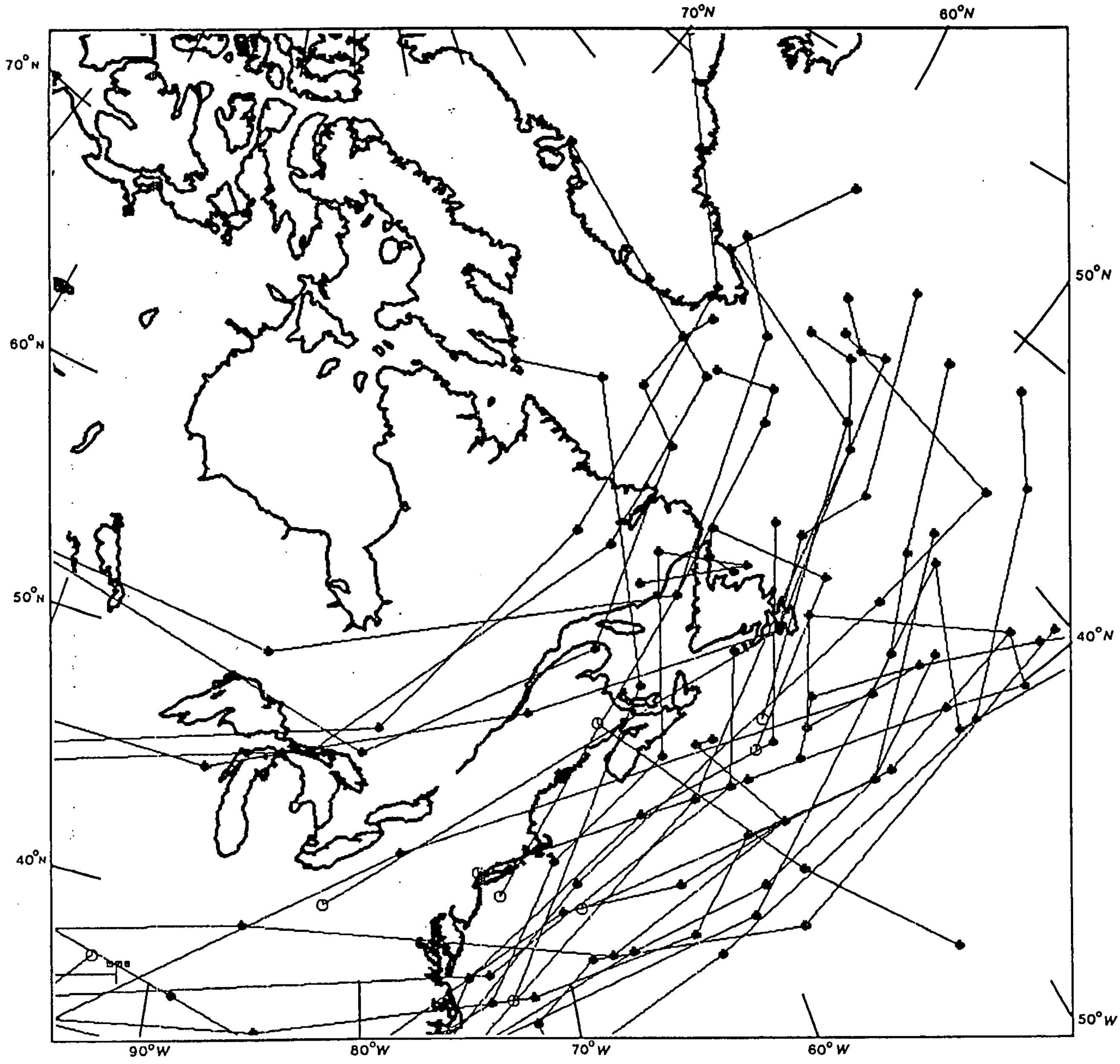


Figure 27. Severe storm tracks for all regions during March.

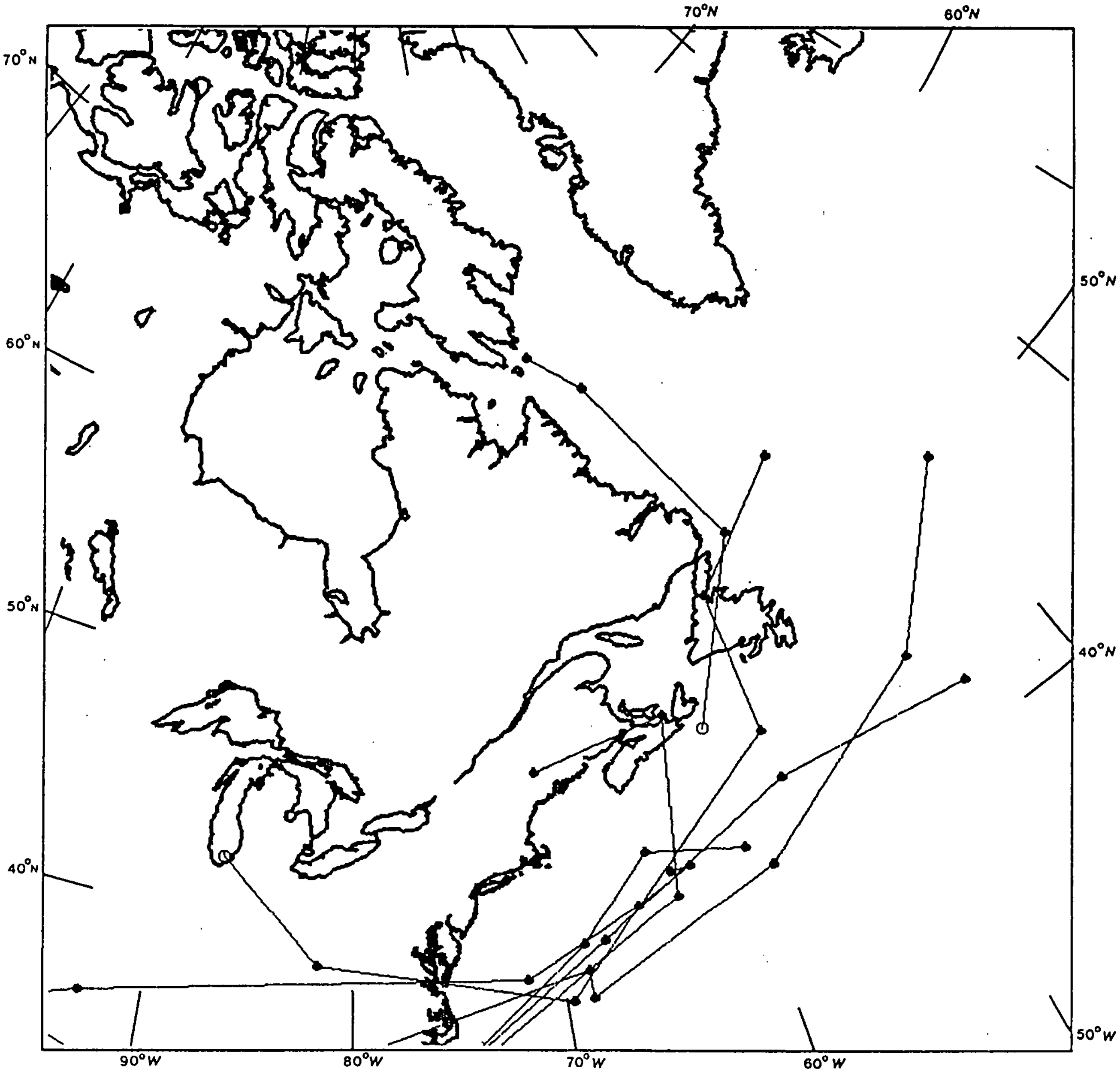


Figure 28. Severe storm tracks for all regions during April.

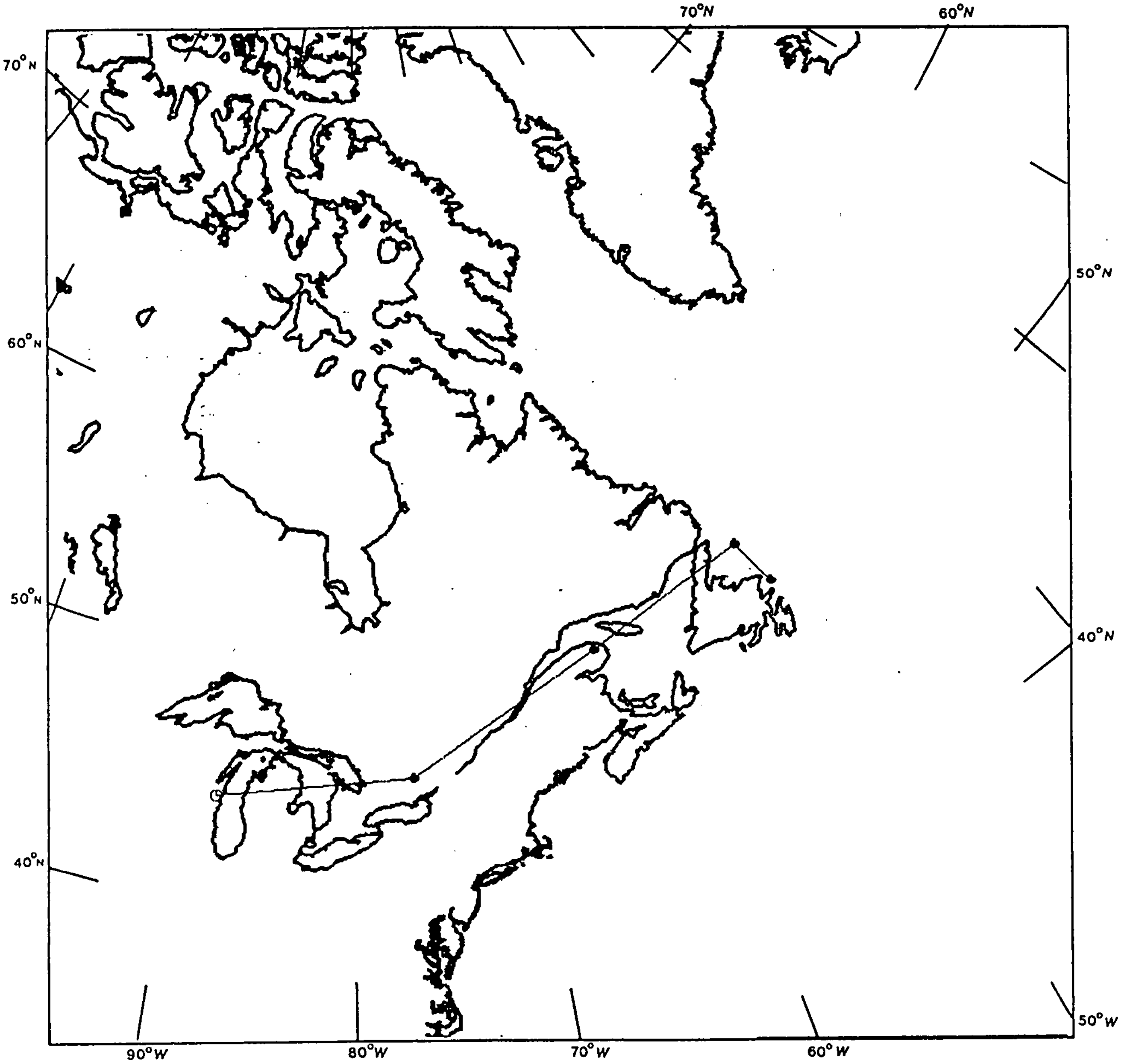


Figure 29. Severe storm tracks for all regions during May.

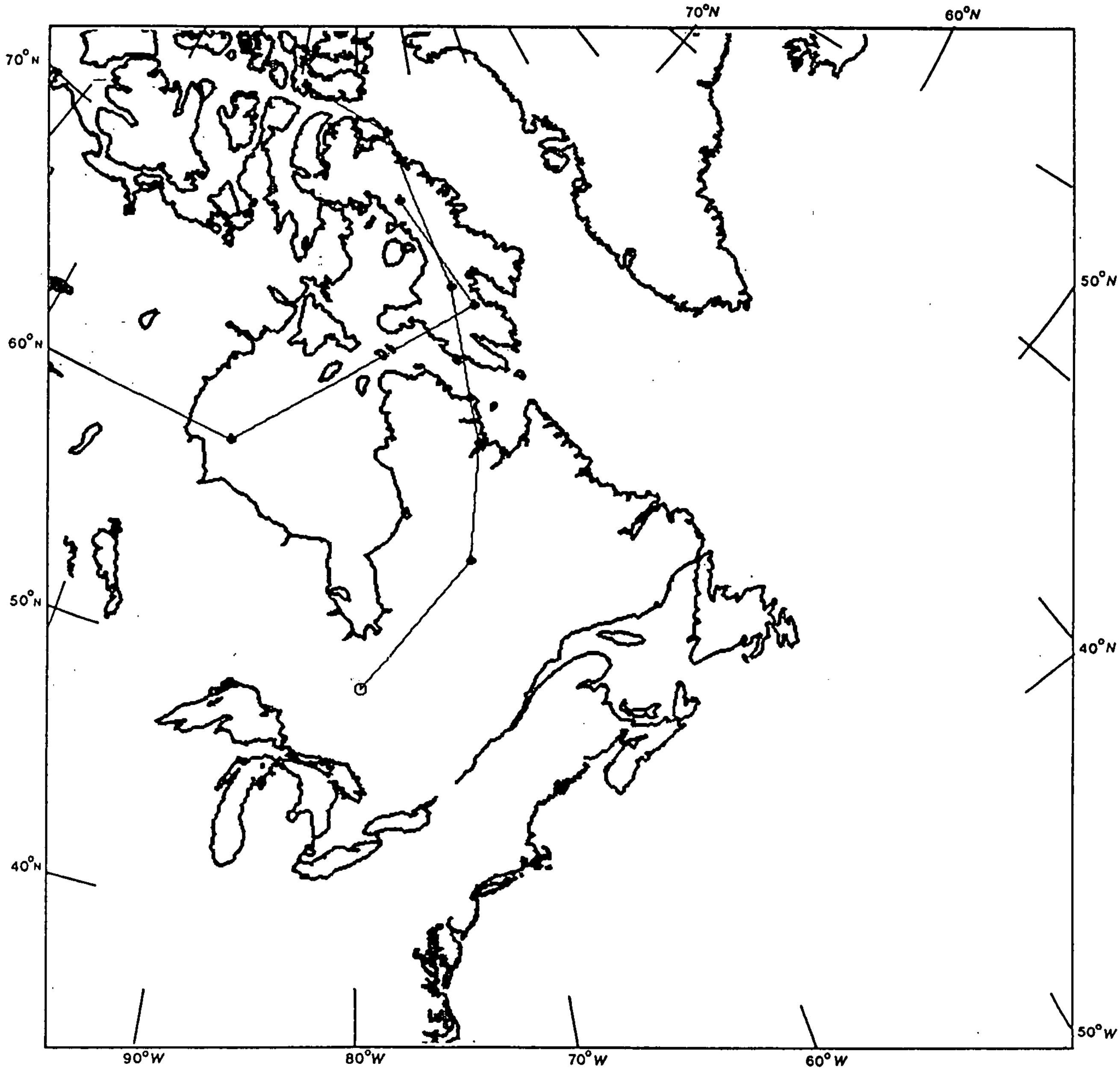


Figure 30. Severe storm tracks for all regions during June, July, and August.

can be seen from Table 22, this process leads to an uneven balance in the ranking system as a result of the fact that storm maximum wave heights were hindcast to the nearest five feet (1.5 m). Thus, many storms obtained equal rankings, and the distribution of rankings was, therefore, not a smooth continuum.

The plots of all storms causing significant wave events in each region, and plots of preferred tracks with percentages indicating frequency of occurrence, are given in Figures 31 to 58. Supporting material presented in Appendix 4 gives a more detailed breakdown of storm track and other relevant information by region.

It should be noted here, in agreement with the comment made by Saulesleja and Phillips (1982), that the notion of a preferred storm track is at best an idealization, given the scatter in the figures.

Region 1. Figure 31 shows storms causing significant wave events in Region 1. As expected, the preferred storm track passes to the south of the region. This track would produce northerly winds over the region, which are usually of greater strength during storms owing to the tendency for cyclones to have tighter gradients along their northern and western edges. Indeed, the majority of severe wave events (84%) were associated with northerly winds (see Appendix 4). Interestingly, although the direction of maximum fetch runs NE-SW in this region, northeasterly winds accounted for only 33% of the events, and only 15% of the top ten storms. This condition results from the strength of northwesterly winds following a storm passage, which are relatively stronger owing to enhanced vertical exchange in the unstable airmass.

Table 22

Comparison of storm-rank distributions for each region

Storm ranking	Total No. of Storms	Number of severe storms in each ranking class						
		Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7
1 - 2	18	2	2	2	3	4	2	3
3 - 5	31	6	7	5	3	2	6	2
6 - 10	28	2	1	3	9	4	3	6
11 - 15	41	7	9	9	0	6	4	6
16 - 20	38	4	1	1	10	11	8	3
> 20	67	11	11	14	5	3	9	14
Total	223	32	31	34	30	30	32	34

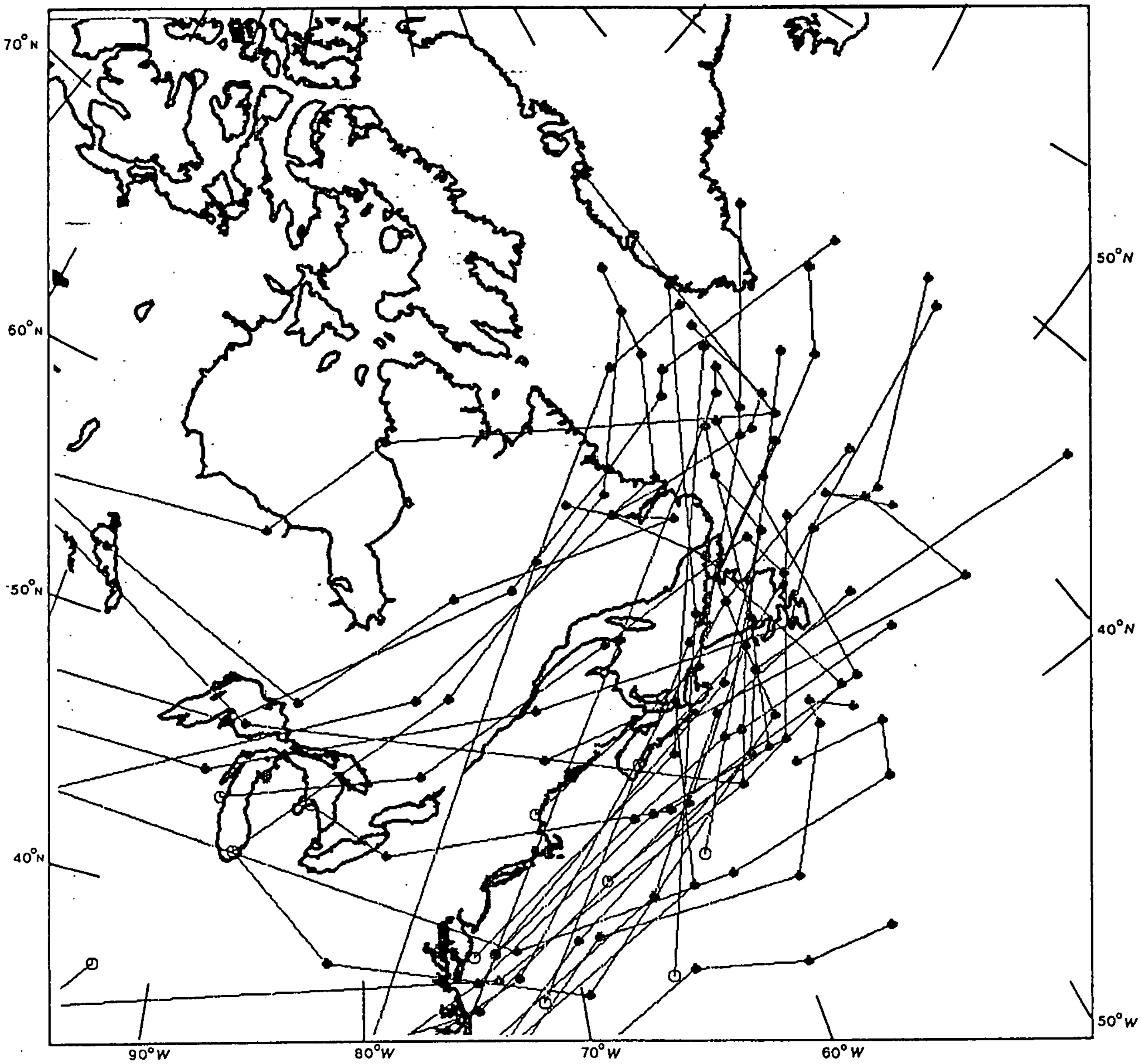


Figure 31. Severe storm tracks for Region 1, Gulf of St. Lawrence.

Figure 32 gives the preferred tracks for Region 1, with the dashed lines indicating tracks of secondary importance. Although only half of the storms originated along the coastal areas of the Gulf of Mexico, nearly 75% of the storms eventually took the coastal route (see Appendix 4). The bulk of the extra coastal storms came east from their Colorado origins (track IVa) towards Cape Hatteras or the Delmarva peninsula (13%) and continued northeast, or else tracked southeast from the lee of the Canadian Rockies in Alberta, crossed the Great Lakes, and redeveloped off the east coast (track Ib, 9%). The remaining 3% represents the redevelopment near Cape Hatteras of a low that became organized over the Great Lakes.

Of those storms that tracked north of Region 1 (25%), the majority orginated in Alberta and moved across the Great Lakes and down the St. Lawrence River valley (16%). Thus, the Atlantic "nor-easter" was the archetypal severe storm in Region 1.

A comparison of Figure 33 and Figure 34 shows that the maximum deepening of the storms occurred ahead of the region, and the severe wave events occurred in the wake of the developed systems as they passed to the northeast. Sixty-three per cent of the storms accomplished their maximum 24-hour deepening before the wave event occurred, with only 19% of the storms still deepening at the time of the event, and 25% of the storms beginning to fill (see Appendix 4). The percentages are similar in the top ten ranked storms, with 50% of these storms accomplishing their maximum 24-hour deepening before the wave event occurred, and only 10% still deepening at the time of the event, with 30% already beginning to fill.

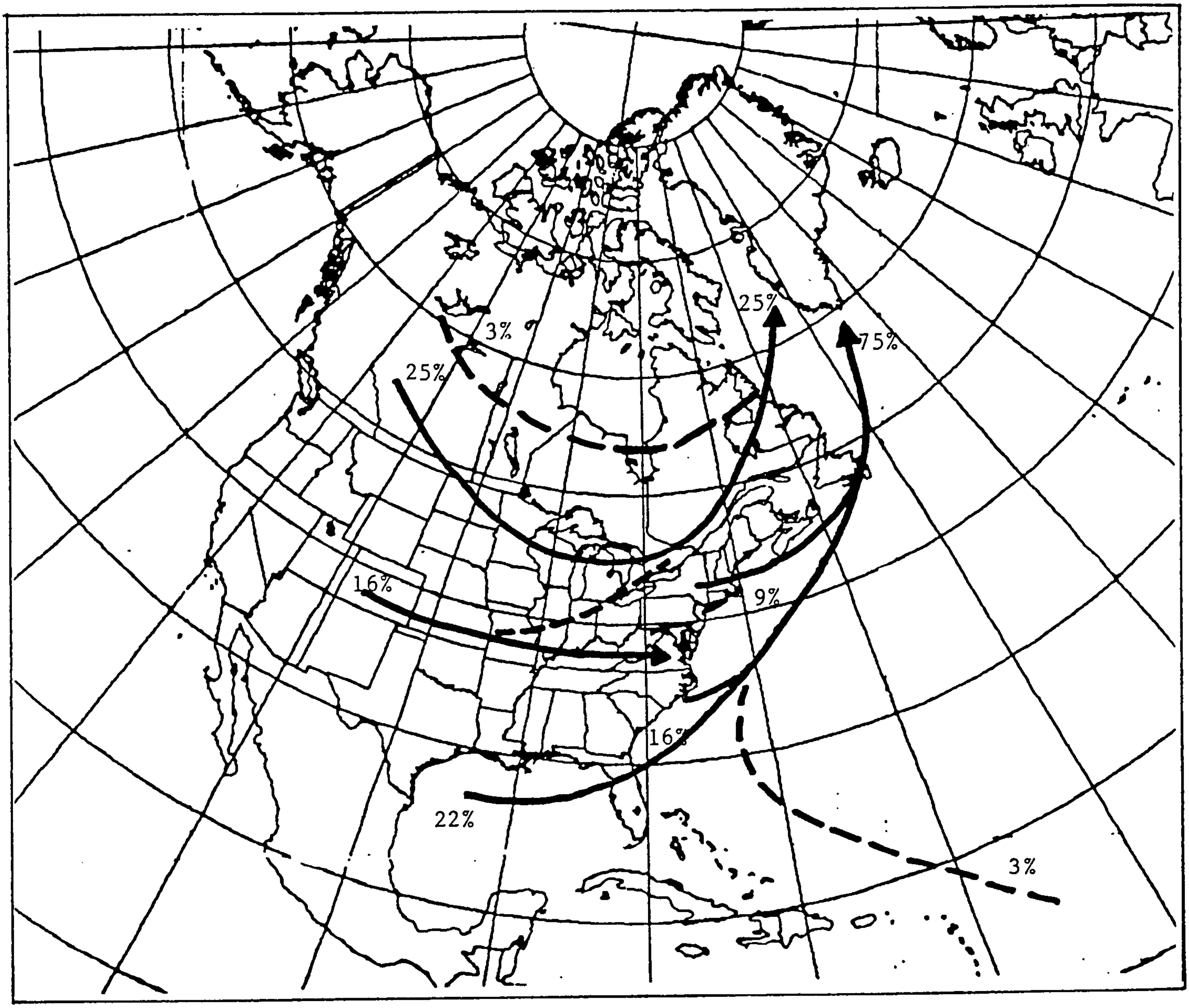


Figure 32. Preferred storm tracks for Region 1, Gulf of St. Lawrence.

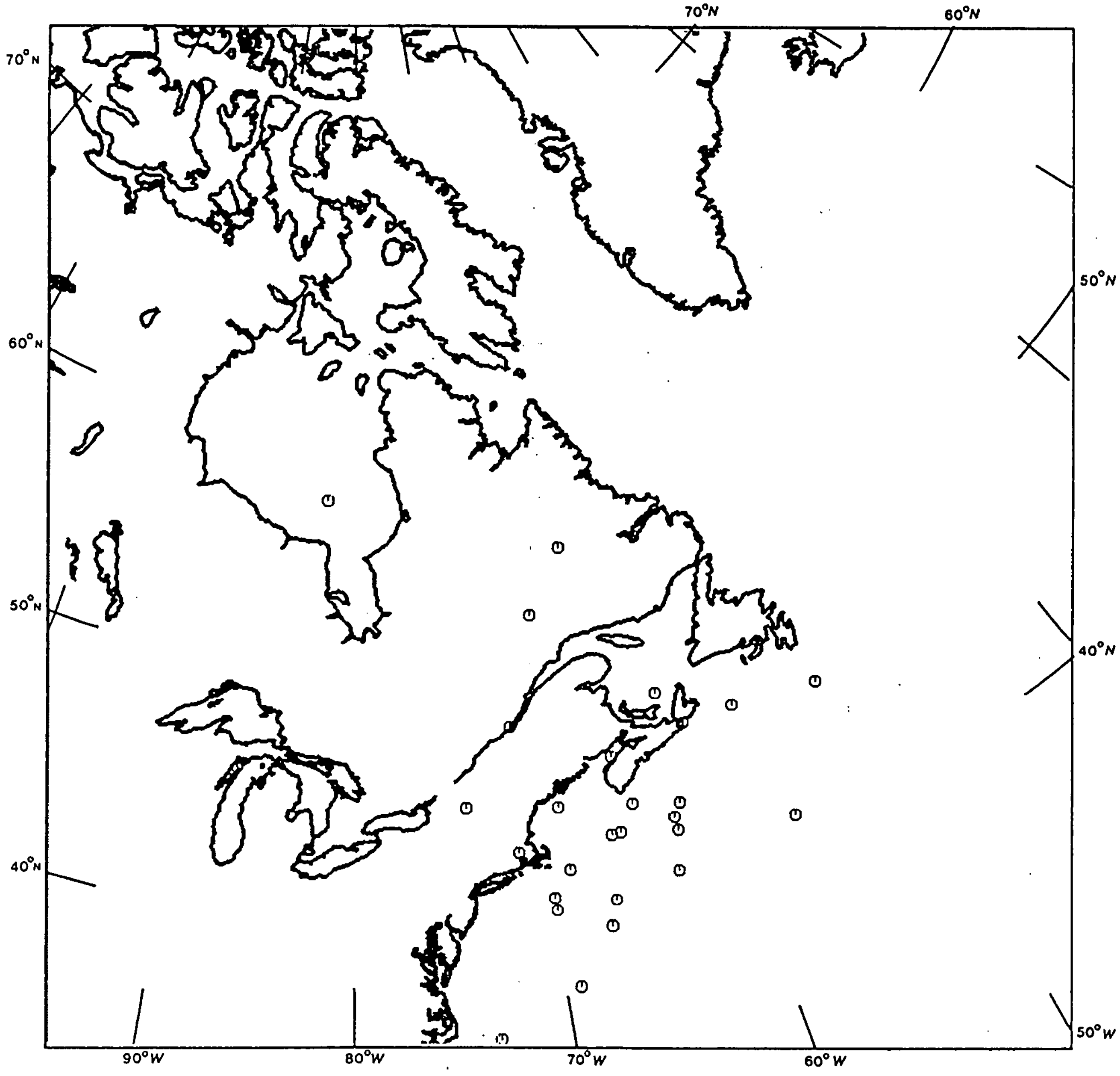


Figure 33. Position of maximum storm deepening for Region 1, Gulf of St. Lawrence.

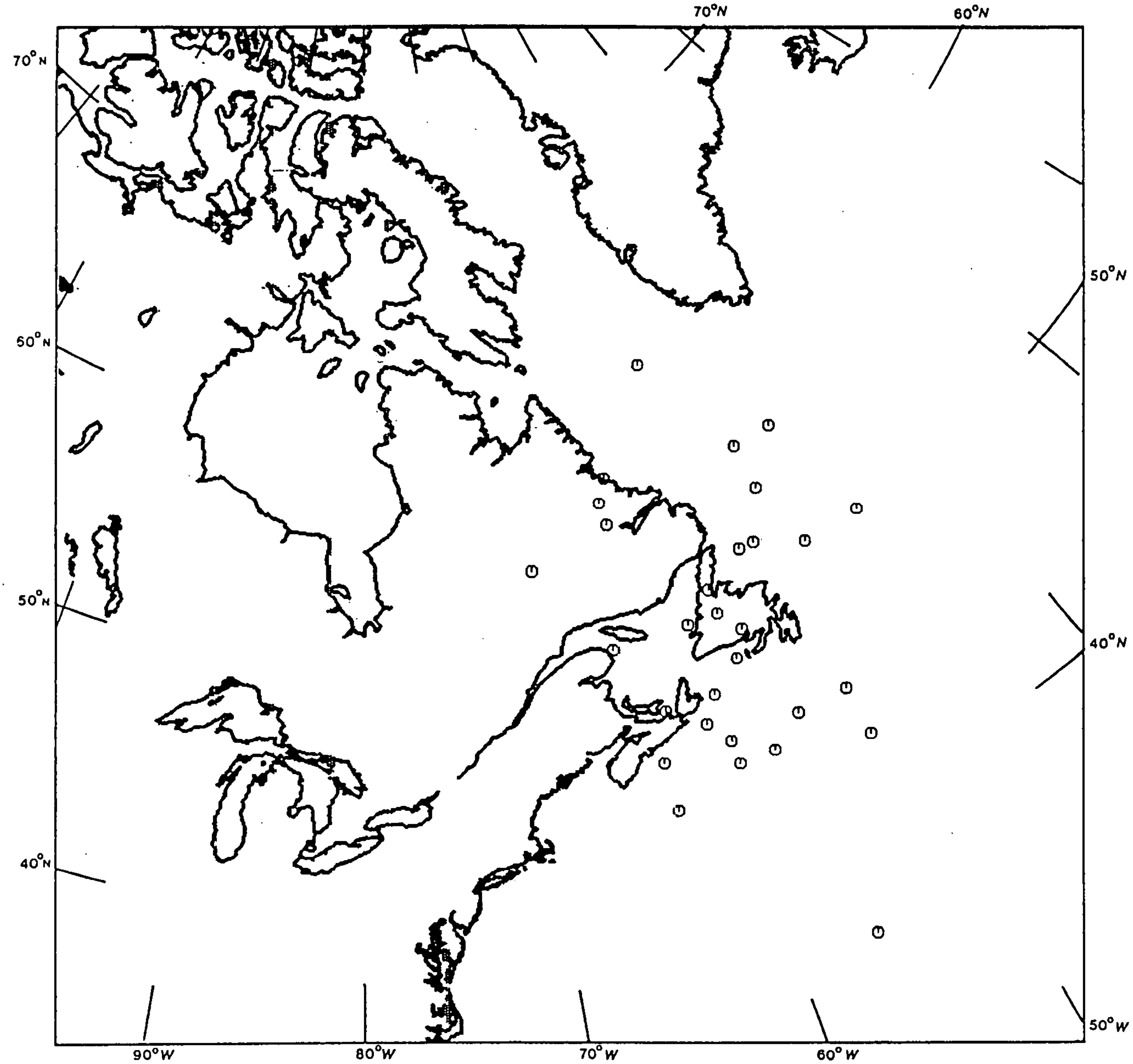


Figure 34. Position of storm at time of wave event for Region 1, Gulf of St. Lawrence.

Clearly the majority of these storms produced the severe wave event at or near the time of their lowest central pressure, or most intense stage. Of 32 storms, 18 were at their lowest central pressure at the time of the event (see Appendix 4). The correlation between storm central pressure at the time of the wave event and storm ranking was +0.27, which is significant at the 90% level for this sample size. A significant correlation between decreasing central pressure and increasing wave height might be expected, because central pressure indicates roughly the degree of storm intensity and the strength of the pressure gradient which in turn drives the winds and waves. However, this relationship does not include the important effects of wind fetch and duration, two factors which are controlled by a host of other variables including storm phase speed, areas of concentrated gradient within the storm, location of the storm with respect to the region, and the coastal geography of the region.

Region 2. Figure 35 shows storms causing significant wave events in Region 2. In this region, the Atlantic coast track is dominant and nearly 90% of all Region 2 storms eventually took the coastal route (see Appendix 4). The main concentration of storms is along a route just south of Region 2, with many storms passing through the region. Again, northerly winds dominate, with northeast winds accounting for over 50% of the wave events, including 75% of the top ten storms (see Appendix 4).

Figure 36 indicates that 58% of the storms originated in the waters of the Atlantic or the Gulf of Mexico. The bulk of the remainder converged upon the Atlantic coastal track from the lee of the Rockies, either in

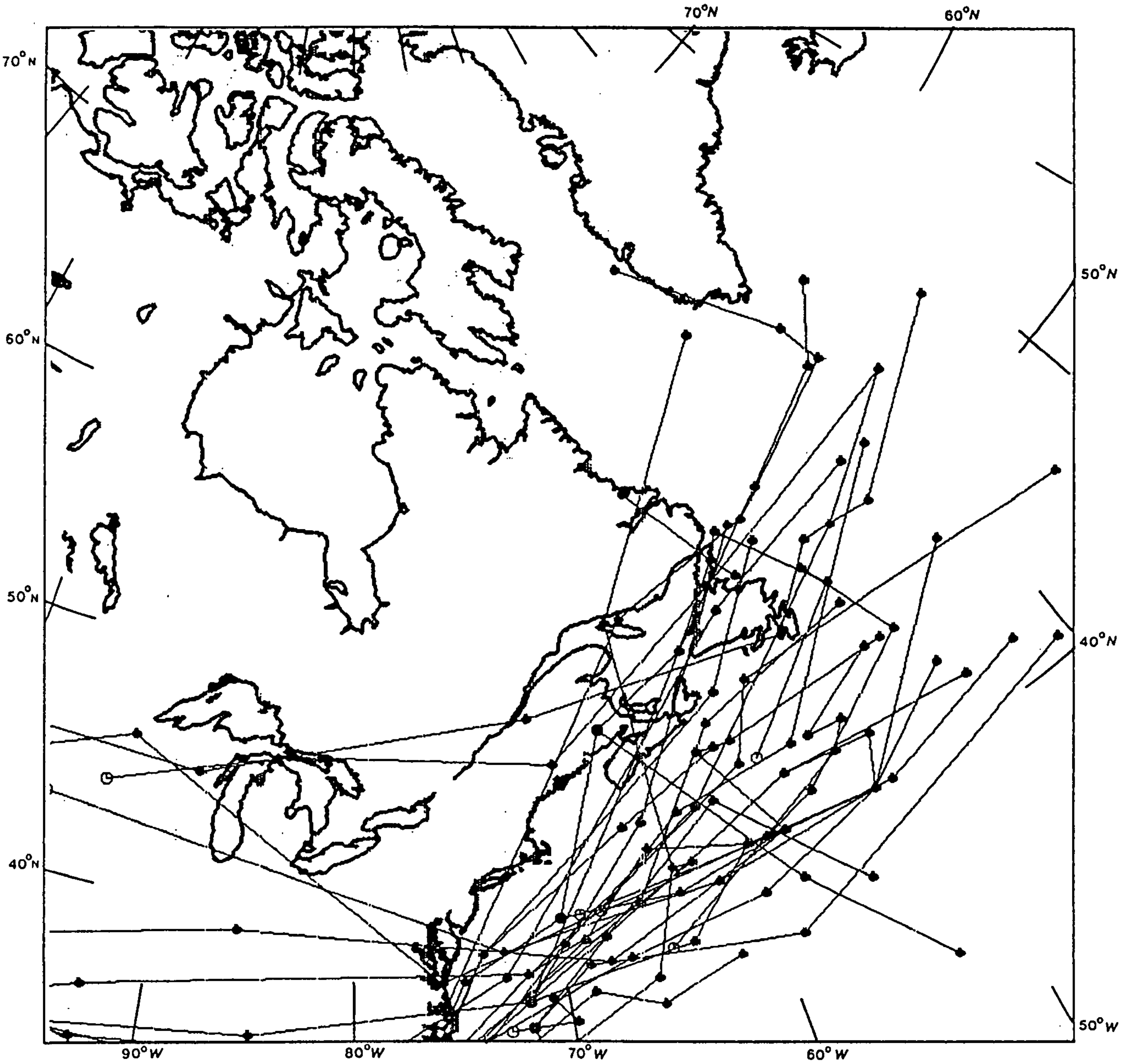


Figure 35. Severe storm tracks for Region 2, Scotian Shelf.

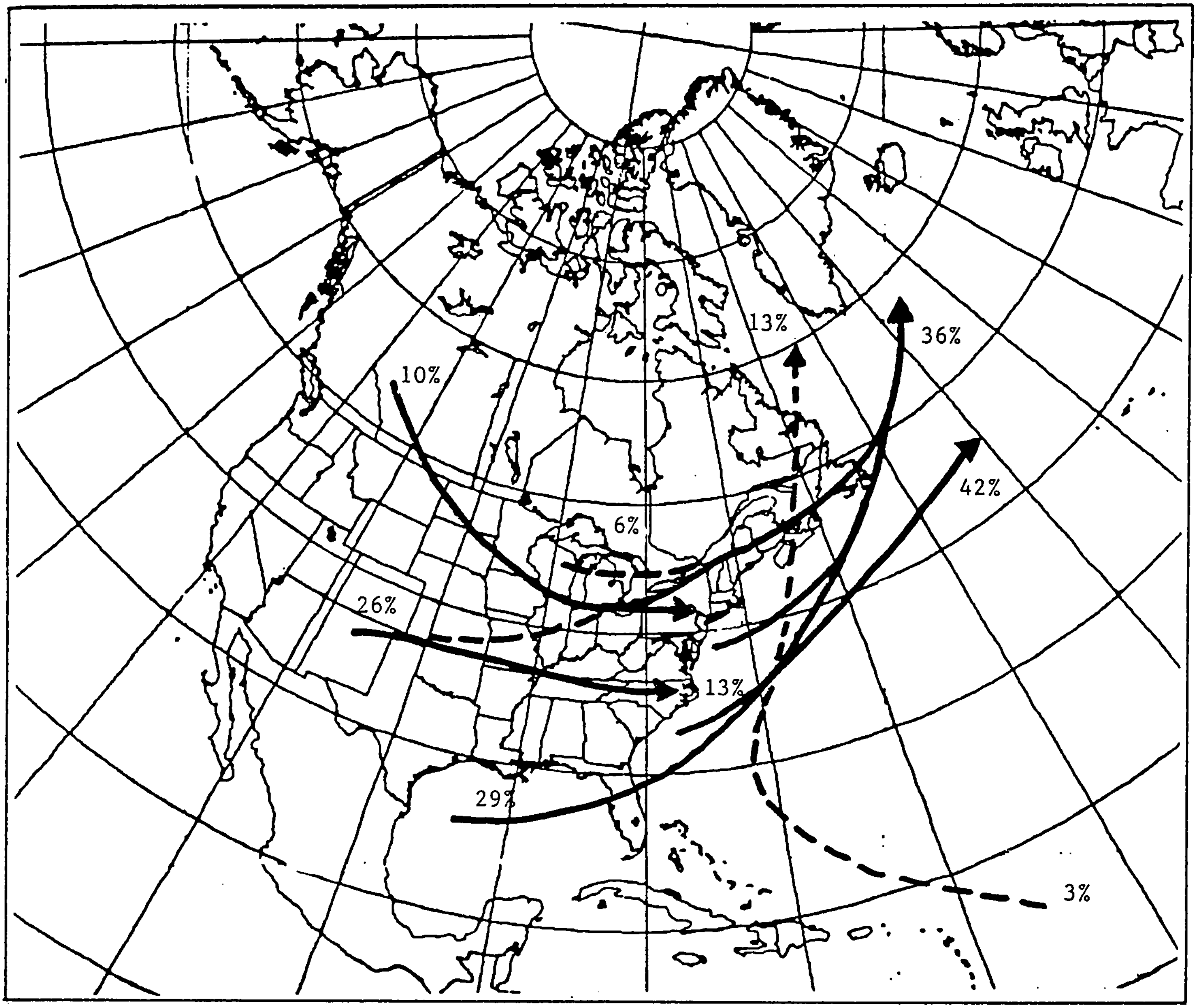


Figure 36. Preferred storm tracks for Region 2, Scotian Shelf.

Colorado (26%) or Alberta (3%). Of the three storms that passed north of the region, two originated in Alberta (track IVa) and one became organized in the Great Lakes area (track Va). As in Region 1, the Atlantic "nor-easter" appears to be the typical storm affecting the region. Unlike Region 1, however, many of these storms produce severe wave events ahead of the storm centre, with maximum deepening occurring well to the south of the region (Figures 37 and 38). Some 77% of these storms were at, or had previously reached, their most intense stage, with 19% beginning to fill (see Appendix 4). In the top ten, almost 88% of the storms were at, or had previously reached their lowest central pressure, with approximately 10% of those storms beginning to fill. As in Region 1, the severe events usually were produced with the storm at its most intense stage, with 18 of 31 storms at their lowest central pressure at the time of the event. The correlation between storm central pressure and storm ranking was +0.26, which is significant at the 90% level for a sample of this size.

Region 3. Figure 39 shows storms causing significant wave events in Region 3. There is again a dominant Atlantic coast track, with about 70% of all storms eventually taking the coastal route. However, Figure 40 shows that the St. Lawrence River valley track became established. Of the storms in Region 3, 21% eventually tracked down the river valley from their origins in Alberta (15%), Colorado (3%), and the Gulf of Mexico (3%)(see Appendix 4). As with Regions 1 and 2, northerly winds dominated, with 68% of the wave events occurring in this flow, including 65% of the top ten storms. The predominant wind direction was northwest, accounting for 58% of the wave events including all of the top ten northerly wind storms.

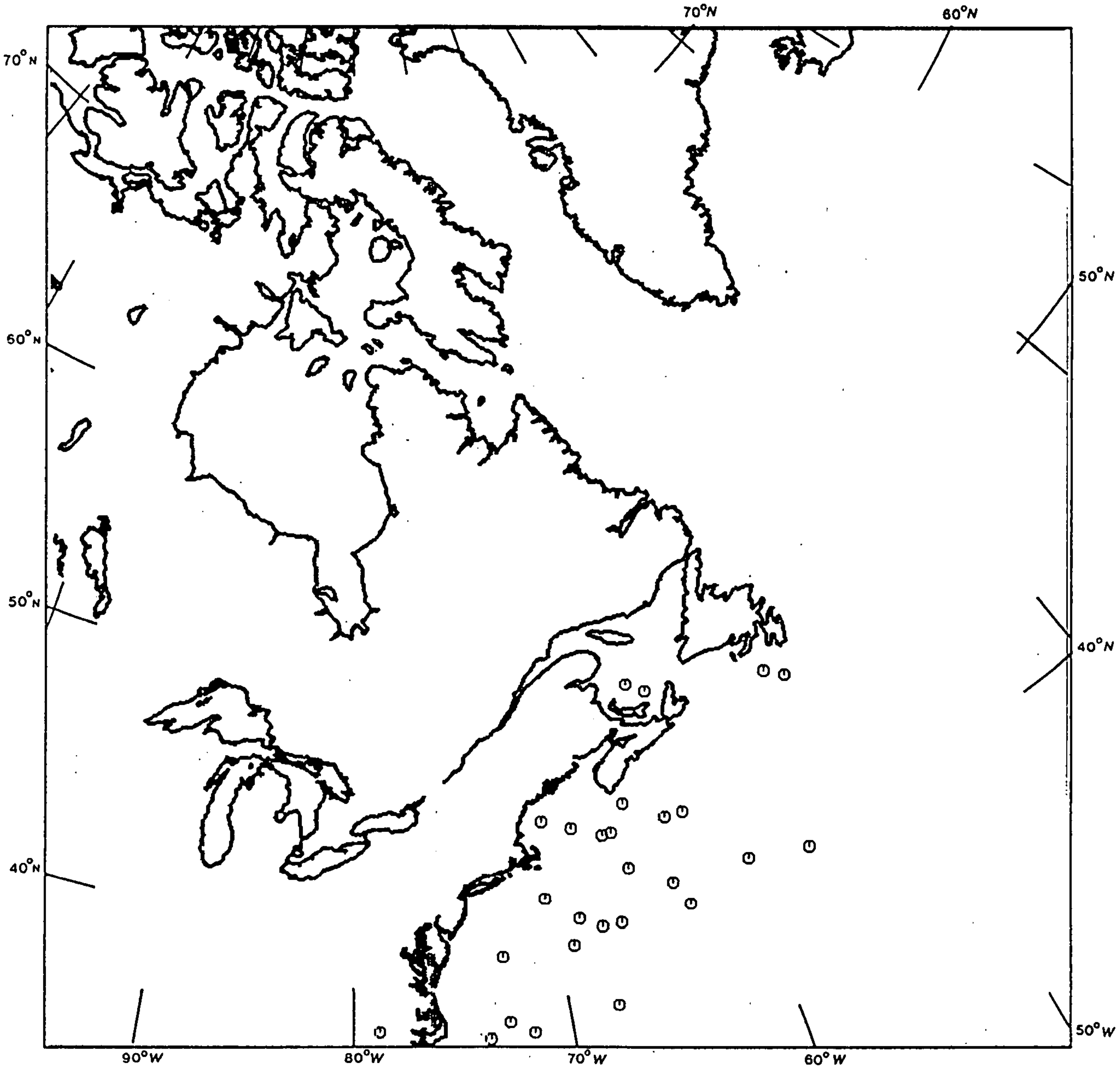


Figure 37. Position of maximum storm deepening for Region 2, Scotian Shelf.

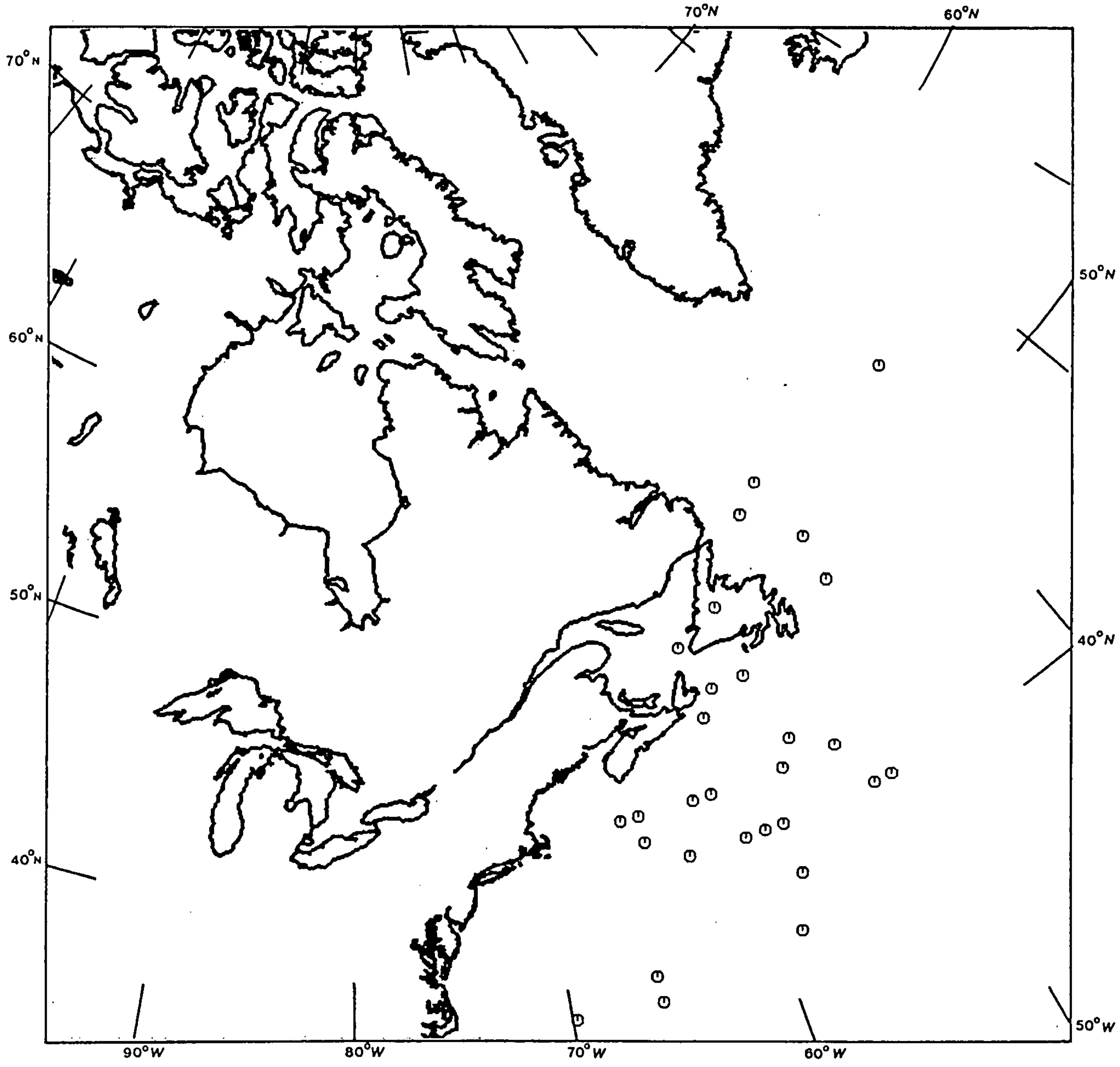


Figure 38: Position of storm at time of wave event for Region 2, Scotian Shelf.

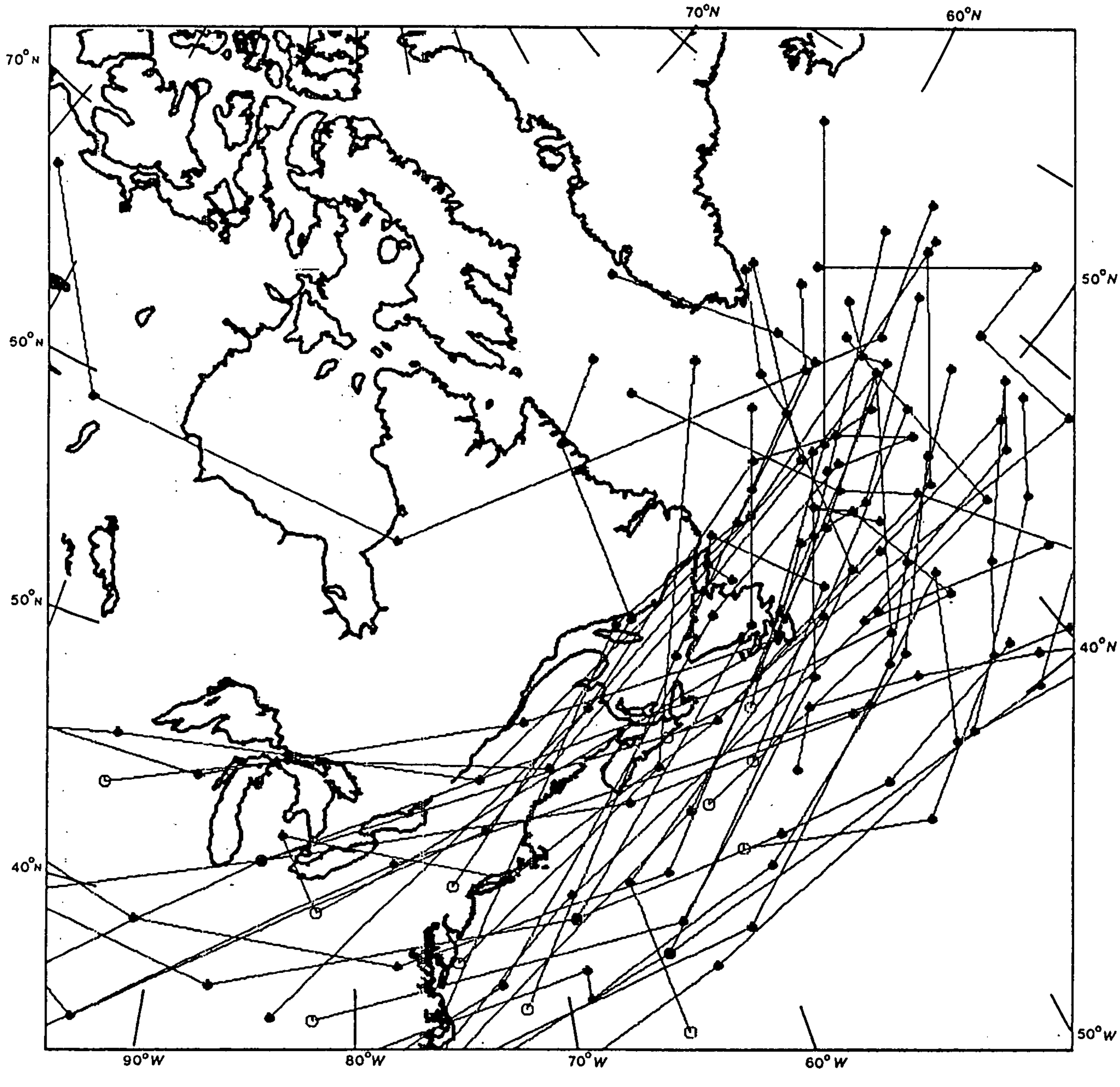


Figure 39. Severe storm tracks for Region 3, Grand Banks.

Figure 40 shows that less than half of the storms originated in the waters of the Atlantic or the Gulf of Mexico. The bulk of the storms originated to the lee of the Rocky Mountains (47%) and converged over the Great Lakes, but almost two-thirds of these storms redeveloped or tracked east over the Atlantic coast to join the coastal route. Once again, it was the ocean-going storms that were responsible for the severe wave events in the region.

The patterns of maximum storm deepening position and the position of storms at the time of severe events as displayed in Figures 41 and 42 are similar to that of Region 1, with the majority of the storms achieving their maximum deepening to the west and southwest of the region (63%). The severe events typically occurred in the wake of the developed systems as they passed northeast, and 70% of the storms were at, or had previously reached their most intense stage, with 12% already beginning to fill(see Appendix 4). In the top ten, almost 84% of the storms were at this stage of development with slightly greater than 30% beginning to fill. As with the other regions, the severe events were usually produced with the storm at its most intense stage, with 20 of 34 storms at their lowest central pressure at the time of the event. The correlation between storm central pressure and storm ranking was quite weak, with a coefficient of +0.15, which is not significant at the 90% level for a sample of this size.

Region 4. Figure 43 shows storms causing significant wave events in Region 4. The Atlantic coastal track is less dominant with only 60% of the storms eventually taking this route. Perhaps the most striking feature of the storm tracks

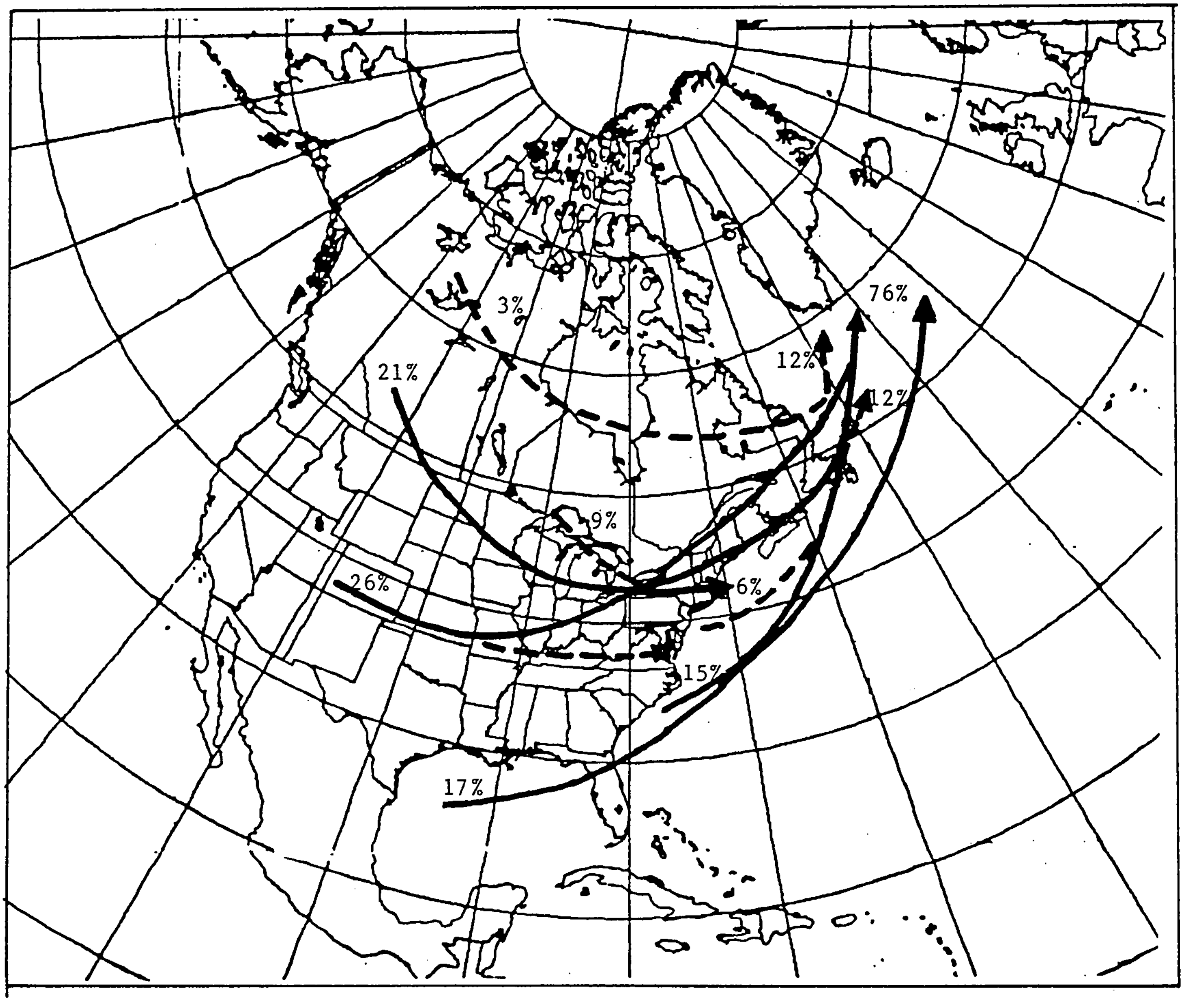


Figure 40. Preferred storm tracks for region 3, Grand Banks.

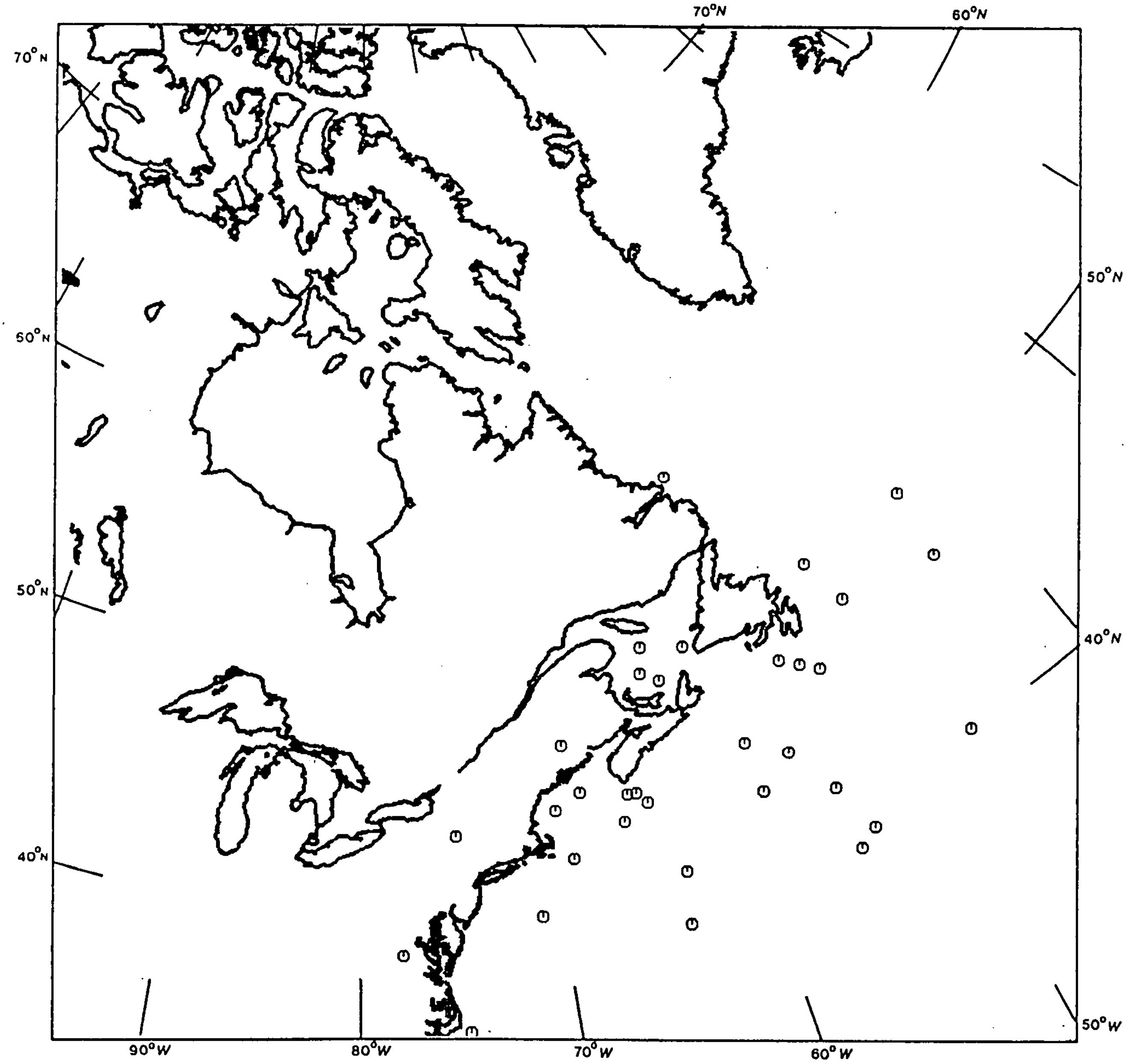


Figure 41. Position of maximum storm deepening for Region 3, Grand Banks.

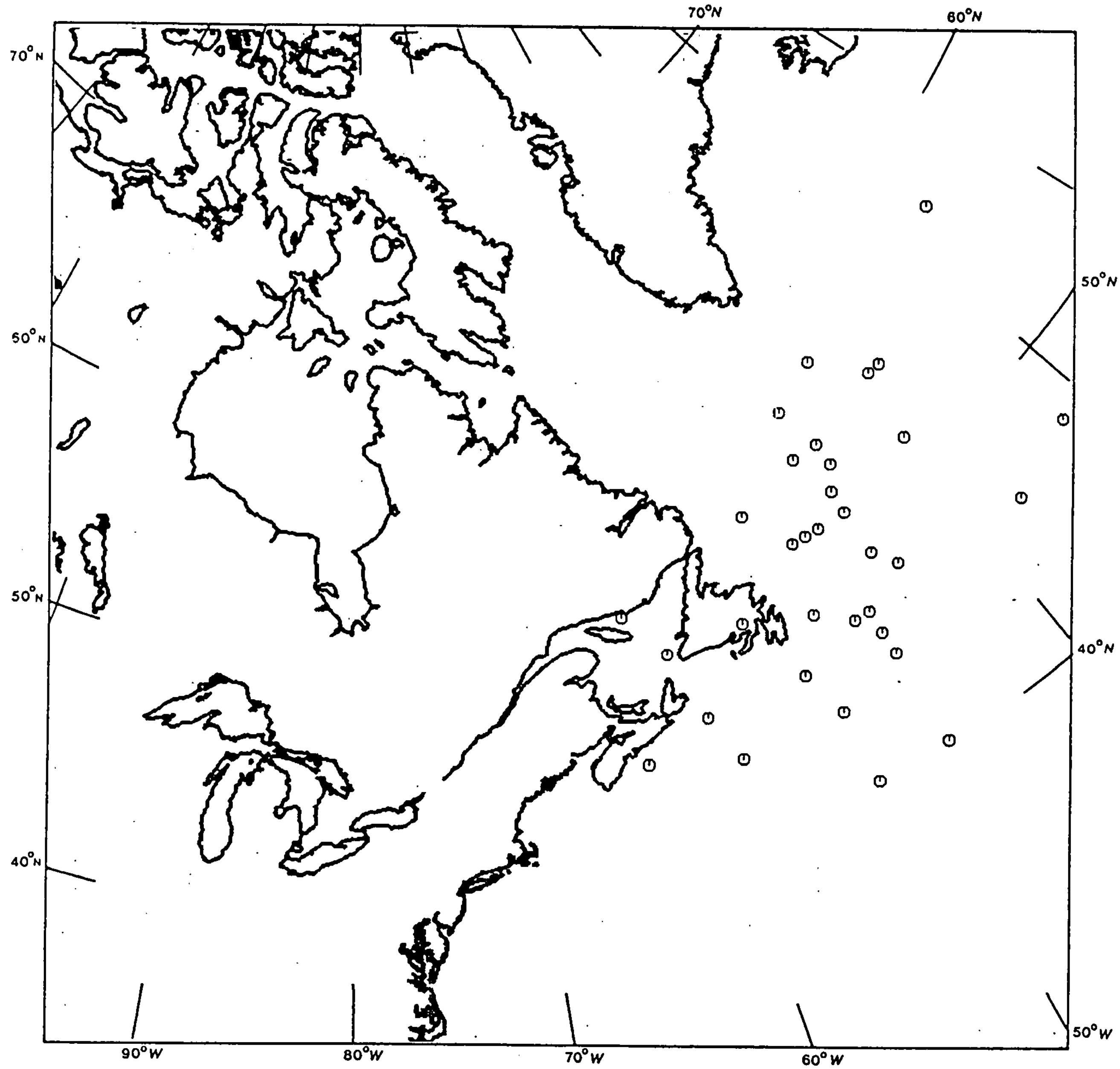


Figure 42. Position of storm at time of wave event for Region 3, Grand Banks.

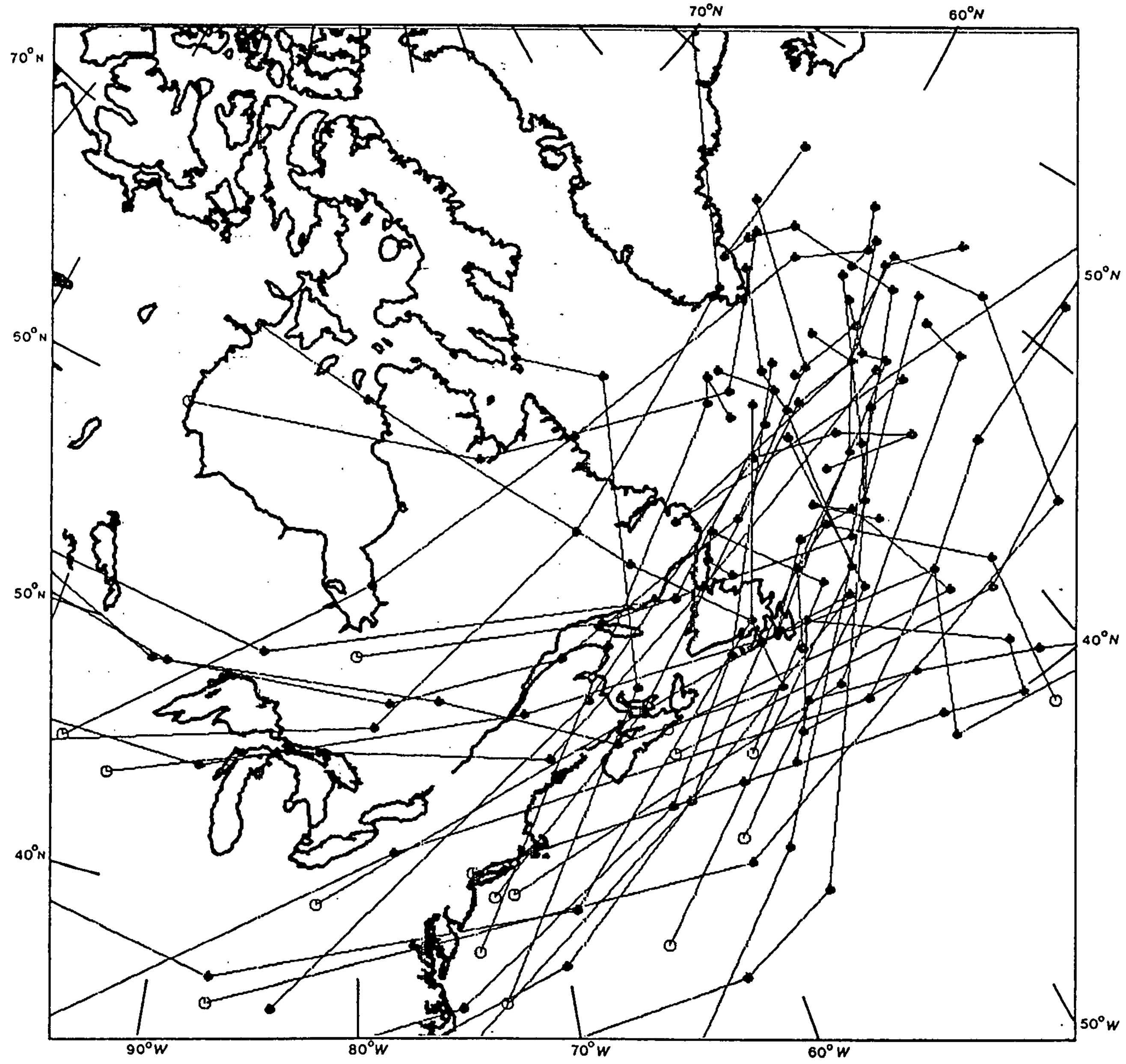


Figure 43. Severe storm tracks for Region 4, northeast Newfoundland Shelf.

is the cluster of slow-moving, cut-off storms east of Region 4. This position corresponds to a slight southwestward shift of the mean Icelandic low, which was mentioned previously as one of the effects of enhanced coastal baroclinicity and rapid cyclonic development. Such storms would be in a position to direct north to northwesterly winds across Region 4 for an extended period of time. As with Regions 1 and 3, northwesterly winds dominate, with 55% of the severe wave events occurring in this flow, including 63% of the top ten ranked storms (see Appendix 4).

Figure 44 indicates that half of the storms originated to the lee of the Rocky Mountains, and as with Region 3, the majority of these redeveloped or tracked east over the Atlantic coast to join the coastal route. Of the 40% that did not follow the coastal track, more than half travelled northeast along the St. Lawrence valley to the north of Region 4. The preponderance of northwest winds suggests that even the storms that passed to the north of the region produced severe events only as the cold air swung around behind the cold front from the northwest (see Appendix 4). This is borne out by a comparison of Figures 45 and 46, which show few storms capable of producing winds from a southerly quadrant.

Already 97% of the storms were at, or had previously reached their most intense stage, with 30% already beginning to fill (see Appendix 4). In the top ten, this was true of all the storms, with one-third already filling. Once again, the majority of the storms were at their most intense stage when the severe event occurred, with 19 out of 30 storms at their lowest central pressure at event time. The correlation between storm central pressure and storm ranking

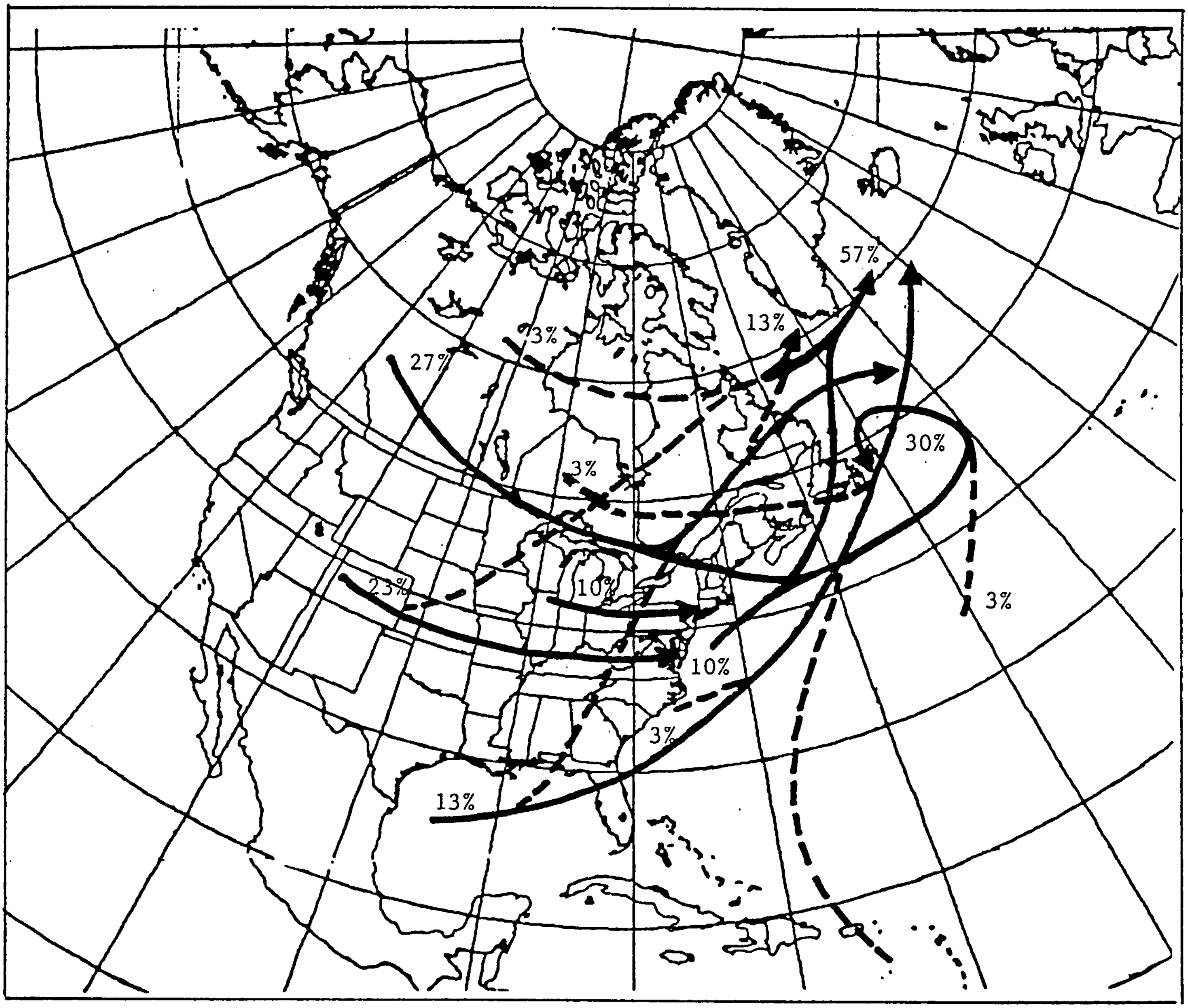


Figure 44. Preferred storm tracks for Region 4, northeast Newfoundland Shelf.

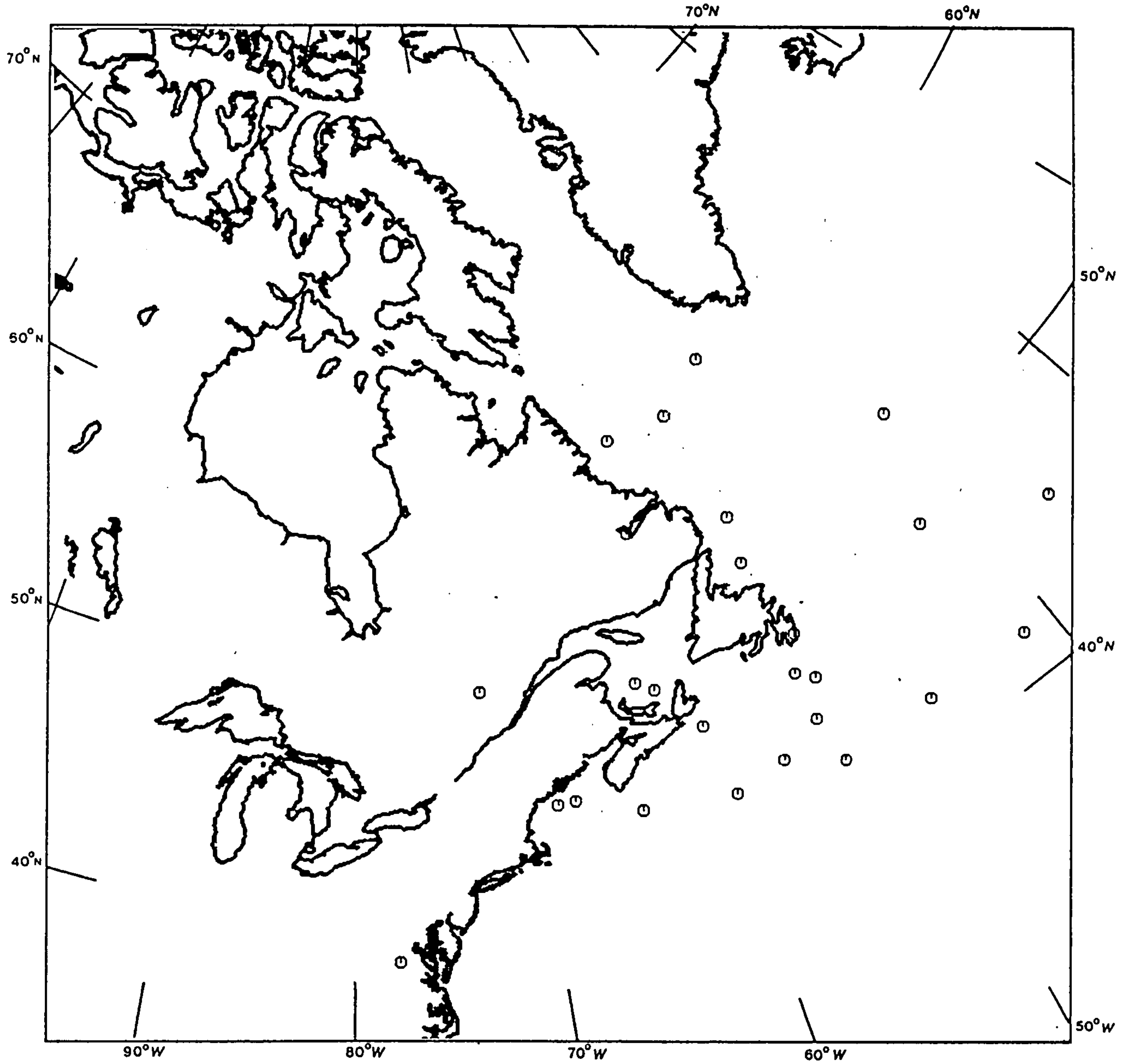


Figure 45. Position of maximum storm deepening for Region 4, northeast Newfoundland Shelf.

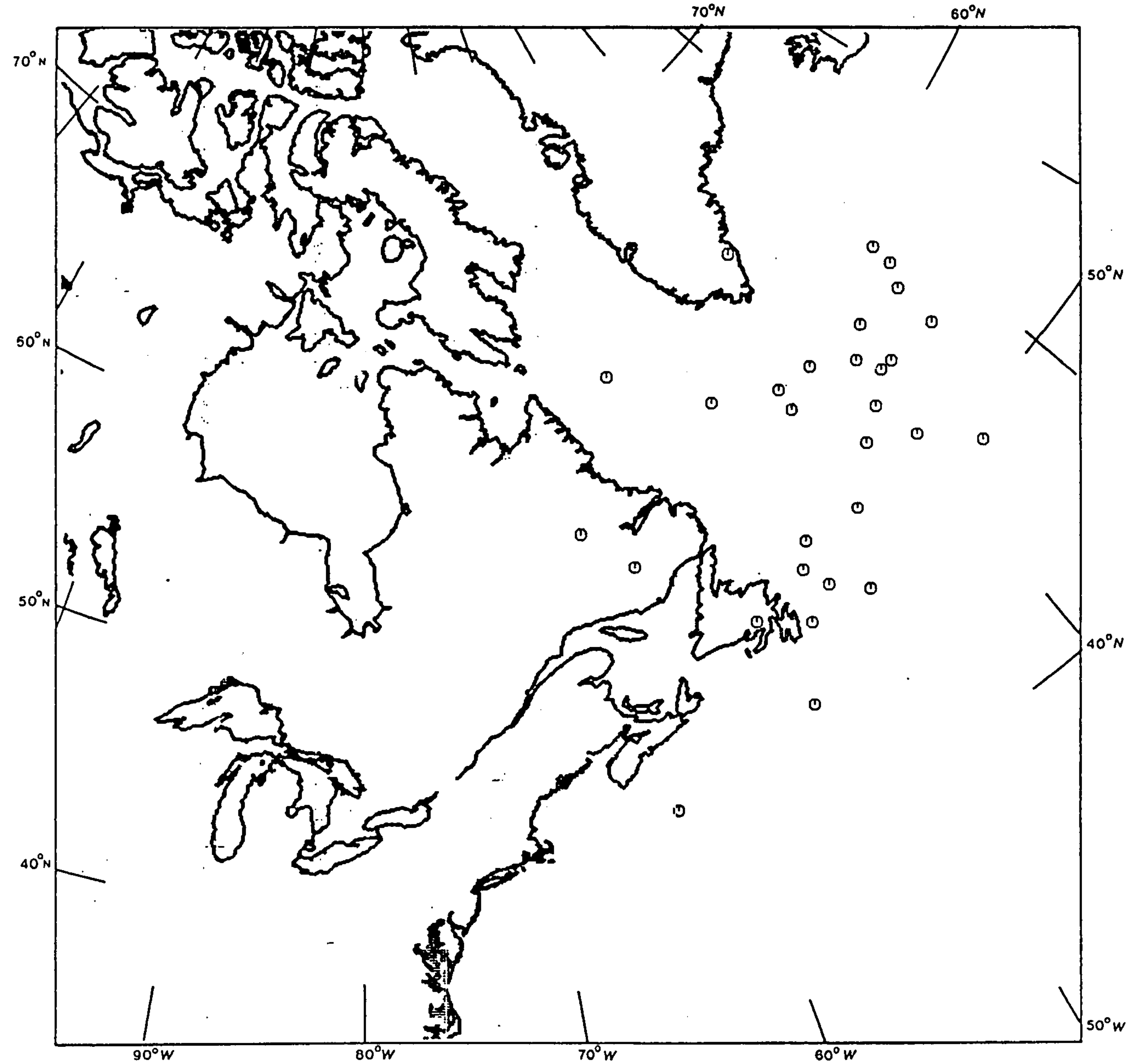


Figure 46. Position of storm at time of wave event for Region 4, northeast Newfoundland Shelf.

was again weak, with a correlation coefficient of +0.22, which is not significant at the 90% level for a sample of this size.

Region 5. Figure 47 shows storms causing significant wave events in Region 5. The Atlantic coastal track recovers somewhat, with about 70% of the storms taking this route. The presence of a cluster of cut-off lows to the east is again evident. Figure 48 indicates that 27% of the lows were of this nature, stagnating to the east of the study domain. It is clear from Figures 47 and 48 that the majority of the storms pass to the south of Region 5; this is evident also in the wind field statistics which show that 90% of the wave events occurred in northerly, and predominately northwesterly, flow (see Appendix 4).

Figure 48 indicates that over half of the coastal storms originated in the waters of the Atlantic or the Gulf of Mexico, with the remaining 17% originating to the lee of the Rockies in Colorado (10%) or Alberta (7%). Of the remainder, 23% tracked along the St. Lawrence River valley from their origins in Alberta (17%), Colorado (3%), or the Gulf of Mexico (3%), and continued just south of Region 5.

One of the more unusual events occurred on 14 January 1974. For several days prior to the event, moderate west to northwesterly flow was maintained through the region, with the remnants of a cyclone that had produced a severe event in Region 6 persisting as a trough near Cape Farewell, Greenland. On 13-14 January, a pulse of energy, in the form of a 500-mb cut-off low, edged across the region and as a result of this new forcing, a redevelopment occurred well to the north of the main baroclinic zone (thermal contrast zone)

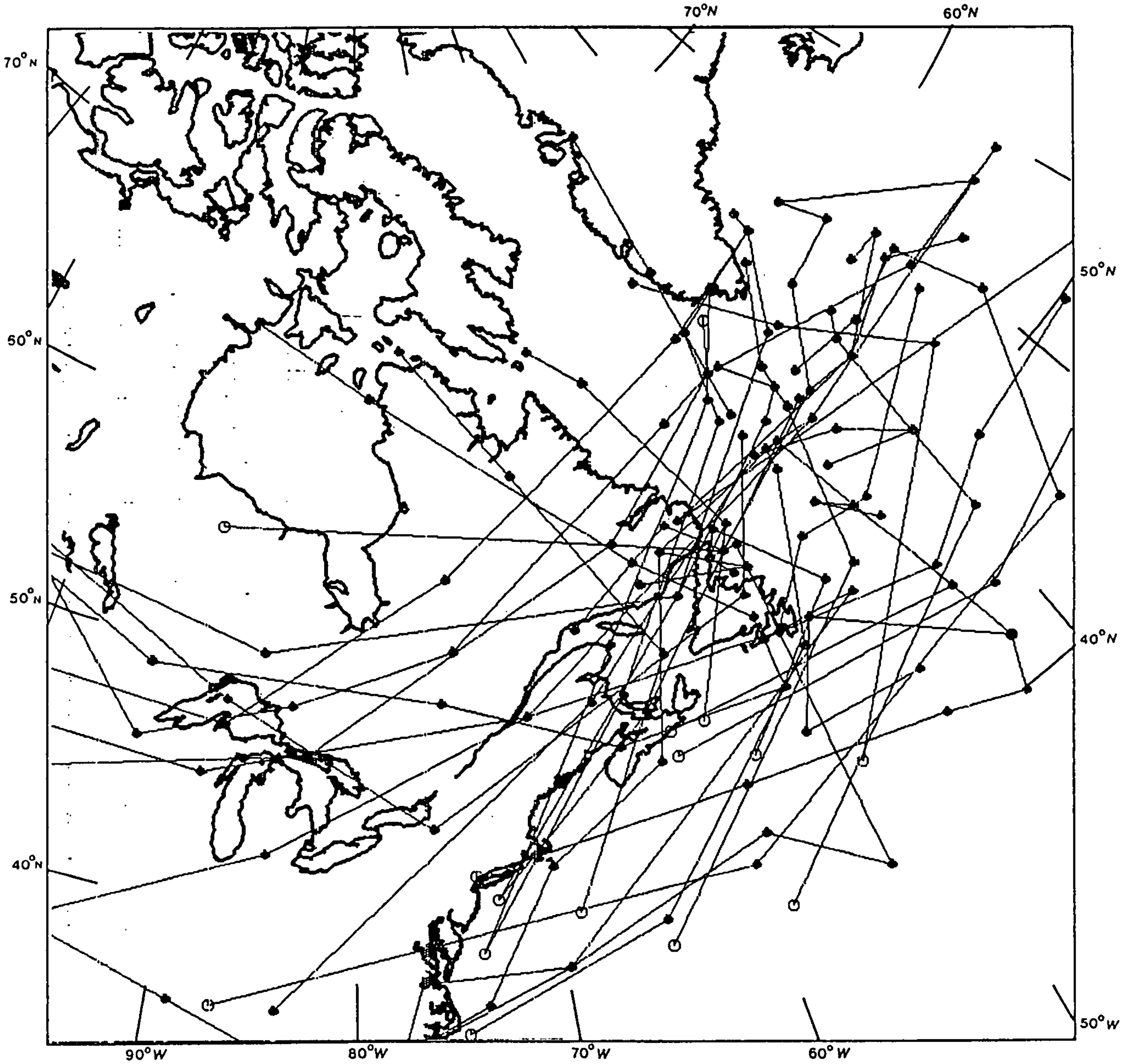


Figure 47. Severe storm tracks for Region 5, Labrador Shelf.

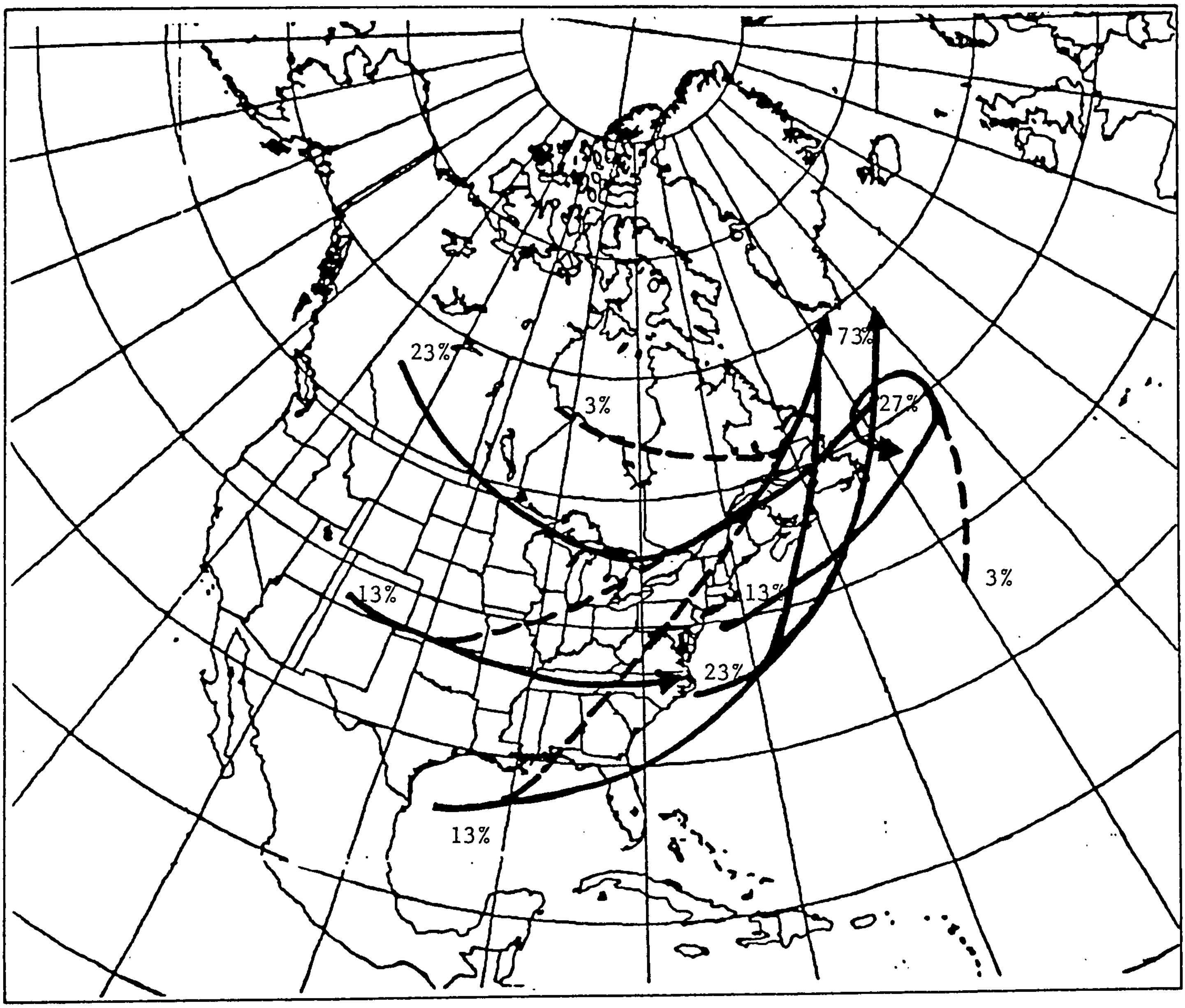


Figure 48. Preferred storm tracks for Region 5, Labrador Shelf.

near Cape Farewell. This "instant-occlusion" strengthened the west and northwesterly flow throughout the area, and produced an extreme wave event of rank 12.

The pattern of maximum storm deepening and position of the storm at event time is displayed in Figures 49 and 50. The patterns suggest that the majority of the storms attained their maximum deepening (and maximum strength) to the southwest of the region, producing severe events as the storms merged and decayed within the mean Icelandic low southeast of Cape Farewell, Greenland. All of the storms had already attained or were at maximum intensity at the time of the event, with one-third already beginning to decay (see Appendix 4). The relationship was much the same in the top ten, the main exception being that all the storms had undergone maximum storm deepening more than 24 hours before the severe event was produced. The correlation between storm central pressure and storm ranking was quite weak, with a coefficient of +0.14, which is not significant at the 90% level for a sample of this size.

Region 6. Figures 51 and 52 show storms causing significant wave events in Region 6. This region represents a major change from the other regions in terms of storm climatology. The Atlantic coastal track is greatly diminished, with only slightly greater than half the storms eventually making their way along this route. Of these only 22% track across or east of Newfoundland, with the remainder tracking to the west across Nova Scotia and the Gulf of St. Lawrence. The most dominant point of origin for Region 6 cyclones is to the lee of the Canadian Rockies in Alberta (41%), the majority of which track down the St. Lawrence River Valley to the Labrador sea (19%). In terms of storm track convergence, 43%

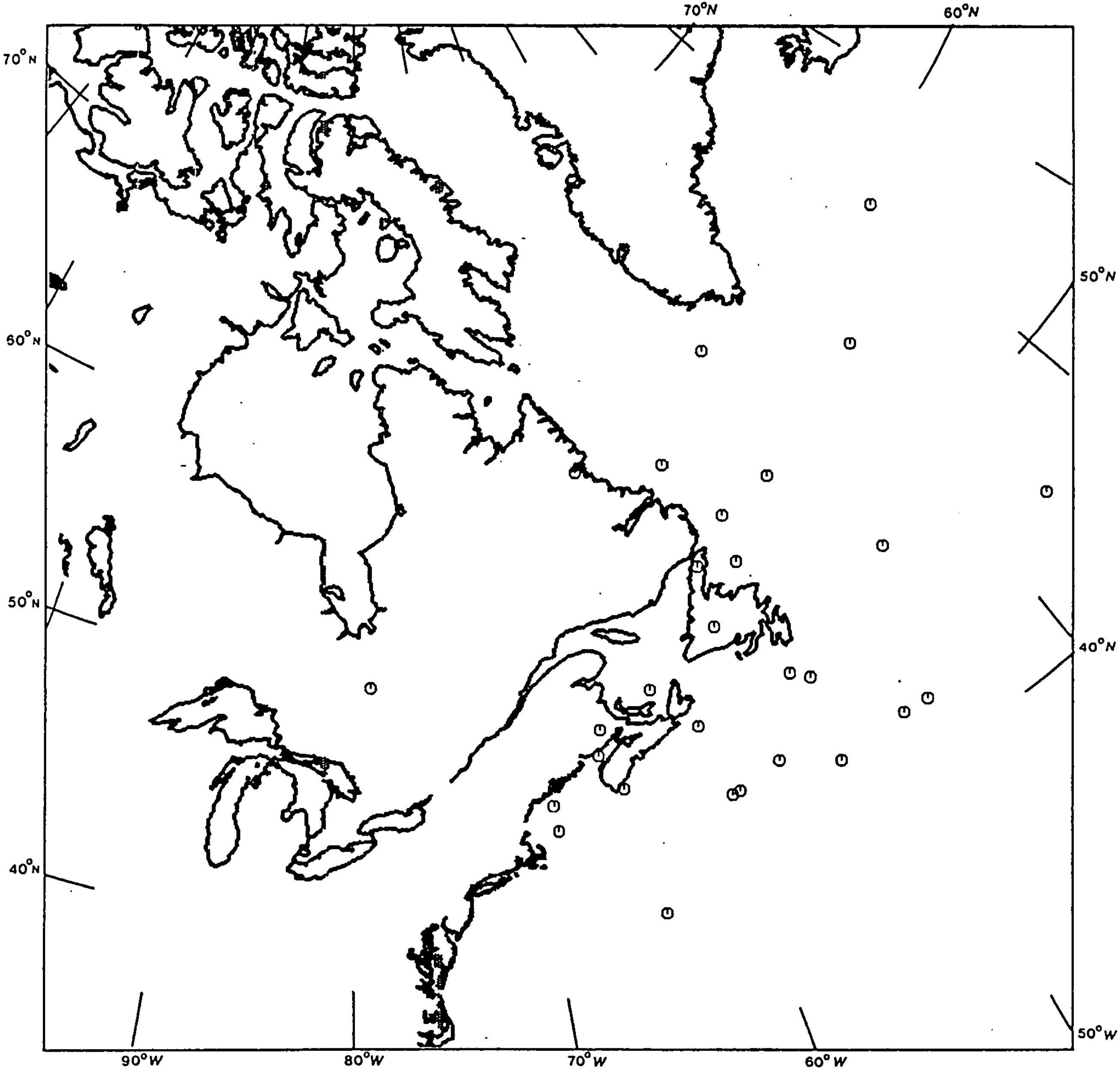


Figure 49. Position of maximum storm deepening for Region 5, Labrador Shelf.

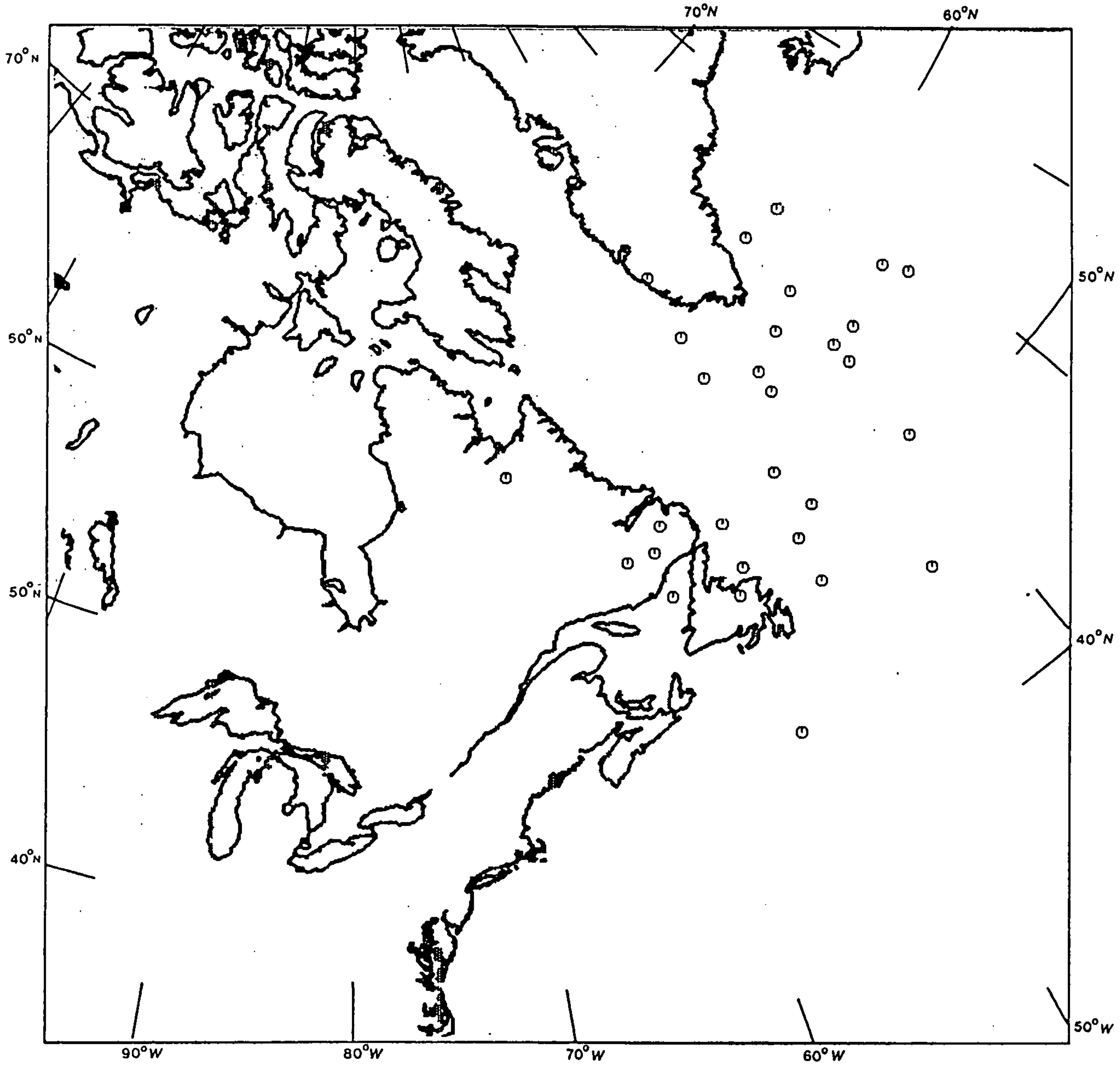


Figure 50. Position of storm at time of wave event for Region 5, Labrador Shelf.

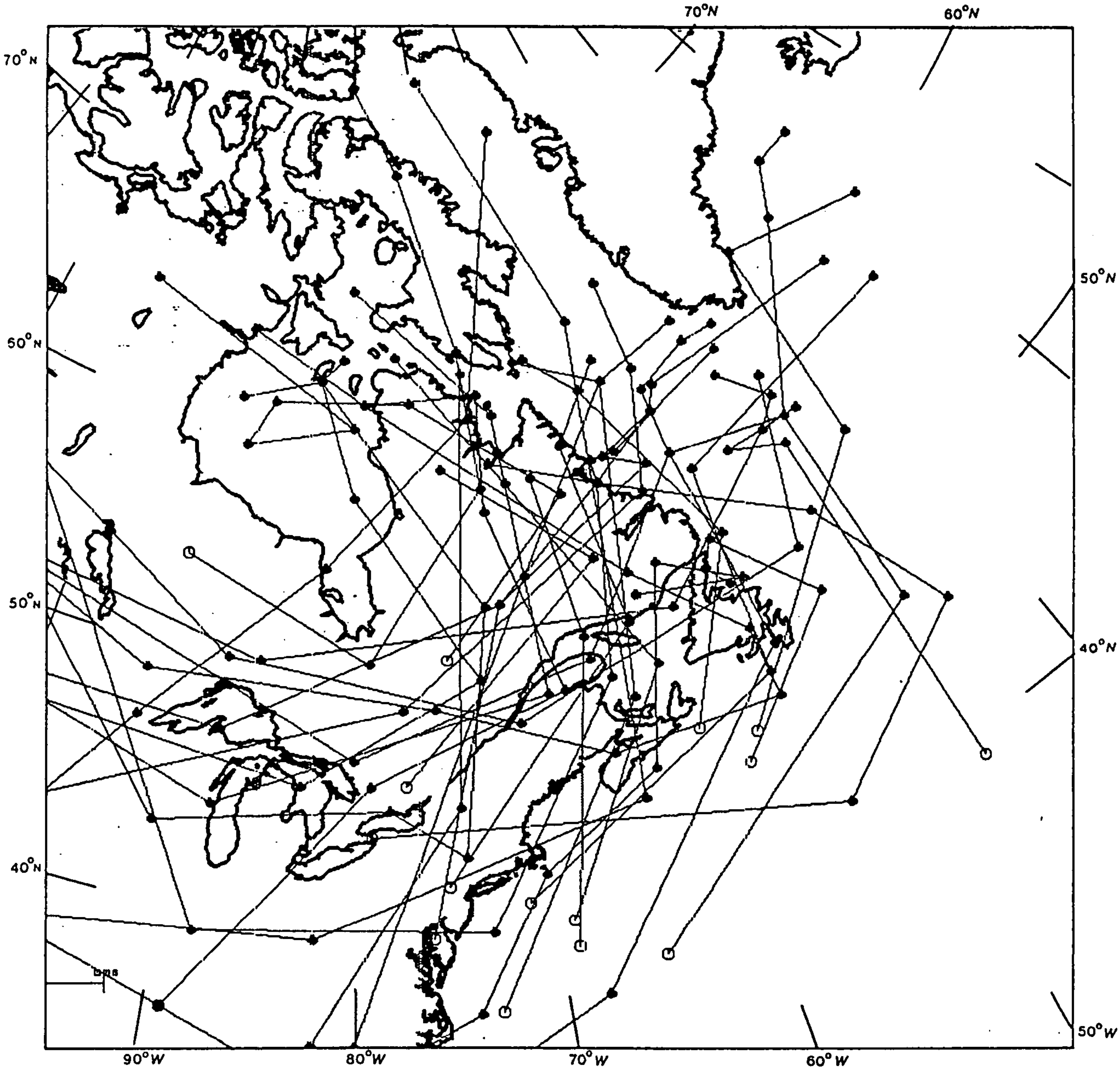


Figure 51. Severe storm tracks for Region 6, Davis Strait.

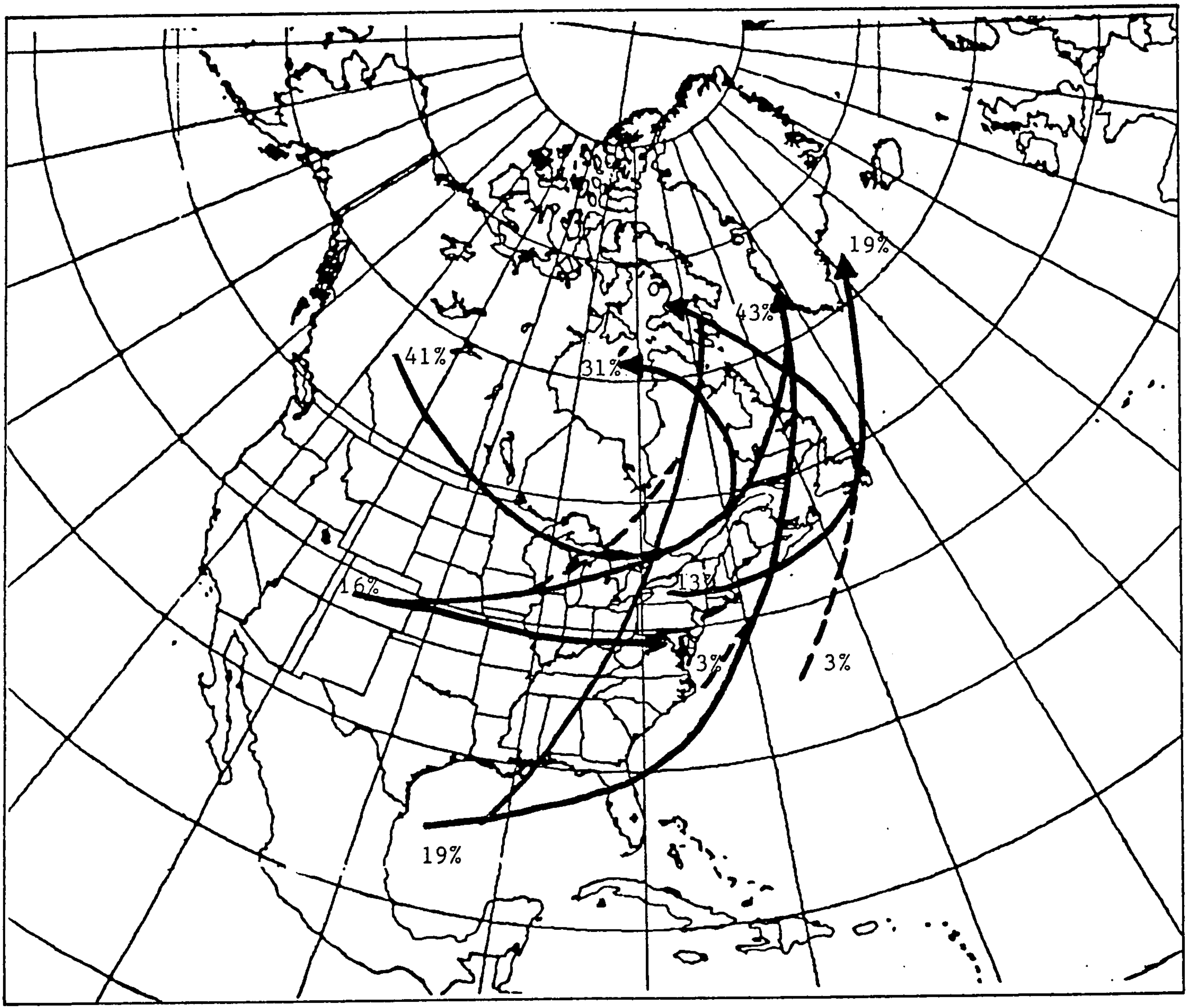


Figure 52. Preferred storm tracks for Region 6, Davis Strait.

of all cyclones end up passing west of Greenland towards Davis Strait, with 31% recurving sharply across northern Quebec, Baffin Island, and Hudson Bay, and only 19% passing to the east of Greenland. There is a clear preference once again for northerly winds, with nearly three-quarters of the wave events occurring in this flow (see Appendix 4). Not surprisingly, there is also a bias along the northwest to southeast fetch through Davis Strait, with 55% of the events occurring in this type of flow.

Figure 53 shows that a large proportion of the storms experienced their maximum deepening over land, many in the St. Lawrence River valley, indicating the inhibition of the coastal track. Figure 54 indicates that almost all of the events occurred with the storm positioned to the south and southwest, suggesting the curvature of the storm track towards the northwest and northern Quebec. Three-quarters of the storms underwent maximum deepening more than 24 hours prior to the event, and all the storms were at, or had previously reached, their most intense stage, including more than one third of the storms that had already begun to decay (see Appendix 4). Somewhat surprisingly, fully three-quarters of the storms were explosive cyclones, despite the fact that this type of storm is usually associated with the warm waters of the Gulf Stream (Sanders and Gyakum 1980; Roebber 1984). Of the 24 storms that developed explosively, only 10 did so in the usual area adjacent to the zone of maximum sea-surface temperature gradient, and 9 accomplished the feat over land. As oceanic explosive cyclones generally display a large cyclogenetic response to relatively weak thermal forcing, in contrast to the one-to-one relationship exhibited by their continental counterparts, these cyclones were probably the product of relatively powerful dynamic and

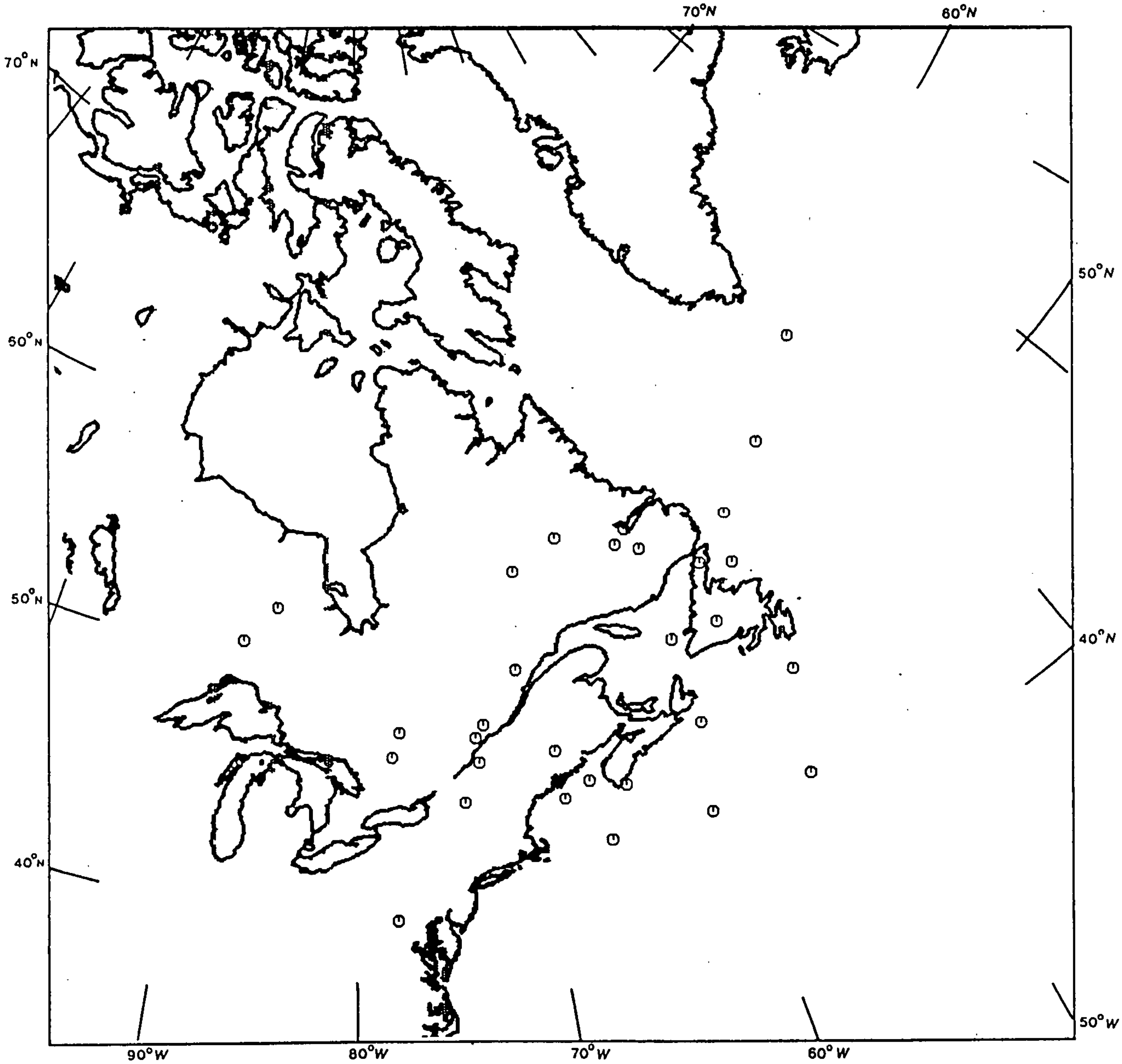


Figure 53. Position of maximum storm deepening for Region 6, Davis Strait.

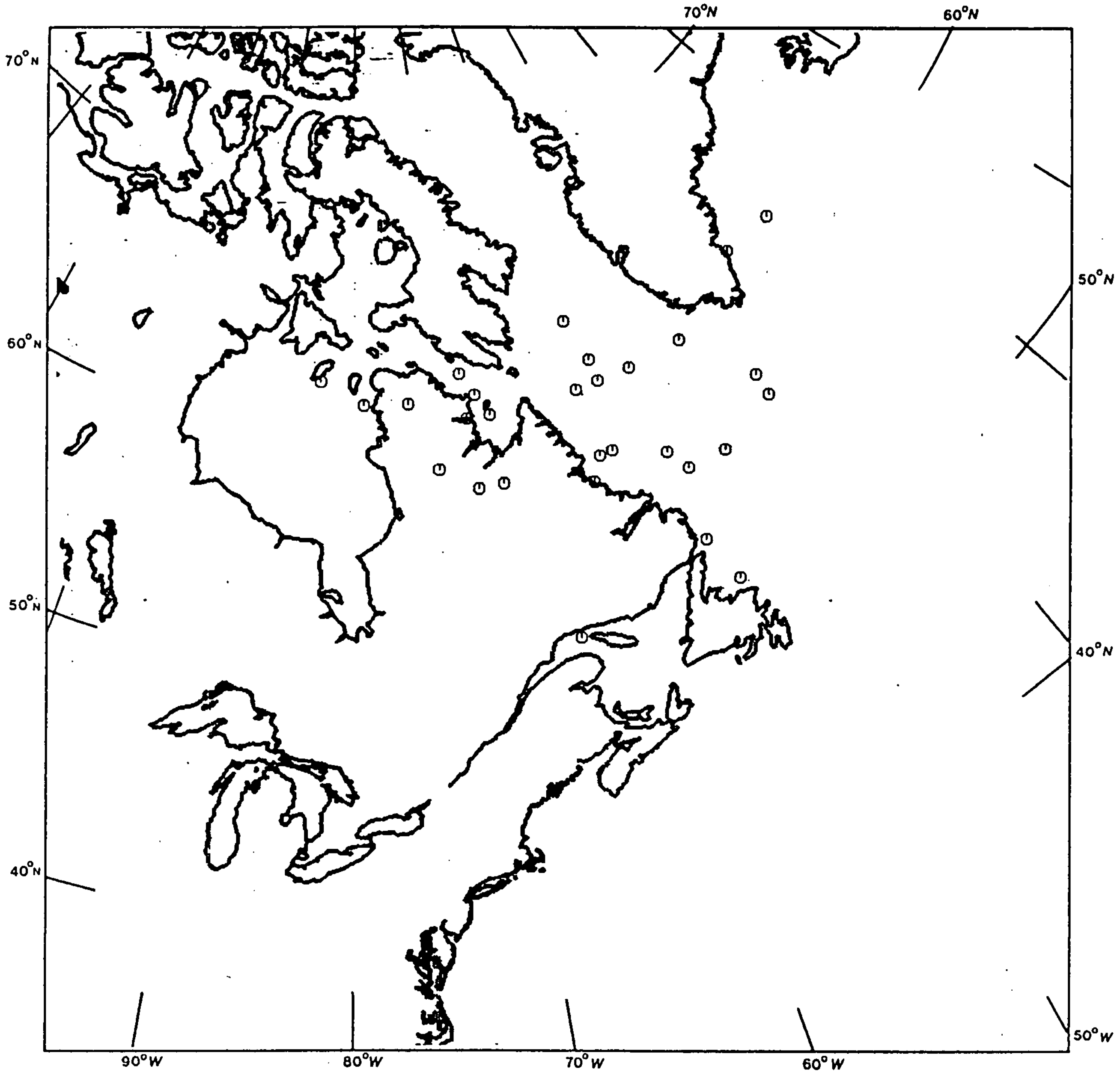


Figure 54. Position of storm at time of wave event for Region 6, Davis Strait.

thermodynamic forcing, and not the result of additional energy provided by diabatic processes (Bosart 1981; Gyakum 1983b). The correlation between storm central pressure and storm ranking was virtually nil, with a correlation coefficient of +0.07, which is not significant at the 90% level for a sample of this size.

Region 7. Region 7 represents a complete change from the general climatological pattern inherent in Regions 1 through 5 and, to a lesser extent, in Region 6. The coastal track represents less than 12% of all storm tracks, with no storms passing to the east of Nova Scotia. Figures 55 and 56 show strong convergence of storm tracks into northern Davis Strait and Baffin Bay, with fully 85% of the cyclones passing in this direction. The reputation of these areas as a "graveyard" for cyclones (Maxwell et al. 1980; Roebber 1984) is also reinforced by the sample of severe wave-producing storms which exhibit a cluster of decaying disturbances in Region 7.

The pattern displayed in Figure 56 is somewhat confused, but the cyclonic rotation of the storm tracks around a point located in northern Hudson Bay is unmistakable. This suggests, in the broad view, that these storms are associated with a closed, upper-level vortex positioned in this area, possibly in combination with blocking downstream. There is no single major cyclogenetical area evident on the figure. However, there was a tendency for these cyclones to form north of 49^{o}N, to the lee of the Canadian Rockies in Alberta and British Columbia and the Mackenzie Mountain range in the Yukon and northwest Territories.

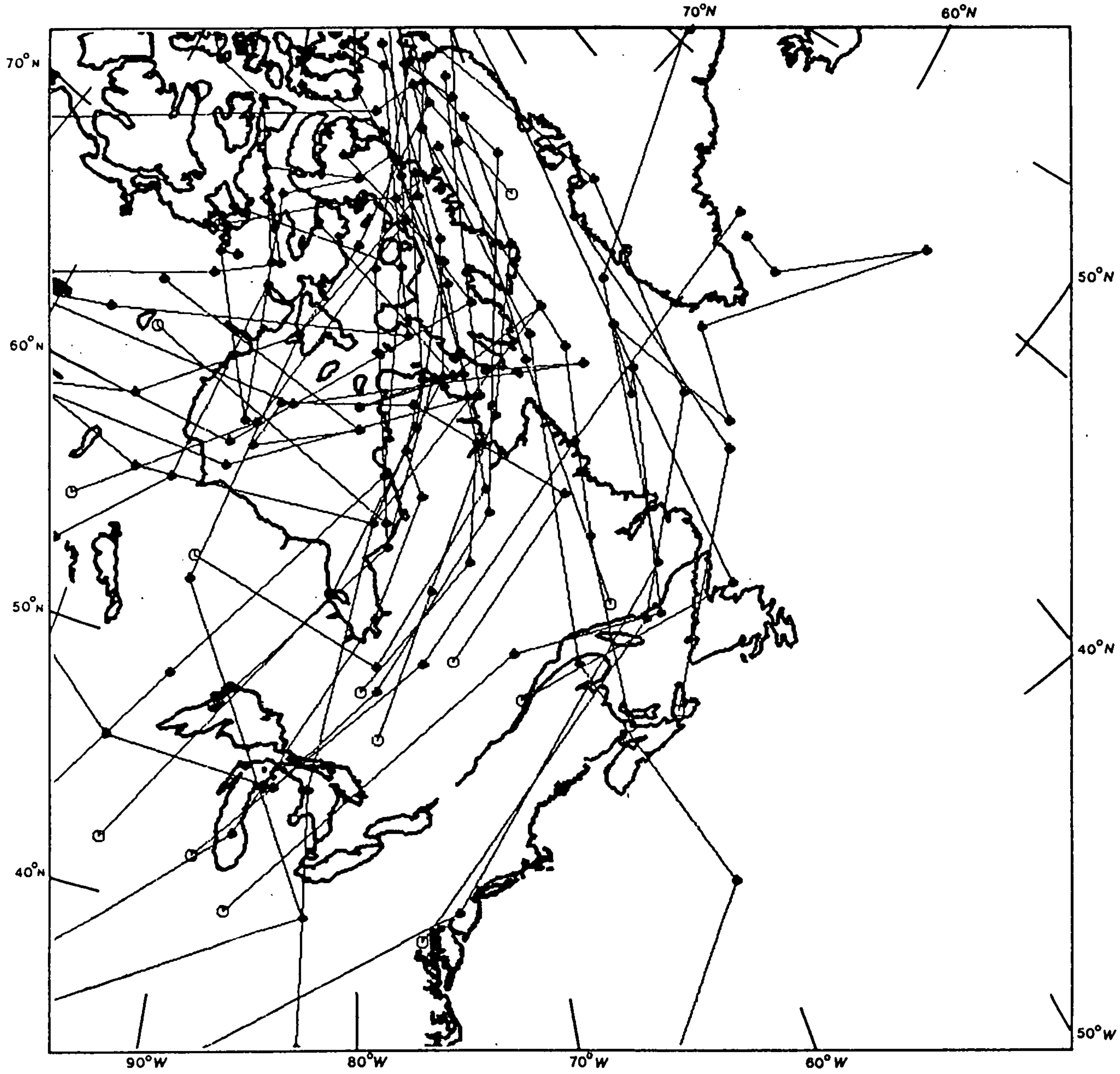


Figure 55. Severe storm tracks for Region 7, Baffin Bay.

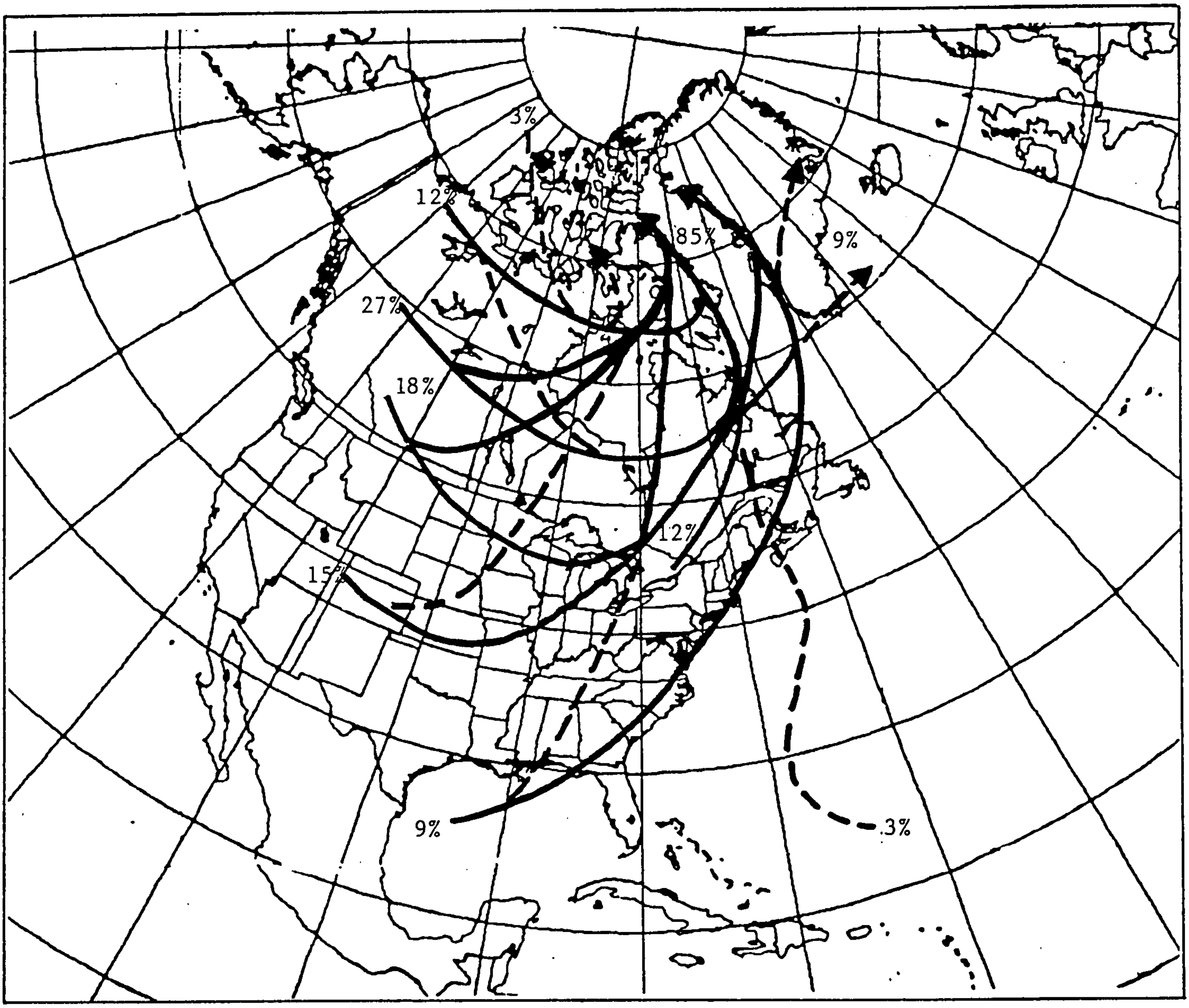


Figure 56. Preferred storm tracks for Region 7, Baffin Bay.

Interestingly, one tropical disturbance that had transformed in nature to a mid-latitude baroclinic cyclone produced a severe event (rank 8) in combination with a low that tracked east from the Yukon. The main convergence zones of cyclone tracks appeared to be through northern Quebec and across west-central and northern Hudson Bay. Unlike the other regions, there is no clear preference for northerly winds in the production of extreme wave events (see Appendix 4). Not unexpectedly, there is a preponderance of winds aligned in the northwest to southeast corridor of Baffin Bay and Davis Strait (50%). Figure 57 indicates no clear pattern in the position of maximum storm deepening. There was some concentration in central and northern Quebec and across Hudson Bay, suggesting that diabatic heat sources may have played a role in a fraction of the storms' development. The position of the storms at the time of the event displayed in Figure 58 shows a clustering in Davis Strait and Baffin Bay, suggesting that many of the wave producers were occluded and were already beginning to dissipate in the cyclone "graveyard". This contention is supported by the statistics, which indicate that more than half of the storms were already dissipating at the time of the event (see Appendix 4). There were few explosive cyclones that affected this region, and they were confined generally to the St. Lawrence River valley-Gulf of St. Lawrence region. The correlation between storm central pressure and storm ranking was almost nil, with a correlation coefficient of -0.04, which is not significant at the 90% level for a sample of this size.

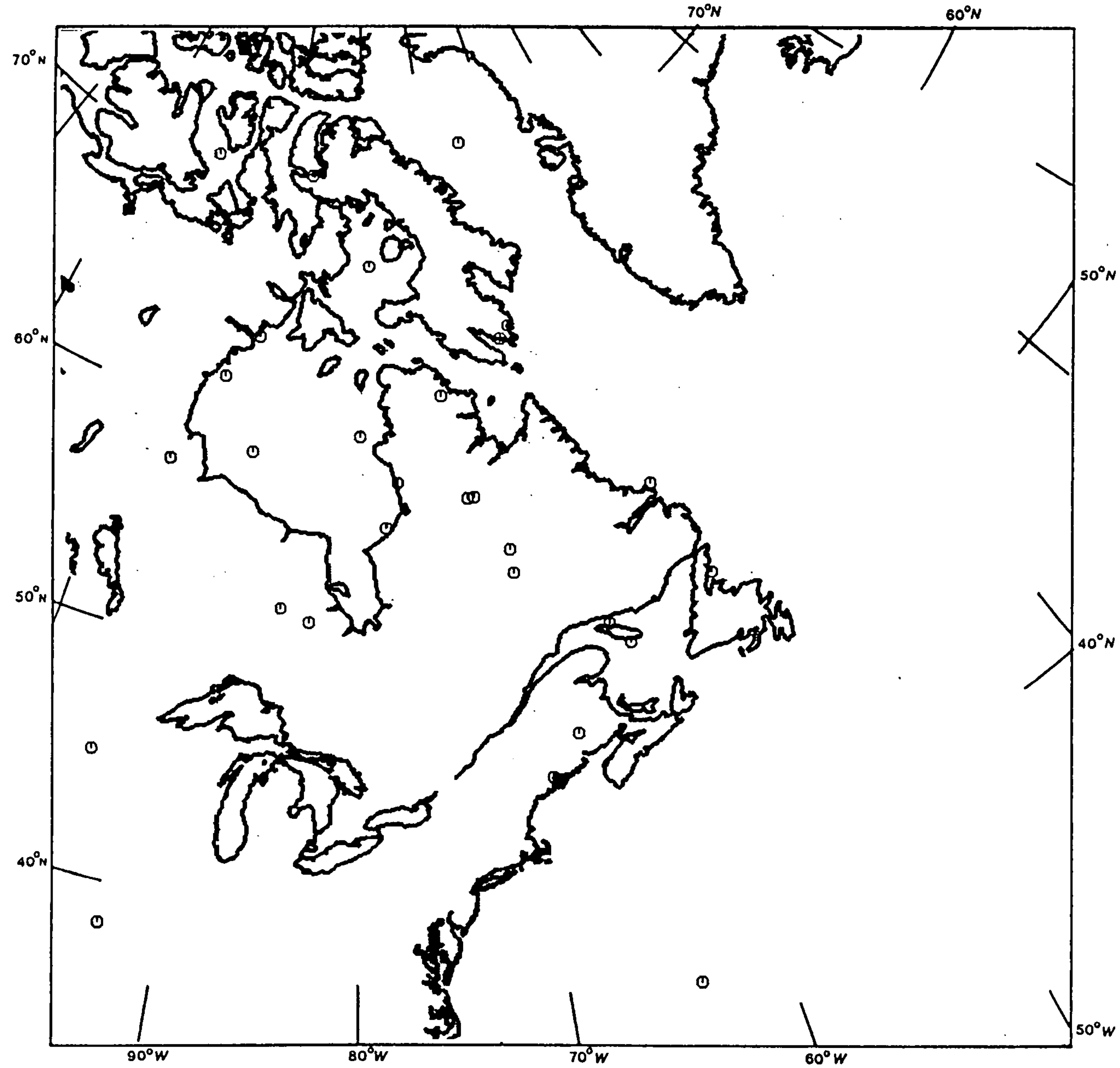


Figure 57. Position of maximum storm deepening for Region 7, Baffin Bay.

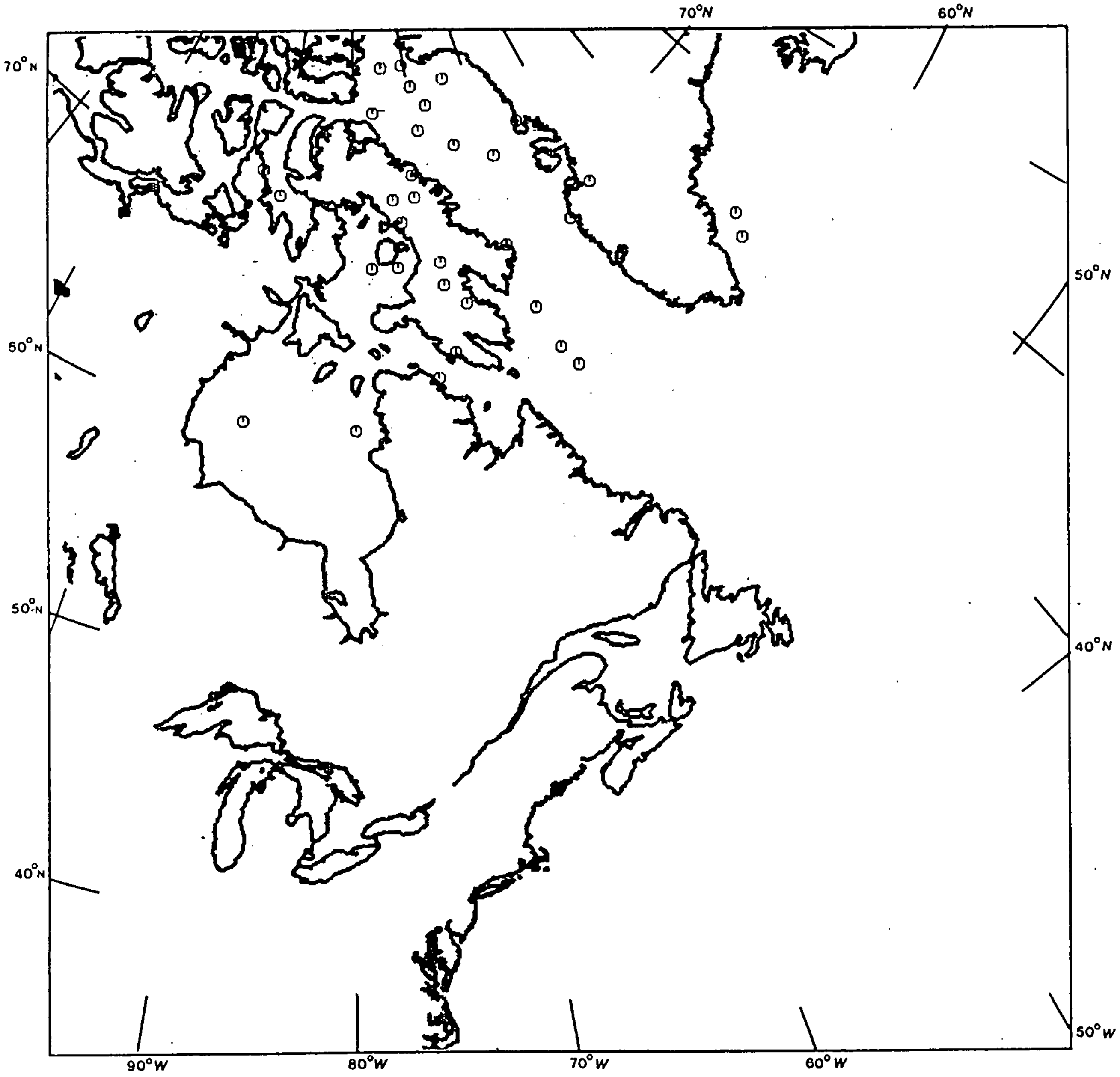


Figure 58. Position of storm at time of wave event for Region 7, Baffin Bay.

APPENDICES

APPENDIX 1

DATA SOURCES FOR SELECTION OF SEVERE STORMS

APPENDIX 1

Table A-1

Summary of data sources used for severe storm identification

DATA SOURCE	DESCRIPTION	PERIOD AVAILABLE	GEOGRAPHIC COVERAGE	COMMENTS
Spectral Ocean Wave Model (SOWM)	Wave hindcast using spectral model. Wind input derived from FNWC objectively analysed pressure fields by boundary layer model. Observed pressure and wind data included in preparation of wind fields	1956 - 75 6-hour interval	Grid spacing of approximately 200 km throughout the east coast area (see Fig. 2)	Does not include seasonal ice cover effects in the model. Tapes of data in time series format archived at MEDS
Waterways Experiment Station (WES)	Wave hindcast using a discrete spectral model (Resio 1981) which includes wave-wave interaction. Wind input derived from FNWC objectively analysed pressure fields augmented by finer grid NWS surface analyses along the US Atlantic Coast. Ship wind observations blended into final fields	1956 - 75 6-hour interval for Phase I grid 3-hour interval for Phase II grid	222 km spacing on spherical orthogonal grid in southern Scotian Shelf area (Phase II grid). North of this, hindcasts have been archived for only selected grid (Phase I) points (see Fig. 2)	Does not include seasonal ice cover effects. Problems indicated by Resio (1982) in the pressure field specification in the Scotian Shelf area. Baird and Readshaw (1981) noted errors in the wind fields of Phase I grid points. Tapes of data in time series format archived at MEDS
Marine Environmental Data Service (MEDS)	Measured wave data from waverider buoys Output products include time series plots and listings of significant wave height; listings and plots are of one-dimensional spectra	Circa 1970 to date for various periods. (See Fig. 5 to 11) Long-term continuous records sparse	Coverage mainly confined to Grand Banks and Scotian Shelf oil exploration sites	The highly variable spatial and temporal nature of available measured wave data severely limits its use in identifying severe storms. Data archived at MEDS

Table A-1 (continued)

DATA SOURCE	DESCRIPTION	PERIOD AVAILABLE	GEOGRAPHIC COVERAGE	COMMENTS
National Oceanic and Atmospheric Administration (NOAA) Buoy Data	Wind, pressure, air temperature, sea temperature and significant wave height in TDF11 format	1977 - 82	Buoy located in the very southwestern part of the Scotian Shelf region (40.8°N, 68.5°W)	Archived at AES, Downsview and accessible through the MAST software system
Weathership Observations	Standard marine weather observations including sea and swell in TDF11 format every 3 hours	"Bravo" 1945 - 72 "Delta" 1946 - 73	"Bravo" Labrador Sea (56.5°N, 51.0°W). "Delta" Southeastern Grand Banks (44.0°N, 41.0°W)	Several small gaps in temporal coverage. Wave observations seemed low compared with hindcast storm values particularly for OSV Bravo. Upper threshold to waveheight of 9.5 meters particularly noticeable Data archived at AES, Downsview and accessible through MAST
Itinerant Ship Observations	Standard marine weather observations including wind, sea and swell in TDF11 format. Observations usually only taken every 6 hours	Circa 1880 to date	Observations tend to be concentrated in main fishing areas and shipping lanes	Quality of wave observations suspect which together with shipping's efforts to stay clear of major storms severely reduces its utility for identification of severe events. Wind speeds also used for storm verification. Data archived at AES, Downsview and accessible through MAST
Canadian Forces Meteorological and Oceanographic Centre (METOC)	Maximum significant wave height in 5 degree lat/lon square digitized from METOC wave analysis charts. These wave heights are based on Bretschneider-based analysis fields and reported wave observations (Actual value of significant wave height at mid-point of 5 degree lat/lon square abstracted by BIO for 17 year period)	1972 - 82 12 hour interval	Northwest Atlantic and Labrador Sea	Data archived in TDF11 format at AES, Downsview and is amenable to MAST type analysis

Table A-1 (continued)

DATA SOURCE	DESCRIPTION	PERIOD AVAILABLE	GEOGRAPHIC COVERAGE	COMMENTS
Atmospheric Environment Service (AES) synoptic and hourly reporting stations	Hourly climatological data reported including wind speed, pressure, cloud cover, visibility, etc. Only island stations used in verifying storms (Grindstone Is., Belle Isle and Sable Is.)	Grindstone Is. 1953 → Belle Is. 1953 → Sable Is. 1953 →	Grindstone Is. - Gulf of St. Lawrence, (47.7°N,61.9°W) Belle Is. - N.E. Newfoundland Shelf, (51.9°N, 55.4°W) Sable Is. - Scotian Shelf (43.9°N, 60.0°W)	Measured wind speeds used to verify severe storm events. Sable Island measured winds had significantly lower number of storm force winds than other two sites. This is related to poor siting of the anemometer. Wind data sets archived at AES, Downsview in TDF11 format for MAST analysis. Data also in standard Digital Archive of Canadian Climate Data
Atmospheric Environment Service (AES) Geostrophic Wind Climatology	Gridded climatology of geostrophic (uncorrected) wind speed and direction derived from FNOC pressure data. Ageostrophic corrections have recently been derived for this wind set (1984)	1946 - 78	Regular 381 km grid over the Atlantic, Pacific and Arctic	Data set archived in TDF11 format at AES, Downsview. Amenable to MAST-type analyses
Naval Environmental Data Network (NEDN) Dataset	Hemispheric gridded dataset with 6 hourly values of meteorological and oceanographic model output from FNOC. Significant wave height values derived from the FNWC spectral model in 'operational' mode	1974 - 82	Northern hemisphere (35°N to Pole) on a 381 km NWC grid	Several months of data are missing in the dataset and several months have incomplete observations. Dataset archived at AES, Downsview, and is accessible using the GASP (Gridded Area Statistics Package) facility developed by AES

APPENDIX 1

Table A-2

Waverider buoy stations for Region 1, Gulf of St. Lawrence

ID	NAME	LOCATION LAT (N)	LOCATION LONG (W)	WATER DEPTH (M)	PERIOD OF OPERATION START	PERIOD OF OPERATION END
008	Port aux Basques	47-33-00	059-06-00	44	05/12/74	04/02/75
091A	Sedco H (Cap Rouge F-52)	47-11-10	061-11-10	61	13/06/73	03/09/73
091B	Sedco H (Bradelle L-49)	47-58-33	063-07-06	58	12/09/73	22/11/73
020	Stephenville	48-29-24	058-42-00	28	07/10/74	26/11/75*
043	Magdalen (Outer)	47-36-06	061-18-04	27	23/05/74	08/12/78*
044	Miscou Island	48-10-30	064-16-00	46	30/05/74	21/11/74

* various periods

APPENDIX 1

Table A-3

Waverider buoy stations for Region 2, Scotian Shelf

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
145	Ben Ocean Lancer (Acadia K-26)	42-51-42	061-55-21	955	03/05/78	03/08/78
166	Bowdrill I (Banquereau C-21)	44-10-42	058-34-00	85	07/01/82	20/10/82
144A	Gulf Tide (Thebaud I-94)	43-44-00	060-20-30	60	09/03/78	06/11/78
144B	Gulf Tide (Venture D-23)	43-47-30	059-37-00	60	06/11/78	10/06/79
037	Osborne Head	44-32-40	063-27-50	30	12/12/70	31/12/81 *
142A	Rowan Juneau (Venture B-13)	44-01-44	059-32-08	24	22/08/80	25/01/81
142B	Rowan Juneau (Venture B-43)	43-51-36	059-27-24	56	31/01/81	28/04/82
142C	Rowan Juneau (South Venture O-59)	43-52-36	059-29-12	50	29/04/82	03/01/83
091A	Sedco H (Ojibwa E-07)	43-46-15	061-46-13	79	04/02/74	27/02/74
091B	Sedco H (Demascotia G-32)	43-41-25	060-49-51	53	04/03/74	19/05/74
091C	Sedco H (Sambro I-29)	43-48-17	062-48-15	199	27-05-74	27-06-74
091D	Sedco H (Jason C-20)	45-29-19	058-32-18	110	04/07/74	30/07/74
091E	Sedco H (North Sydney P-05)	46-34-45	059-45-00	100	16/08/74	03/09/74
091F	Sedco H (Montagnais I-94)	42-53-41	064-13-47	113	15/09/74	28/09/74
091G	Sedco H (North Sydney F-24)	46-33-23	059-48-46	60	16/06/76	10/07/76
091H	Sedco H (Penobscot L-30)	44-09-44	060-04-09	138	26/07/76	27/09/76
091I	Sedco H (Wenonah J-75)	43-34-26	060-25-45	67	01/10/76	15/11/76
091J	Sedco H (Moneida P-15)	43-04-55	062-16-43	110	14/01/77	11/02/77

Table A-3 (continued)

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
091K	Sedco H (Penobscot B-41)	44-10-02	060-06-32	61	24/02/77	29/03/77
090A	Sedco J (Citnalta I-59)	44-08-42	059-37-30	59	25/02/74	19/04/74
090B	Sedco J (Intrepid L-80)	43-49-37	059-56-44	37	14/06/74	11/08/74
090C	Sedco J (Adventure F-80)	45-19-30	057-56-30	99	22/01/75	01/02/75
133	Sedco 709 (Shubenacadie H-100)	42-53-18	061-30-48	1114	09/11/82	23/12/82
167	Vinland (West Esperanto B-78)	44-47-12	058-25-24	92	21/09/82	24/12/82
165	Zapata Scotian (Olympia A-12)	44-04-30	059-48-30	55	27/04/82	10/01/83*

* more or less continuously

APPENDIX 1

Table A-4

Waverider buoy stations for Region 3, Grand Banks

ID	NAME	LOCATION LAT (N)	LOCATION LONG (W)	WATER DEPTH (M)	PERIOD OF OPERATION START	PERIOD OF OPERATION END
136	Glomar Atlantic (Hibernia P-15)	46-46-20	048-46-00	82	01/06/79	21/10/79
016	Logy Bay	47-38-18	052-28-18	168	1972	1982 *
156A	Ocean Ranger (Hibernia G-55)	46-43-36	048-53-30	80	02/12/80	23/02/81
156B	Ocean Ranger (Hibernia K-18)	46-47-58	048-47-58	80	02/03/81	05/06/81
156C	Ocean Ranger (Hibernia J-34	46-43-57	048-50-43	78	13/12/81	09/02/82
091	Sedco H (Emerillon C-56)	45-15-03	054-23-14	120	06/12/73	22/01/74
093A	Sedco I (Egret K-36)	46-25-38	048-50-22	86	16/08/73	10/09/73
093B	Sedco I (Spoonbill D-30)	45-49-06	049-04-06	64	13/09/73	14/10/73
093C	Sedco I (Brant P-87)	44-16-59	052-42-19	86	02/12/73	10/12/73
093D	Sedco I (Coot K-56)	45-45-41	052-08-32	86	20/02/74	21/02/74
093E	Sedco I (Carey J-34)	45-23-32	052-35-02	86	28/04/74	04/07/74
093F	Sedco I (Skua E-41)	45-20-27	048-52-26	85	10/09/74	29/09/74
090A	Sedco J (Flying Foam I-13)	47-02-42	048-46-31	91	12/10/73	26/11/73
090B	Sedco J (Bonnition H-32)	45-51-27	048-19-32	108	08/12/73	30/12/73
090C	Sedco J (Adolphus D-50)	46-59-05	048-22-29	113	26/10/74	31/10/74
134A	Sedco 706 (Hibernia B-08)	46-47-05	048-45-26	110	22/03/80	06/01/81
134B	Sedco 706 (Hebron I-13)	46-32-48	048-32-23	94	29/01/81 22/07/81	25/05/81 - 10/09/81

Table A-4 (continued)

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
134C	Sedco 706 (Nautilus C-92)	46-51-21	048-44-55	90	22/10/81	14/07/82
133	Sedco 709 (Hibernia O-35)	46-44-21	048-49-00	72	07/01/80	11/07/80
092	Sedneth (Osprey H-84)	44-43-29	049-27-33	59	27/07/73	30/08/73
140A	Zapata Ugland (Hibernia P-15)	46-46-20	048-46-00	82	25/11/79	07/01/80
140B	Zapata Ugland (Ben Nevis I-45)	46-34-36	048-21-15	98	31/01/80	30/08/80
140C	Zapata Ugland (South Tempest G-88)	47-07-55	047-58-12	150	30/09/80	02/04/81
140D	Zapata Ugland (Hibernia K-18)	46-48-23	048-47-35	70	26/06/81	03/11/81
140E	Zapata Ugland (West Flying Foam L-23)	47-03-12	048-44-48	95	15/11/81	19/02/82
140F	Zapata Ugland (Bonanza M-71)	47-30-47	048-12-40	195	20/05/82 16/10/82	16/09/82 11/12/82

* various periods

APPENDIX 1

Table A-5

Waverider buoy stations for Region 4, NE Newfoundland Shelf

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
131	Discoverer 7-Seas (Blue H-28)	49-37-34	049-18-29	1524	16/05/79	17/08/79
094	Havdrill (Bonavista C-99)	49-08-00	051-14-00	335	11/06/75 17/08/75	11/08/75 21/10/75
156	Ocean Ranger (Sheridan J-87)	48-26-50	049-57-58	209	25/06/81	04/11/81
023	Petrel (Verrazano L-77)	52-26-05	054-12-00	107	03/09/76	22/09/76
090	Sedco J (Cumberland B-55)	48-24-12	050-07-58	195	08/08/75	13/10/75
134	Sedco 706 (Linnet E-63)	48-12-48	050-25-50	157	23/07/82	06/11/82
132	Sedco 707 (Hare Bay E-21)	51-10-23	051-04-30	241	12/06/79	18/10/79

APPENDIX 1

Table A-6

Waverider buoy stations for Region 5, Labrador Shelf

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
141	Ben Ocean Lancer (Hopedale E-33)	55-52-00	058-51-00	562	18/08/78	28/09/78
138	Ben Ocean Lancer (Nth Bjarni F-06)	55-31-06	057-42-27	144	27/06/81	05/10/81
136	Glomar Atlantic (Sth Labrador N-79)	55-48-50	058-26-37	490	31/07/80	25/09/80
094	Havdrill (Indian Harbour M-52)	54-21-51	054-23-49	196	17/08/75	21/10/75
135A	Neddrill II (Roberval C-02)	54-51-37	054-44-41	273	06/07/80	03/09/80
135B	Neddrill II (Bjarni O-82)	55-31-35	057-40-38	156	16/09/80	17/10/80
135C	Neddrill II (Corte Real P-85)	56-05-20	058-12-12	438	16/07/82	14/10/82*
155	Neddrill II-B (Roberval C-02)	54-52-30	055-45-06	285	22/08/80	08/09/80
154	Pacnorse I (Rut H-11)	59-10-18	062-16-47	137	27/07/81 06/08/82	31/08/81 11/10/82
137A	Pelerin (Skolp E-07)	58-26-00	061-46-00	75	20/08/78	17/09/78
137B	Pelerin (Roberval K-92)	55-00-00	055-30-00	269	16/07/79	01/10/79
137C	Pelerin (Ogmund E-72)	57-31-30	060-26-36	159	16/08/80	08/10/80
137D	Pelerin (North Leif I-05)	54-25-00	055-15-00	146	08/07/81	28/09/81
137E	Pelerin (Pothurst P-19)	58-48-54	060-31-30	192	11/07/82	20/10/82
017A	Pelican (Leif M-48)	54-17-46	055-07-20	165	31/07/73	29/08/73
017B	Pelican (Bjarni H-81)	55-30-00	057-42-00	139	31/08/73 30/09/74	25/10/73 17/10/74

Table A-6 (continued)

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
017C	Pelican (Gudrid H-55)	54-54-00	055-52-00	300	19/08/74	01/09/74
017D	Pelican (Freydis B-87)	53-56-13	054-42-35	188	05/07/75	05/08/75
017E	Pelican (Karlsefni A-13)	58-52-00	061-46-00	180	11/08/75 13/09/76	23/09/75 23/10/76
017F	Pelican (Cartier D-70)	54-39-00	055-40-00	310	27/09/75	29/10/75
017G	Pelican (Snorri J-90)	57-20-00	059-58-00	141	29/08/76	07/09/76
017H	Pelican (Tyrk P-100)	55-30-00	058-14-00	137	27/07/79	25/08/79
017I	Pelican (Gilbert F-53)	58-52-06	062-06-20	183	14/09/79 18/07/80	08/10/79 11/09/80
023A	Petrel (Cabot G-91)	59-50-00	061-45-00	91	01/08/76	28/08/76
023B	Petrel (Bjarni O-82)	55-31-47	057-42-34	144	30/07/79	20/10/79
090	Sedco J (Indian Harbour M-52)	54-22-00	054-24-00	198	27/09/76	12/10/76
018	Sedco 445 (Snorri J-90)	57-19-45	059-57-44	141	01/08/75	09/10/75
024	Zapata Ugland (Herjolf M-92)	55-31-00	057-45-00	73	30/08/76	20/11/76

* various periods

APPENDIX 1

Table A-7

Waverider buoy stations for Region 6, Davis Strait

ID	NAME	LOCATION		WATER DEPTH (M)	PERIOD OF OPERATION	
		LAT (N)	LONG (W)		START	END
138	Ben Ocean Lancer (Hekja)	62-11-08	062-58-17	360	22/07/79 25/07/80	10/08/79 05/10/80
023	Petrel (Ralegh N-18)	62-17-53	062-32-51	357	13/09/82	02/10/82

APPENDIX 2

EXAMPLES OF STORMSCAN OUTPUT AND REGIONAL STORM FILE

APPENDIX 2

Table A-8

Example of STORMSCAN output for SOWM point #153/9

```
GRID POINT 153     LATITUDE 53.5      LONGITUDE  45.9
STORM       START       FINISH     MAX-DATE       MAX-HT     MAX-PER     MAX-DIR     MEAN    DURATION       SSI
  1     100156  9   100156  9   100156  9        6.3        12          99        6.3        6         37.80
  2     270156 21   310156  3   290156  9       11.3        18          99        9.0       78        702.00
  3      10256  9    30256  9    20256 15        8.5        12          99        7.0       48        336.00
  4      50256  3    50256 21    50256  9        7.3        12          99        6.8       18        122.40
  5      60256 21    80256 15    80256  3        9.9        12          99        7.9       42        331.80
  6      90256 21   110256 21   100256  9        8.9        12          99        8.0       48        384.00
  7     170256 21   180256 21   180256  3        7.1        12          99        6.7       24        160.80
  8     210256  3   220256 15   210256 21        9.8        12          99        8.3       36        298.80
  9     270256  3   290256 21   270256 21        9.2        12          99        7.7       66        508.20
 10      10356 15    10356 21    10356 15        6.3        12          99        6.1        6         36.60
 11      80356 21   150356  9   110356 21       12.6        18          99        9.3      156       1450.80
 12     160356  3   190356  3   170356  3       11.6        16          99        8.4       72        604.80
 13     260356  3   270356  9   260356 15        7.9        12          99        6.7       30        201.00
 14     100556 15   110556 15   100556 21        7.1        12          99        6.7       24        160.80
 15     120556 15   120556 15   120556 15        6.2        12          99        6.2        6         37.20
 16      71056 15    71056 15    71056 15        6.5         5          99        6.5        6         39.00
 17     191056 21   211056  9   201056  9        7.6        12          99        6.8       36        244.80
 18      41156  3   101156  9    71156 21       11.3        16          99        8.2      150       1230.00
 19     161156 15   171156 21   161156 15        8.8        12          99        7.5       30        225.00
 20     181156 15   181156 15   181156 15        6.2        12          99        6.2        6         37.20
 21     201156 15   211156  3   201156 21        7.2        12          99        6.8       12         81.60
 22     221156 21   231156 15   231156  3        6.5        12          99        6.3       18        113.40
 23     281156 21   291156 21   281156 21        6.6        12          99        6.4       24        153.60
 24      61256  3   111256  3    91256 21       11.7        16          99        8.4      120       1008.00
 25     111256 21   161256 21   161256  3       11.7        16          99        8.7      120       1044.00
 26     181256  3   181256 21   181256  3        6.5        12          99        6.4       18        115.20
 27     191256 21   211256  3   201256  9       10.0        12          99        8.2       30        246.00
 28     231256 15   251256  3   241256  3        9.4        12          99        8.0       36        288.00
 29     271256 15   291256 15   281256 15        8.8        12          99        7.8       48        374.40
 30     301256 21   311256 21   311256 15        8.0        12          99        7.4       24        177.60
 31      10157  3    20157  3    10157  9        8.2        12          99        7.2       24        172.80
 32      30157  3    30157 15    40157 21       11.1        16          99        8.0      132       1056.00
 33      90157 15    90157 21    90157 21        6.5        12          99        6.4        6         38.40
 34     100157 15   100157 15   100157 15        6.1        12          99        6.1        6         36.60
 35     110157 21   120157 15   120157  3        8.3        12          99        7.5       18        135.00
 36     140157  9   150157  3   140157 15        6.9        12          99        6.4       18        115.20
 37     180157 15   280157  3   250157 15       22.8        23          99       10.7      228       2439.60
 38     290157  3    50257  3   300157  3       13.4        18          99       10.2      168       1713.60
 39      70257 15    80257  3    70257 21        6.5        12          99        6.2       12         74.40
 40      90257 15   100257 21   100257  9        8.3        12          99        7.1       30        213.00
 41     110257 15   140257  3   120257 15        9.0        12          99        7.5       60        450.00
 42     180257 15   180257 15   180257 15        6.0        12          99        6.0        6         36.00
 43     210257  9   230257 15   210257 21        9.8        12          99        8.2       54        442.80
 44     260257  9   260257 15   260257  9        6.6        12          99        6.5        6         39.00
 45     270357 15   300357 21   280357  3        8.6        12          99        7.1       78        553.80
 46      80457  9    90457  3    80457  9        6.6        12          99        6.6       18        118.80
 47     110457 15   110457 15   110457 15        6.1        11          99        6.1        6         36.60
 48     150457 15   160457 21   150457 21        8.8        12          99        8.1       30        243.00
 49     190457 15   200457 15   200457  3        7.4        12          99        6.7       24        160.80
 50     230457 15   240457  3   230457 21        7.4        12          99        7.0       12         84.00
 51     260457 21   270457  9   260457 21        6.2        12          99        6.1       12         73.20
 52      20557  9    40557 21    20557 15        8.3        12          99        7.4       60        444.00
 53     100857  9   100857  9   100857  9        6.0         9          99        6.0        6         36.00
 54     210957 21   220957  3   210957 21        6.1        12          99        6.0        6         36.00
 55      61057 21    81057  9    71057 21        7.5        12          99        6.7       36        241.20
 56     141057  3   151057 21   151057  3        8.2        12          99        7.0       42        294.00
 57     301057 21   311057 15   301057 21        8.8        12          99        8.0       18        144.00
 58      91157  3    91157  9    91157  9        6.4        12          99        6.3        6         37.80
 59     181157 15   191157  3   181157 15        6.7        12          99        6.5       12         78.00
```

APPENDIX 2

Table A-9

Example of regional storm file ranked by maximum height of storm waves

GRID#	STORM#	START	FINISH	MAX-DATE	MAX-HT	MAX-PER	MAX-DIR	MEAN	DURATION	SSI
20W1	224	150266 12	200266 18	160266 18	16.6	16	10	10.5	126	1323.00
279	343	220267 9	240267 3	230267 9	16.5	18	99	12.9	42	541.80
279	87	70259 15	110259 21	80259 15	16.1	18	99	10.7	102	1091.40
279	317	150266 9	200266 21	170266 9	15.9	20	99	10.8	132	1425.60
279	147	210161 9	240161 3	220161 3	15.7	18	99	10.1	66	666.60
278	133	210161 3	220161 15	220161 3	15.6	18	99	11.3	36	406.80
279	565	280374 15	310374 9	290374 9	15.2	18	99	10.7	66	706.20
279	11	150356 21	190356 3	160356 15	15.2	18	99	9.8	78	764.40
279	557	60374 3	130374 21	120374 9	15.1	18	99	10.1	186	1878.60
268	211	140364 15	190364 3	180364 3	15.1	18	99	10.7	108	1155.60
279	540	30174 9	70174 21	40174 15	15.0	20	99	11.4	108	1231.20
278	328	220267 3	240267 3	230267 3	14.9	18	99	10.7	48	513.60
279	171	161261 21	191261 9	171261 15	14.9	18	99	11.3	60	678.00
278	546	50374 3	130374 21	120374 9	14.8	18	99	8.8	210	1848.00
268	468	50374 21	130374 9	120374 9	14.6	18	99	8.9	180	1602.00
268	263	150266 9	200266 9	170266 9	14.5	18	99	10.8	120	1296.00
24W1	243	200169 18	230169 12	220169 0	14.5	15	7	10.2	66	673.20
278	155	161261 15	191261 9	181261 3	14.3	18	99	11.3	66	745.80
287	191	260166 15	280166 21	280166 21	14.2	16	99	9.2	54	496.80
278	86	70259 15	110259 15	80259 9	14.2	18	99	9.3	96	892.80
278	551	280374 9	310374 3	280374 21	14.2	18	99	10.6	66	699.60
20W1	186	170364 0	190364 12	180364 6	14.2	14	7	9.7	60	582.00
279	318	220266 15	250266 21	240266 15	14.1	18	99	10.1	78	787.80
287	192	290166 15	10266 3	290166 15	14.1	18	99	8.6	60	516.00
279	502	121272 3	201272 15	161272 15	14.1	20	99	9.8	204	1999.20
0W1	225	220266 18	260266 18	240266 18	14.1	15	3	10.0	96	960.00
279	128	200360 3	220360 15	210360 3	14.0	18	99	10.5	60	630.00
267	441	110374 9	130374 9	120374 9	13.9	18	99	9.6	48	460.80
24W1	145	170264 12	200264 6	190264 6	13.9	12	6	9.9	66	653.40
278	295	150266 9	190266 21	170266 9	13.8	18	99	10.6	108	1144.80
24W1	147	10364 6	20364 6	10364 18	13.8	14	3	10.4	24	249.60
279	238	120164 15	170164 21	160164 3	13.7	16	99	10.2	126	1285.20
279	433	170171 3	190171 15	170171 21	13.6	18	99	10.2	60	612.00
24W1	176	90166 18	120166 0	100166 12	13.6	11	11	9.5	54	513.00
268	402	180472 21	210472 9	200472 9	13.6	18	99	9.6	60	576.00
279	455	10172 21	100172 9	20172 15	13.5	18	99	9.7	204	1978.80
20W1	172	120164 6	140164 12	140164 0	13.5	13	5	10.0	54	540.00
278	417	170171 3	190171 3	170171 21	13.5	16	99	10.5	48	504.00
279	252	140364 15	190364 9	170364 15	13.4	18	99	10.0	114	1140.00
268	285	220267 9	240267 3	230267 3	13.3	18	99	10.6	42	445.20
267	255	220267 3	240267 3	220267 21	13.2	16	99	9.8	48	470.40
20W1	120	161261 12	201261 18	171261 6	13.2	14	7	9.1	102	928.20
287	93	210161 3	220161 9	220161 3	13.1	16	99	9.3	30	279.00
268	137	161261 15	191261 9	171261 15	13.1	18	99	10.3	66	679.80
268	471	280374 15	310374 3	290374 9	13.0	18	99	11.1	60	666.00
277	255	170267 3	180267 3	170267 9	13.0	11	99	9.5	24	228.00
277	256	220267 3	230267 15	220267 21	12.9	18	99	10.2	36	367.20
278	232	140364 15	180364 21	180364 3	12.9	16	99	9.5	102	969.00
267	382	180472 15	200472 21	190472 21	12.8	18	99	9.2	54	496.80
266	322	180472 15	200472 15	190472 21	12.8	18	99	9.7	48	465.60
266	1	80156 15	110156 3	80156 21	12.8	18	99	9.4	60	564.00
279	504	281272 9	301272 9	291272 3	12.8	16	99	9.2	48	441.60
279	32	220157 3	280157 3	260157 3	12.8	20	99	8.8	144	1267.20
268	71	70259 15	120259 3	80259 15	12.7	18	99	8.9	108	961.20
277	97	210161 3	220161 15	210161 21	12.7	16	99	9.8	36	352.80
24W1	110	250262 18	280262 0	260262 18	12.7	14	3	10.3	54	556.20
279	342	120267 3	210267 9	180267 3	12.6	12	99	8.6	222	1909.20
278	254	180265 9	190265 21	190265 9	12.6	18	99	10.0	36	360.00
24W1	247	60369 12	100369 12	90369 12	12.6	14	9	8.6	96	825.60
267	446	280374 9	300374 15	280374 21	12.6	16	99	9.7	54	523.80
24W1	98	91261 18	131261 6	101261 6	12.6	14	6	8.3	84	697.20

APPENDIX 3

DIGITAL STORM DATA BASE

DIGITAL STORM DATA BASE

Following the ranking process for selection of the final set of storms for each region, a detailed meteorological summary was compiled for each storm. These summaries were used for developing the storm climatology. Rather than present all these summaries in written format (more than 200 typed pages), it was decided to develop a digital storm data base which could be used for a variety of analysis and display purposes.

It was not possible to follow all storms from genesis to decay in the data base as many storm histories included multiple redevelopments and/or merging with other low-pressure systems. Therefore, the storm information given in the data base represents the track of the storm from its last position of significant redevelopment, or the track of the dominant low-pressure system where lows joined.

An example of the data base format is shown in Table A-10. Each record can be read with an unformatted read statement of the form:

```
READ(LU,*)IDATE,SLAT,SLON,PPP,IPEN,(IREG(I),
     WMAX(I),IRANK(I),I=1,3),ICON

IF (ICON.EQ.7) THEN
     READ (LU,*)(IREG(I),WMAX(I),IRANK(I),I=1,2)
END IF
```

where LU = Tape drive logical unit number

IDATE = Storm data (GMT) in YYMMDDHH format

SLAT = Latitude of storm centre

SLON = Longitude of storm centre

APPENDIX 3

Table A-10

Format of Digital Storm Data Base

IDATE	SLAT	SLON	PPP	IPEN	IREGION	WMAX	IRANK	IREGION	WMAX	IRANK	IREGION	WMAX	IRANK	ICON
59011912	63.	81.	968.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59020612	37.	65.	1015.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
59020712	48.	48.	968.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59020812	55.	46.	933.	1	3	18.3	5	4	19.8	4	0	0.0	0	9
59020912	57.	46.	958.	1	5	21.3	1	0	0.0	0	0	0.0	0	9
59021012	61.	42.	975.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59041212	33.	85.	1012.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
59041312	37.	69.	1004.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59041412	36.	69.	993.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59041512	39.	59.	965.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59041612	44.	48.	963.	1	3	21.3	1	0	0.0	0	0	0.0	0	9
59041712	50.	40.	969.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59110112	46.	64.	998.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
59110212	54.	63.	974.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59110312	62.	60.	968.	1	7	4.0	31	0	0.0	0	0	0.0	0	9
59110412	72.	68.	984.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59112412	42.	87.	995.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
59112512	48.	75.	983.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
59112612	55.	62.	962.	1	1	8.5	30	0	0.0	0	0	0.0	0	9
59112712	62.	55.	964	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60010912	39.	43.	994.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
60011012	45.	41.	953.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60011112	50.	48.	958.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60011212	49.	51.	973.	1	4	12.8	26	0	0.0	0	0	0.0	0	9
60011312	46.	53.	989.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60011212	42.	43.	989.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
60011312	54.	48.	984.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60011412	52.	59.	990.	1	5	14.6	28	0	0.0	0	0	0.0	0	9
60031712	26.	87.	1004.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
60031812	32.	78.	1003.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60031912	42.	62.	988.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60032012	52.	44.	962.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60032112	55.	40.	959.	1	4	13.7	17	0	0.0	0	0	0.0	0	9
60032212	57.	41.	963.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60102312	58.	125.	989.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
60102412	63.	112.	988.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60102512	66.	96.	993.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60102612	67.	89.	994.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
60102712	71.	93.	994.	1	7	5.5	12	0	0.0	0	0	0.0	0	9
60102812	71.	80.	992.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61011812	39.	99.	1013.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
61011912	37.	87.	1004.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61012012	39.	69.	973.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61012112	48.	55.	963.	1	3	12.8	21	4	21.3	2	0	0.0	0	9
61012212	56.	48.	968.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120312	40.	60.	1014.	0	0	0.0	0	0	0.0	0	0	0.0	0	9
61120412	38.	51.	1003.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120512	42.	44.	978.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120612	45.	41.	969.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120712	50.	33.	968.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120812	48.	36.	974.	1	0	0.0	0	0	0.0	0	0	0.0	0	9
61120912	46.	49.	974.	1	3	12.2	22	0	0.0	0	0	0.0	0	9
61121012	44.	38.	979.	1	0	0.0	0	0	0.0	0	0	0.0	0	9

PPP = Storm central pressure (mb)

IPEN = Identifier for new storms (used for plotting tracks). 0 = first record

IREG = Region that the severe wave event occurred in (position in storm file indicates date of severe event)

WMAX = Maximum storm significant wave height (meters) determined from synoptic charts and Bretschneider nomogram

IRANK = Storm regional ranking based on WMAX

ICON = Record continuation flag used for one storm where the number of regional storm events exceeds the record length for one day.

The last record in the database is an end-of-file marker.

A FORTRAN program 'STORMMAP' was written to use the digital data base. STORMMAP was designed to plot storm tracks based on user-selected criteria. These include:

- Region
- Month
- Maximum storm significant wave height
- Storm rank
- Storm central pressure.

This software allows the user to select storm tracks for plotting: for example, the plotting of the top 10 ranked storms in Region 1.

Software was also developed to determine storm deepening rates using the storm data base. This program adjusts deepening rates to a reference latitude of 60°N.

APPENDIX 4

STORM SUMMARY DATA BY REGION

APPENDIX 4

STORM SUMMARY DATA BY REGION

For each region the following notes and tables are given:

1. Storm track description and frequency.
2. Storm type summary.
3. Storm statistical summary.
4. Wind direction quadrants.

Notes for Tables A-11,A-14,A-17,A-20,A-23,A-26,A-29

Storm Type Summary. $\pm$ PPP indicates central pressure at time of event, and whether or not the pressure rose or fell in the following 24 hours. An L in parentheses indicates storm central pressure was at lowest point at the time of the event. ΔP_{max} is the maximum adjusted 24-hour deepening rate of the storm over the entire period the storm was tracked while ΔP_{event} is the adjusted 24-hour deepening rate prior to the maximum wave event. Deepening rates were adjusted to a reference latitude of 60^{o}N following the method outlined by Sanders and Gyakum (1980).

Notes for Tables A-12, A-15, A-18, A-21, A-24, A-27, A-30

Storm Statistical Summary. Frequencies of storm variables by storm type for all storms, and for the top ten storms based on rank. Storm position at event time indicates which region storm was within or nearest to at the time of the severe wave. Under Pressure Characteristics, A indicates storm wave event occurred at end of 24-hour maximum deepening period, and B indicates 24-hour maximum deepening occurred prior to the wave event. The sub-headings D, L, and F indicate that the low continued to deepen, was at its lowest pressure, and was beginning to fill, respectively, at the time of the wave event. The first column under Pressure Characteristics refers to all storms within that section, while the second column pertains to explosive cyclones alone (adjusted 24-hour deepening rate $\geq$-24 mb).

REGION 1: Gulf of St. Lawrence

Storm Track Description and Frequency

25% I. Storm originates to lee of Canadian Rockies (Alberta), tracks SE near international border and across the Great Lakes and

16% a) continues NE down the St. Lawrence River Valley and towards Labrador (9%) or Newfoundland (6%).

9% b) redevelops off the east coast near Cape Hatteras/Delmarva (6%) or New England (3%) and tracks NE towards Nova Scotia and Newfoundland.

25% II. Storm develops off the east coast near

16% a) Cape Hatteras/Delmarva and tracks NE across Gulf of St. Lawrence (9%) or Newfoundland (6%).

9% b) New England and tracks NE across Nova Scotia and Newfoundland.

22% III. Storm develops in Gulf of Mexico, tracks NE along east coast towards Gulf of St. Lawrence (6%) or Newfoundland (16%).

16% IV. Storm originates to lee of American Rockies (near Colorado) and

13% a) tracks east towards Cape Hatteras/Delmarva, and continues NE off the east coast towards Nova Scotia and Newfoundland.

3% b) tracks NE across the Great Lakes and down the St. Lawrence Valley towards Labrador.

REGION 1: Gulf of St. Lawrence (Cont'd)

13%	V.	Other	
6%		a)	Storm becomes organized over or near Great Lakes and tracks NE down the St. Lawrence (3%) or forms redevelopment off east coast near Cape Hatteras (3%).
3%		b)	Storm organizes to lee of northern Canadian Rockies and tracks across northern prairies/Hudson Bay towards Labrador.
3%		c)	Storm organizes from extratropical remnants of tropical storm/hurricane and tracks NE towards Newfoundland.

Note: About 75% of storms eventually took coastal route.

Table A-11

Region 1: Storm Type Summary.

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
MAR 2/49	22	Ib	973(L)	-20.4	-12.8
FEB 20/52	23	III	+984	-32.3	0.0
MAR 3/52	11	IVa	+990	-15.0	+14.8
NOV 13/52	11	IIa	967(L)	-22.2	-22.2
NOV 19/52	18	III	+980	-34.7	+15.1
JAN 29/54	30	IIb	-984	-19.4	-11.4
JAN 5/55	3	IVa	+969	-58.4	+10.6
SEP 21/55	11	Vc	964(L)	-27.2	-27.2
JAN 8/56	11	IIa	+990	-46.7	- 4.5
NOV 26/59	30	IVb	962(L)	-23.2	-23.2
DEC 17/61	9	IIb	953(L)	-41.6	-12.9
JAN 28/62	23	Vb	-963	-11.4	- 9.3
FEB 10/63	2	III	+972	-22.3	+ 4.4
APR 9/63	10	III	978(L)	-24.8	- 5.1
JAN 28/66	11	III	962(L)	-28.7	-21.3
JAN 6/68	3	IIa	+967	-67.3	+ 4.5
DEC 6/70	25	Ib	966(L)	-29.4	- 4.5
JAN 27/72	19	Ia	952(L)	-26.7	- 6.2
FEB 20/72	25	Ib	-968	-19.8	-19.8
APR 10/72	25	Va2	+987	-14.8	+ 4.7
SEP 11/72	25	Ia	984(L)	-20.9	-12.1
DEC 2/72	3	IIa	-964	-49.1	-49.1
FEB 2/74	3	Ia	948(L)	-25.7	-25.7

Table A-11 (continued)

Region 1: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
FEB 6/74	3	IVa	968(L)	-27.2	-27.2
FEB 18/74	19	IVa	964(L)	-44.9	-27.5
MAR 29/74	11	Ia	959(L)	-29.6	-22.0
MAY 3/74	25	Va1	983(L)	-21.3	- 6.8
OCT 21/74	3	IIa	980(L)	-21.8	-21.8
FEB 3/76	11	III	-953	-43.6	-43.6
DEC 8/77	30	IIb	-969	-10.9	-10.9
JAN 16/82	19	III	954(L)	-43.2	-43.2
JAN 19/82	1	Ia	954(L)	-21.6	-21.6

Table A-12

Region 1: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
ALL STORMS	I	16	9	R1	0	0	A	D	0	0	A	D	3	0
				R2	0	6	6	L	6	3	3	L	0	0
				R3	3	0	B	D	0	0	B	D	0	0
				R4	3	0	9	L	9	6	6	L	6	3
				R5	9	3		F	0	0		F	0	0
	II	16	9	R1	6	0	A	D	3	3	A	D	3	0
				R2	3	0	9	L	6	0	3	L	0	0
				R3	0	6	B	D	0	0	B	D	3	0
				R4	6	3	6	L	0	0	6	L	3	3
				R5	0	0		F	6	6		F	0	0
	III	22		R1	3		A	D	3	3				
				R2	9		6	L	3	3				
				R3	0		B	D	0	0				
				R4	3		16	L	6	6				
				R5	6			F	9	6				
	IV	13	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	6	0	3	L	3	3	3	L	3	0
				R3	6	0	B	D	0	0	B	D	0	0
				R4	0	0	9	L	3	3	0	L	0	0
				R5	0	3		F	6	3		F	0	0
	V	13		R1	0		A	D	0	0				
				R2	3		3	L	3	3				
				R3	3		B	D	3	0				
				R4	3		9	L	3	0				
				R5	3			F	3	0				
GRAND TOTAL	I-V	100		R1	9		A	D	13	6				
				R2	28		37	L	25	13				
				R3	19		B	D	6	0				
				R4	19		63	L	31	22				
				R5	25			F	25	16				

Table A-12 (continued)

Region 1: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
TOP TEN	I	6	0	R1	0	0	A	D	0	0				
				R2	0	0	6	L	6	3				
				R3	0	0	B	D	0	0				
				R4	0	0	0	L	0	0				
				R5	6	0		F	0	0				
	II	9	3	R1	6	0	A	D	3	3	A	D	0	0
				R2	0	0	6	L	3	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	3	3	3	L	0	0	3	L	3	3
				R5	0	0		F	3	3		F	0	0
	III	6		R1	3		A	D	0	0				
				R2	0		0	L	0	0				
				R3	0		B	D	0	0				
				R4	0		6	L	3	3				
				R5	3			F	3	0				
	IV	6	0	R1	0	0	A	D	0	0				
				R2	3	0	3	L	3	3				
				R3	3	0	B	D	0	0				
				R4	0	0	3	L	0	0				
				R5	0	0		F	3	3				
	V													
TOP TEN TOTAL	I-V		31	R1	9		A	D	3	3				
				R2	3		16	L	13	6				
				R3	3		B	D	0	0				
				R4	6		16	L	6	6				
				R5	9			F	9	6				

Table A-13

Wind direction quadrants, Region 1.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS			REGION: 1	
		NE	NW	SE	SW	Variable
1 - 2	2	0.5	1		0.5	
3 - 5	6	1	3.5		1.5	
6 - 10	2		2			
11 - 15	7	2	3		1	1
16 - 20	4	2	2			
>20	11	5	5	0.5	0.5	
Totals		10.5	16.5	0.5	3.5	1

REGION 2: Scotian Shelf

Storm Track Description and Frequency

29% I. Storm develops in Gulf of Mexico, tracks NE along coast towards Nova Scotia and Newfoundland (13%) or farther out to sea (16%).

26% II. Storm develops off the east coast near

- 13% a) Cape Hatteras and tracks NE towards Nova Scotia and Newfoundland (6%) or farther out to sea (6%).
- 13% b) Delmarva and tracks NE towards Newfoundland.

26% III. Storm originates to lee of American Rockies (near Colorado) and

- 23% a) tracks east towards Cape Hatteras/Delmarva and continues NE towards Nova Scotia/Newfoundland (6%) or farther out the sea (16%).
- 3% b) tracks NE across the Lower Great Lakes and sparks a redevelopment off Cape Hatteras/Delmarva which proceeds towards the NE.

10% IV. Storm originates to lee of Canadian Rockies (Alberta), tracks SE across the international border towards the Great Lakes and

- 6% a) continues down the St. Lawrence River Valley or across Northern New England towards Nova Scotia/Newfoundland.
- 3% b) continues SE towards the Delmarva region, and then NE towards Newfoundland or out to sea.

REGION 2: Scotian Shelf (Cont'd)

10% V. Other

6% a) Storm becomes organized over or near Great Lakes and tracks down the St. Lawrence River Valley or across Northern New England towards Nova Scotia/Newfoundland or forms redevelopment off east coast near Cape Hatteras/Delmarva.

3% b) Storm organizes from extratropical remnants of tropical storm/hurricane and tracks NE towards Newfoundland.

Note: About 90% of storms eventually took coastal route.

Table A-14

Region 2: Storm Type Summary.

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
APR 5/49	22	I	-982	-20.9	-14.8
MAR 3/51	15	Va	-994	-18.1	-18.1
FEB 18/52	22	I	975(L)	-32.3	-32.3
DEC 1/52	21	IIa	-993	-32.0	-32.0
DEC 3/53	15	IIb	+984	-48.0	+ 7.7
JAN 4/55	5	IIIa	961(L)	-58.4	-15.0
JAN 14/55	5	IVb	947(L)	-71.0	-71.0
SEP 21/55	22	Vb	964(L)	-27.2	-27.2
JAN 9/56	10	IIa	-979	-16.6	-16.6
MAR 29/58	11	IIIa	-989	-12.7	0.0
APR 2/58	1	IIIa	978(L)	-17.5	-13.6
MAR 8/62	4	I	978(L)	-19.1	- 1.5
MAR 23/62	1	IIIa	973(L)	-19.5	-19.5
MAR 24/64	11	I	972(L)	-16.5	-16.5
JAN 29/66	15	I	+974	-28.7	+14.8
FEB 23/67	22	IVa	+966	-49.3	+13.2
APR 29/67	5	IIIa	+986	-29.5	+10.9
JAN 6/68	11	IIa	+967	-67.3	+ 4.5
FEB 19/69	30	I	979(L)	-22.4	-22.4
NOV 15/71	22	IIb	-988	-21.8	-21.8
JAN 4/72	22	IIIb	962(L)	-40.6	-17.8
FEB 12/73	15	I	+994	-24.2	+ 9.2
MAR 24/73	5	IIIa	974(L)	-19.4	- 7.0

Table A-14 (continued)

Region 2: Storm Type Summary.

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
NOV 2/73	30	IIa	971(L)	-25.6	- 3.6
FEB 6/74	15	IIIa	968(L)	-27.2	-27.2
MAR 12/74	5	Va	944(L)	-37.0	-36.4
MAR 29/74	3	IVa	959(L)	-29.6	-22.0
DEC 23/75	22	IIb	988(L)	-19.3	-19.3
MAR 8/81	22	IIb	962(L)	-21.8	- 1.4
JAN 16/82	11	I	954(L)	-43.2	-43.2
FEB 14/82	20	I	-984	(-36.1)	-35.4

Table A-15

Region 2: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)							(b)
ALL STORMS	I	29		R1	0		A	D	3	3				
				R2	23		16	L	13	6				
				R3	3		B	D	3	0				
				R4	3		13	L	3	0				
				R5	0			F	6	6				
	II	13	13	R1	3	0	A	D	6	3	A	D	3	0
				R2	6	6	6	L	0	0	6	L	3	0
				R3	0	6	B	D	0	0	B	D	0	0
				R4	3	0	6	L	3	3	6	L	3	0
				R5	0	0		F	3	3		F	3	3
	III	23	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	19	0	6	L	6	3	0	L	0	0
				R3	3	3	B	D	3	0	B	D	0	0
				R4	0	0	16	L	10	3	3	L	3	3
				R5	0	0		F	3	3		F	0	0
	IV	6	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	3	0	L	0	0	3	L	3	3
				R3	0	0	B	D	0	0	B	D	0	0
				R4	6	0	6	L	3	3	0	L	0	0
				R5	0	0		F	3	3		F	0	0
	V	6	3	R1	0	0	A	D	3	0	A	D	0	0
				R2	3	3	3	L	0	0	3	L	3	3
				R3	3	0	B	D	0	0	B	D	0	0
				R4	0	0	3	L	3	3	0	L	0	0
				R5	0	0		F	0	0		F	0	0
GRAND TOTAL	I-V		100	R1	3		A	D	16	6				
				R2	65		45	L	29	16				
				R3	19		B	D	6	0				
				R4	13		55	L	29	16				
				R5	0			F	19	19				

Table A-15 (continued)

Region 2: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
Top Ten	I	3		R1	0		A	D	0	0				
				R2	3		0	L	0	0				
				R3	0		B	D	0	0				
				R4	0		3	L	3	0				
				R5	0			F	0	0				
	II	3	0	R1	0	0	A	D	3	0				
				R2	3	0	3	L	0	0				
				R3	0	0	B	D	0	0				
				R4	0	0	0	L	0	0				
				R5	0	0		F	0	0				
	III	16	0	R1	0	0	A	D	0	0				
				R2	13	0	3	L	3	0				
				R3	3	0	B	D	0	0				
				R4	0	0	13	L	10	3				
				R5	0	0		F	3	3				
	IV	3	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	3	0	L	0	0	3	L	3	3
				R3	0	0	B	D	0	0	B	D	0	0
				R4	3	0	3	L	3	3	0	L	0	0
				R5	0	0		F	0	0		F	0	0
	V	3	0	R1	0	0	A	D	0	0				
				R2	0	0	0	L	0	0				
				R3	3	0	B	D	0	0				
				R4	0	0	3	L	3	3				
				R5	0	0		F	0	0				
Top Ten Total	I-V		32	R1	0		A	D	3	0				
				R2	23		10	L	6	3				
				R3	6		B	D	0	0				
				R4	3		23	L	19	10				
				R5	0			F	3	3				

Table A-16

Wind direction quadrants, Region 2.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS			REGION: 2	
		NE	NW	SE	SW	Variable
1 - 2	2	1.5	0.5			
3 - 5	7	5	2			
6 - 10	1	1				
11 - 15	9	4	4.5		0.5	
16 - 20	1		0.5		0.5	
> 20	11	4.5	4.5		1	1
Totals		16	12		2	1

REGION 3: Grand Banks

Storm Track Description and Frequency

26% I. Storm organizes to lee of American Rockies (near Colorado) and

9% a) tracks east towards Cape Hatteras/Delmarva, and continues NE towards Nova Scotia and Newfoundland.

17% b) tracks NE across the lower Great Lakes and continues down the St. Lawrence River Valley towards Newfoundland/Labrador (3%) or sparks a redevelopment off the east coast (15%) which then proceeds NE towards Newfoundland (9%) or farther out to sea (6%).

21% II. Storm organizes to lee of Canadian Rockies (Alberta), tracks SE across the international border towards the Great Lakes and

15% a) continues down the St. Lawrence River Valley or across Northern New England towards Labrador/Newfoundland.

6% b) sparks a redevelopment off Cape Hatteras/Delmarva which proceeds NE towards Nova Scotia/Newfoundland.

21% III. Storm develops off the east coast near

15% a) Cape Hatteras/Delmarva and tracks NE towards Nova Scotia/Newfoundland (3%) or farther out to sea (12%).

6% b) New England and tracks NE across Nova Scotia/Newfoundland.

REGION 3: Grand Banks (Cont'd)

17% IV. Storm develops in Gulf of Mexico, tracks NE along coast towards Newfoundland (6%) or farther out to sea (12%).

15% V. Other

9% a) Storm becomes organized over/near Great Lakes and tracks east across New England to Nova Scotia/Newfoundland (6%) or spawns secondary development off Cape Hatteras/Delmarva (3%) which proceeds NE.

3% b) Storm develops in Yukon, tracks across northern prairies, Hudson Bay, and Quebec to Labrador.

3% c) Storm develops in Gulf of Mexico, tracks west of Appalachians and down St. Lawrence River Valley to Newfoundland/Labrador.

Note: About 70% of storms eventually took coastal route.

Table A-17

Region 3: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
DEC 14/51	15	IIIa	-988	-43.3	-12.6
MAR 16/56	15	Va	949(L)	-30.3	-30.3
JAN 24/57	22	IIa	-963	-34.8	-34.8
FEB 9/57	22	Vb	968(L)	-26.4	0.0
DEC 6/57	11	Ia	-989	-26.1	+ 6.1
FEB 8/59	5	IIb	933(L)	-60.2	-38.7
APR 16/59	1	IV	963(L)	-39.8	- 2.6
JAN 21/61	21	Ia	963(L)	-43.6	-12.6
DEC 9/61	22	IIa	+974	-19.5	0.0
DEC 17/61	1	IIIb	953(L)	-41.6	-12.9
FEB 27/62	22	Ib	-978	-23.1	+ 5.1
JAN 11/64	22	Ib	958(L)	-48.6	-48.6
MAR 1/64	15	IV	966(L)	-37.7	-20.3
MAR 15/64	22	IV	961(L)	-49.2	- 5.1
JAN 26/65	22	Ib	977(L)	-19.2	- 6.3
FEB 19/65	15	IV	962(L)	-23.7	- 4.5
JAN 10/66	22	Va	958(L)	-41.9	-15.5
FEB 17/66	3	Vc	+966	-25.8	+ 1.1
FEB 17/67	5	IIa	-967	-22.0	-22.0
FEB 23/67	7	IIa	+966	-49.3	+13.2
JAN 5/68	15	IIIa	963(L)	-67.3	-67.3
JAN 22/70	7	IIIa	954(L)	-35.2	-35.2
JAN 17/71	13	IIIa	-953	-52.3	-52.3

Table A-17 (continued)

Region 3: Storm Type Summary.

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
JAN 5/72	22	Ib	962(L)	-40.6	0.0
FEB 20/72	22	IIb	-968	-19.8	-19.8
DEC 15/72	22	Ib	944(L)	-47.8	-47.8
DEC 29/72	22	Ia	-964	-27.5	-27.5
JAN 20/74	10	Ib	-993	(-28.4)	-23.9
MAR 11/74	20	Va	-974	-37.0	-37.0
MAR 29/74	11	IIa	959(L)	-29.6	-22.0
MAR 4/78	13	IIIa	954(L)	-44.0	-12.1
MAR 8/81	22	IIIb	962(L)	-21.8	- 1.4
JAN 17/82	4	IV	+963	-43.2	+10.1
FEB 15/82	7	IV	954(L)	-36.1	-36.1

Table A-18

Region 3: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
ALL STORMS	I	9	17	R1	0	3	A	D	3	3	A	D	3	3
				R2	0	3	3	L	0	0	9	L	6	6
				R3	6	6	B	D	3	3	B	D	3	0
				R4	3	3	6	L	3	3	9	L	6	3
				R5	0	3		F	0	0		F	0	0
	II	15	6	R1	0	0	A	D	6	3	A	D	3	0
				R2	0	3	6	L	0	0	3	L	0	0
				R3	6	0	B	D	0	0	B	D	0	0
				R4	9	0	9	L	3	3	3	L	3	3
				R5	0	3		F	6	3		F	0	0
	III	15	6	R1	3	0	A	D	3	3	A	D	0	0
				R2	0	0	9	L	6	6	0	L	0	0
				R3	12	3	B	D	3	3	B	D	0	0
				R4	0	3	6	L	3	3	6	L	6	3
				R5	0	0		F	0	0		F	0	0
	IV	17		R1	0	0	A	D	0	0				
				R2	0	0	3	L	3	3				
				R3	9	0	B	D	0	0				
				R4	9	0	15	L	12	9				
				R5	0	0		F	3	3				
	V	15		R1	0		A	D	3	3				
				R2	3		6	L	3	3				
				R3	3		B	D	0	0				
				R4	6		9	L	6	6				
				R5	3			F	3	3				
GRAND TOTAL	I-V		100	R1	6		A	D	21	15				
				R2	9		37	L	17	17				
				R3	44		B	D	9	6				
				R4	32		63	L	41	32				
				R5	9			F	12	9				

Table A-18 (continued)

Region 3: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
TOP TEN	I	0	3	R1	0	0	A	D	0	0	A	D	3	3
				R2	0	3	0	L	0	0	3	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	0	0	0	L	0	0	0	L	0	0
				R5	0	0		F	0	0		F	0	0
	II	6	3	R1	0	0	A	D	3	0	A	D	0	0
				R2	0	0	3	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	6	0	3	L	0	0	3	L	3	3
				R5	0	3		F	3	3		F	0	0
	III	3	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	3	L	3	3	0	L	0	0
				R3	3	0	B	D	0	0	B	D	0	0
				R4	0	3	0	L	0	0	3	L	3	3
				R5	0	0		F	0	0		F	0	0
	IV	9		R1	0		A	D	0	0				
				R2	0		3	L	3	3				
				R3	3		B	D	0	0				
				R4	6		6	L	3	3				
				R5	0			F	3	3				
	V	3		R1	0		A	D	0	0				
				R2	0		0	L	0	0				
				R3	0		B	D	0	0				
				R4	3		3	L	0	0				
				R5	0			F	3	3				
TOP TEN TOTAL	I-V		29	R1	0		A	D	6	3				
				R2	3		12	L	6	6				
				R3	6		B	D	0	0				
				R4	17		17	L	9	9				
				R5	3			F	9	9				

Table A-19

Wind direction quadrants, Region 3.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS				REGION: 3
		NE	NW	SE	SW	Variable
1 - 2	2		1		1	
3 - 5	4		3.5		0.5	
6 - 10	4		2		1	1
11 - 15	9	1	7			1
16 - 20	1	0.5	0.5			
>20	14	2.5	5	1	1.5	4
Totals		4	19	1	4	6

REGION 4: Northeast Newfoundland Shelf

Storm Track Description and Frequency

27% I. Storm organizes to lee of Canadian Rockies (Alberta), tracks towards the Great Lakes and

17% a) continues down the St. Lawrence River Valley across Labrador towards the Labrador Sea.

10% b) sparks a redevelopment off the east coast which proceeds NE across Newfoundland towards the Labrador Sea.

23% II. Storm organizes to lee of American Rockies (near Colorado) and

20% a) tracks east towards Cape Hatteras/Delmarva, redevelops (7%) and/or tracks NE across Newfoundland towards the Labrador Sea (7%), meanders NE to SE of Newfoundland (7%), or continues south of Greenland (7%).

3% b) tracks NE across the lower Great Lakes, James Bay/Quebec towards Labrador/Labrador Sea.

13% III. Storm develops in Gulf of Mexico, and

10% a) tracks NE along the coast towards the east of Newfoundland.

3% b) tracks west of Appalachians and down St. Lawrence River Valley to Labrador/Labrador Sea.

REGION 4: Northeast Newfoundland Shelf (Cont'd)

13% IV. Storm develops off the east coast near

3% a) Cape Hatteras/Delmarva and tracks NE towards Nova Scotia/Newfoundland to the Labrador Sea.

10% b) New England and tracks towards Nova Scotia, cutting off and meandering NE to SE of Newfoundland.

23% V. Other

10% a) Storm becomes organized over/near Great Lakes and tracks east across New England to Nova Scotia/Newfoundland and south of Greenland (3%) or spawns secondary development off Cape Hatteras/Delmarva and proceeds SE and east of Newfoundland (7%).

3% b) Storm develops in N.W.T. and tracks east across Hudson Bay, Quebec, Labrador passing to the south of Greenland.

3% c) Storm organizes from extratropical remnants of tropical storm/hurricane and tracks NE to southeast and east of Newfoundland.

3% d) Storm organizes in NW Ontario/James Bay and tracks east across Quebec/Gulf of St. Lawrence to the south of Greenland.

3% e) Storm organizes well out to sea, cuts off, and recurves NW, meandering to the east and south of Newfoundland.

Note: About 60% of storms eventually took coastal/ocean route.

Table A-20

Region 4: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
JAN 15/46	17	Ia	959(L)	-23.3	-16.0
OCT 23/47	10	Vc	958(L)	-36.2	-11.1
FEB 1/50	17	IIb	944(L)	-16.2	-14.1
JAN 23/55	10	IIIa	965(SL)	-32.5	-10.0
MAR 16/56	10	Va	949(L)	-30.3	-30.3
FEB 10/57	5	IVb	963(SL)	-26.7	-15.7
MAR 5/58	26	IVb	978(L)	-26.7	-26.7
FEB 8/59	4	Ib	933(L)	-60.2	-38.7
JAN 12/60	26	Ve	+973	-53.1	+17.1
MAR 21/60	17	IIIa	959(L)	-30.8	- 3.2
JAN 21/61	2	IIa	963(L)	-43.6	-12.6
DEC 17/61	2	IVb	953(L)	-41.6	-12.9
MAR 3/62	16	IIa	+983	-23.1	+ 7.5
FEB 16/64	10	Va	964(L)	-27.7	-27.7
FEB 22/65	9	Ib	+990	-39.2	+22.6
JAN 20/66	17	IIIa	+971	-40.1	+ 1.2
FEB 17/66	1	IIIb	+966	-25.8	+ 1.1
FEB 23/67	10	Ia	+966	-49.3	+13.2
JAN 8/72	8	IIa	+948	-40.8	+ 5.4
FEB 2/72	10	IIa	+954	-33.7	+ 2.1
MAR 9/72	17	Ia	-993	(-20.5)	+ 4.5
DEC 3/72	7	IVa	950(L)	-49.1	-15.2
JAN 14/73	17	Vd	938(L)	-33.8	-33.8

Table A-20 (continued)

Region 4: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
JAN 19/73	26	Vb	+959	-26.7	+14.7
JAN 4/74	26	IIa	-959	-38.2	-15.9
FEB 18/74	17	IIa	964(L)	-44.9	-27.5
MAR 10/74	17	Ia	959(L)	-21.8	0.0
MAR 12/74	17	Va	944(L)	-37.0	-36.4
MAR 26/74	26	Ib	964(L)	-34.5	-34.5
MAR 29/74	5	Ia	959(L)	-29.6	-22.0

Table A-21

Region 4: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
ALL STORMS	I	17	10	R1	0	3	A	D	3	0	A	D	0	0
				R2	0	0	3	L	0	0	3	L	3	3
				R3	0	0	B	D	0	0	B	D	0	0
				R4	7	0	13	L	10	3	7	L	3	3
				R5	10	7		F	3	3		F	3	3
	II	20	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	3	0	0	L	0	0	0	L	0	0
				R3	7	0	B	D	3	3	B	D	0	0
				R4	3	0	20	L	7	7	3	L	3	0
				R5	7	3		F	10	7		F	0	0
	III	10	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	7	3	10	L	7	7	3	L	0	0
				R5	3	0		F	3	3		F	3	3
	IV	3	10	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	3	L	3	3
				R3	0	3	B	D	0	0	B	D	0	0
				R4	0	3	3	L	3	3	7	L	7	7
				R5	3	3		F	0	0		F	0	0
	V	23		R1	0		A	D	0	0				
				R2	0		10	L	10	10				
				R3	7		B	D	0	0				
				R4	10		13	L	7	7				
				R5	7			F	7	7				
GRAND TOTAL	I-V		100	R1	3		A	D	3	0				
				R2	3		20	L	17	17				
				R3	17		B	D	3	3				
				R4	33		80	L	47	36				
				R5	44			F	30	27				

Table A-21 (continued)

Region 4: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
TOP TEN	I	7	7	R1	0	3	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	7	0	7	L	3	3	7	L	3	3
				R5	0	3		F	3	3		F	3	3
	II	10	0	R1	0	0	A	D	0	0				
				R2	0	0	0	L	0	0				
				R3	3	0	B	D	0	0				
				R4	3	0	10	L	3	3				
				R5	3	0		F	7	7				
	III	3	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	3	3	3	L	3	3	3	L	0	0
				R5	0	0		F	0	0		F	3	3
	IV	3	7	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	0	3	3	L	3	3	7	L	7	7
				R5	3	3		F	0	0		F	0	0
	V	10		R1	0		A	D	0	0				
				R2	0		7	L	7	7				
				R3	3		B	D	0	0				
				R4	7		3	L	3	3				
				R5	0			F	0	0				
TOP TEN TOTAL	I-V		50	R1	3		A	D	0	0				
				R2	0		7	L	7	7				
				R3	7		B	D	0	0				
				R4	27		43	L	27	27				
				R5	13			F	17	17				

Table A-22

Wind direction quadrants, Region 4.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS				REGION: 4
		NE	NW	SE	SW	Variable
1 - 2	3		2			1
3 - 5	3	1	2			
6 - 10	9		5.5	1	1.5	1
11 - 15	0					
16 - 20	10	4	6			
>20	5	1	1		2	1
Totals		6	16.5	1	3.5	3

REGION 5: Labrador Shelf

Storm Track Description and Frequency

36% I. Storm develops off the east coast near

23% a) Cape Hatteras/Delmarva and tracks NE across Nova Scotia/Gulf of St. Lawrence towards Greenland (7%), across Newfoundland to the south of Greenland (13%), or meanders near Newfoundland (3%).

13% b) New England and tracks towards Nova Scotia, cutting off and meandering near Newfoundland (10%) or continuing across Gulf of St. Lawrence/Newfoundland to Labrador (3%).

23% II. Storm organizes to lee of Canadian Rockies (Alberta), tracks towards the Great Lakes and

17% a) continues down the St. Lawrence River Valley across Gulf of St. Lawrence/Labrador towards the Labrador Sea (10%) or moves across Quebec/Labrador to Davis Strait (7%).

7% b) sparks a redevelopment off the east coast which proceeds NE across Nova Scotia/Newfoundland to Labrador (3%) or south of Greenland (3%).

13% III. Storm organizes to lee of American Rockies (near Colorado) and

10% a) tracks east towards Cape Hatteras/Delmarva, redevelops (3%) and/or tracks NE across Nova Scotia/Gulf of St. Lawrence towards the Labrador Sea (3%), or south of Nova Scotia/Newfoundland towards Greenland (7%).

REGION 5: Labrador Shelf (Cont'd)

3% b) tracks NE across the Great Lakes/St. Lawrence River Valley towards Labrador and south of Greenland.

13% IV. Storm develops in Gulf of Mexico, and

10% a) tracks NE along the coast towards Nova Scotia/Gulf of St. Lawrence and across Labrador (3%) or across Newfoundland (7%) to the south of Greenland.

3% b) tracks west of Appalachians and down St. Lawrence River Valley to Labrador/Labrador Sea.

13% V. Other

3% a) Storm becomes organized over/near Great Lakes and spawns secondary development off Cape Hatteras/Delmarva, continues NE, cuts off and meanders east to NE of Newfoundland.

3% b) Storm develops in Northern Ontario and tracks east-SE across Quebec/Newfoundland and recurves to the south of Greenland.

3% c) Storm organizes well out to sea, cuts off, and recurves NW, meandering to the east and south of Newfoundland.

3% d) Storm organizes near Greenland well to the north of the main baroclinic zone, via the "instant occlusion" mode of development.

Note: About 70% of storms eventually took coastal route.

Table A-23

Region 5: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
JAN 25/48	29	IIa	-948	-17.2	-10.3
OCT 7/54	17	Vb	948(L)	-27.1	-10.3
FEB 10/57	7	Ib	963(SL)	-26.7	-15.7
MAR 6/58	19	Ia	+982	-26.7	+ 4.9
JAN 6/59	5	Ia	954(L)	-49.3	-22.0
FEB 9/59	1	IIb	+958	-60.2	+26.1
JAN 14/60	28	Vc	+990	- 5.8	+ 6.5
DEC 18/61	29	Ib	+963	-41.6	+11.2
FEB 22/65	20	IIb	+990	-39.2	+22.6
JAN 19/66	20	IVa	+974	-40.1	0.0
FEB 17/66	7	IVb	+966	-25.8	+ 1.1
MAR 6/69	20	IVa	954(L)	-36.2	-20.0
DEC 28/70	12	Ib	+978	-27.7	+24.0
JAN 16/72	20	IIa	959(L)	-14.5	- 5.0
FEB 2/72	20	IIIa	+954	-33.7	+ 2.1
MAR 2/72	12	IIIa	954(L)	-25.7	-25.7
DEC 4/72	10	Ia	+962	-49.1	+12.3
DEC 19/72	12	IVa	954(L)	-38.5	- 5.1
FEB 23/73	12	IIa	973(L)	-48.2	-48.2
JAN 4/74	20	IIIa	-959	-38.2	-15.9
JAN 14/74	12	Vd	964(L)	-14.1	-14.1
JAN 27/74	20	IIIb	939(L)	-24.3	-24.3
MAR 10/74	5	IIa	959(L)	-21.8	0.0

Table A-23 (continued)

Region 5: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
MAR 12/74	2	Va	944(L)	-37.0	-36.4
MAR 29/74	2	IIa	959(L)	-29.6	-22.0
APR 1/75	17	Ia	958(L)	-28.9	-28.9
OCT 9/75	2	Ia	974(L)	-45.3	- 4.6
MAR 18/76	20	Ia	954(L)	-36.7	-36.7
FEB 18/79	11	Ib	964(L)	-18.9	-18.9
JAN 23/82	7	Ia	954(L)	-51.8	-11.1

Table A-24

Region 5: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
ALL STORMS	I	23	13	R1	3	0	A	D	0	0	A	D	0	0
				R2	3	0	7	L	7	7	3	L	3	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	7	3	17	L	10	10	10	L	3	3
				R5	10	10		F	7	7		F	7	7
	II	17	7	R1	0	3	A	D	0	0	A	D	0	0
				R2	0	0	3	L	3	3	0	L	0	0
				R3	0	0	B	D	3	0	B	D	0	0
				R4	7	0	13	L	10	3	7	L	0	0
				R5	10	3		F	0	0		F	7	7
	III	10	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	3	L	3	3	3	L	3	3
				R3	0	0	B	D	3	3	B	D	0	0
				R4	0	0	7	L	0	0	0	L	0	0
				R5	10	3		F	3	3		F	0	0
	IV	10	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	7	3	10	L	7	7	3	L	0	0
				R5	3	0		F	3	3		F	3	3
	V	13		R1	3		A	D	0	0				
				R2	0		3	L	3	0				
				R3	3		B	D	0	0				
				R4	3		10	L	7	7				
				R5	3			F	3	0				
GRAND TOTAL	I-V		100	R1	10		A	D	0	0				
				R2	3		23	L	23	17				
				R3	3		B	D	7	3				
				R4	30		77	L	37	30				
				R5	53			F	33	30				

Table A-24 (continued)

Region 5: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
TOP TEN	I	13	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	3	0	13	L	10	10	3	L	3	3
				R5	10	3		F	3	3		F	0	0
	II	7	3	R1	0	0	A	D	0	0	A	D	0	0
				R2	0	0	0	L	0	0	0	L	0	0
				R3	0	0	B	D	0	0	B	D	0	0
				R4	3	0	7	L	7	3	3	L	0	0
				R5	3	3		F	0	0		F	3	3
	III													
	IV	0	3	R1	0	0					A	D	0	0
				R2	0	0					0	L	0	0
				R3	0	0					B	D	0	0
				R4	0	3					3	L	0	0
				R5	0	0						F	3	3
	V	3		R1	0		A	D	0	0				
				R2	0		0	L	0	0				
				R3	3		B	D	0	0				
				R4	0		3	L	3	3				
				R5	0			F	0	0				
TOP TEN TOTAL	I-V		33	R1	0		A	D	0	0				
				R2	0		0	L	0	0				
				R3	3		B	D	0	0				
				R4	10		33	L	23	20				
				R5	20			F	10	10				

Table A-25

Wind direction quadrants, Region 5.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS			REGION: 5	
		NE	NW	SE	SW	Variable
1 - 2	4	1.5	2.5			
3 - 5	2	1	1			
6 - 10	4	0.5	3.5			
11 - 15	6	1	4	1		
16 - 20	11	3	6	1.5	0.5	
>20	3	1	2			
Totals		8	19	2.5	0.5	0

REGION 6: Davis Strait

Storm Track Description and Frequency

41% I. Storm organizes to lee of Canadian Rockies (Alberta), tracks towards the Great Lakes and

28% a) across Central Ontario to N. Quebec and Baffin Island (3%), or continues down the St. Lawrence River Valley and across the Gulf of St. Lawrence to Labrador/Newfoundland and the Labrador Sea (19%), or recurves across Quebec to Hudson Bay (6%).

13% b) sparks a redevelopment off the east coast which proceeds across Nova Scotia/Gulf of St. Lawrence to Labrador and recurves westward towards Baffin Island/N. Quebec.

19% II. Storm develops in Gulf of Mexico, and

10% a) tracks NE along the coast towards Nova Scotia/Gulf of St. Lawrence and across Labrador (6%) or across Newfoundland towards Labrador Sea/Greenland (3%).

10% b) tracks west of Appalachians and across Great Lakes/St. Lawrence River Valley towards N. Quebec (6%) or Labrador/Labrador Sea (3%).

16% III. Storm organizes to lee of American Rockies (near Colorado) and

10% a) tracks east-NE towards Delmarva, redevelops (6%) and/or tracks NE across Nova Scotia/Gulf of St. Lawrence towards Labrador/Labrador Sea (6%) or south of Nova Scotia/Newfoundland towards Greenland (3%).

REGION 6: Davis Strait (Cont'd)

6% b) tracks NE across the lower Great Lakes/St. Lawrence River Valley and curves northwards towards James Bay/N. Quebec and Baffin Island (3%) or sparks a coastal redevelopment which proceeds NE near Newfoundland towards Greenland (3%).

16% IV. Storm develops near the east coast along

13% a) Great Lakes/New England and tracks NE across Nova Scotia/Gulf of St. Lawrence and east of Labrador (3%), or tracks east and north of Newfoundland and westwards towards Labrador (10%).

3% b) Cape Hatteras/Delmarva and tracks NE across Nova Scotia/Newfoundland towards Greenland.

10% V. Other

3% a) Storm organizes well out to sea and tracks NE near Newfoundland and east of Greenland.

6% b) Storm organizes to lee of Canadian Rockies (Alberta) and tracks SE towards Cape Hatteras/Delmarva (3%) and recurves NE across the Gulf of St. Lawrence to Labrador, or tracks east-NE across Ontario/Quebec towards Labrador (3%), and recurves westward towards N. Quebec.

Note: About 55% of storms eventually took coastal route.

Table A-26

Region 6: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
NOV 26/47	29	Ia	968(L)	-21.7	-10.7
JAN 7/49	29	IIIb	973(L)	-22.4	- 4.1
NOV 28/55	17	IIa	+968	-58.8	+10.0
FEB 22/56	5	IVa	964(L)	-31.4	-15.1
JAN 2/57	19	Vb	959(SL)	-49.1	- 9.3
JAN 18/59	5	Ia	964(L)	-27.2	- 4.1
JAN 25/63	1	IIIa	944(L)	-42.3	-42.3
DEC 1/63	31	IIb	954(L)	-28.6	-19.5
JAN 13/64	31	IIIa	+976	-48.6	+10.1
JAN 6/65	14	Va	+978	-31.4	+13.2
FEB 23/65	12	Ib	+982	-39.2	- 8.3
NOV 16/65	14	Vb	+990	-16.3	+ 4.1
FEB 6/69	5	IIb	+982	-33.4	+ 8.1
MAR 6/69	12	IIa	954(L)	-36.2	-20.0
DEC 28/70	3	IVa	+978	-27.7	+24.0
JAN 29/71	2	Ia	962(L)	-12.3	-12.3
JAN 27/72	9	Ia	952(L)	-26.7	- 6.2
FEB 7/72	19	IIa	969(L)	-24.3	- 4.2
MAR 2/72	5	IIIb	954(L)	-25.7	-25.7
OCT 18/72	24	Ia	+983	-28.6	+ 9.7
NOV 17/72	9	IIIa	964(L)	-22.5	-22.5
JAN 10/74	9	Ia	969(L)	-17.4	-16.2
FEB 2/74	16	Ia	948(L)	-25.7	-25.7

Table A-26 (continued)

Region 6: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
MAR 10/74	24	Ia	959(L)	-21.8	0.0
MAR 13/74	24	IVa	+959	-37.0	+17.0
MAR 26/74	19	Ib	964(L)	-34.5	-34.5
APR 2/75	24	IVb	+973	-28.9	+15.7
NOV 21/75	24	IVa	959(L)	-20.2	-20.2
JAN 23/76	19	Ib	964(L)	-42.4	-42.4
FEB 4/76	19	IIb	948(L)	-43.6	- 5.2
MAR 2/76	17	Ia	+969	-31.7	0.0
JAN 28/77	5	Ib	973(L)	-23.0	0.0

Table A-27

Region 6: Storm Statistical Summary

CATEGORY	STORM TRACK	(a)	(b)	STORM POSITION AT EVENT TIME	(a)	(b)	PRESSURE CHARACTERISTICS (a)				(b)			
ALL STORMS	I	28	13	R1	0	3	A	D	0	0	A	D	0	0
				R3	0	0	6	L	6	3	6	L	6	6
				R4	0	0	B	D	0	0	B	D	0	0
				R5	22	6	22	L	16	6	6	L	3	0
				R6	6	3		F	6	6		F	3	3
	II	10	10	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	0	L	0	0	0	L	0	0
				R4	3	0	B	D	0	0	B	D	0	0
				R5	6	3	10	L	6	6	10	L	6	6
				R6	0	6		F	3	3		F	3	3
	III	10	6	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	6	L	6	3	3	L	3	3
				R4	0	0	B	D	0	0	B	D	0	0
				R5	6	6	3	L	0	0	3	L	3	0
				R6	3	0		F	3	3		F	0	0
	IV	13	3	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	3	L	3	0	0	L	0	0
				R4	3	0	B	D	0	0	B	D	0	0
				R5	10	3	10	L	3	0	3	L	0	0
				R6	0	3		F	6	6		F	3	3
	V	3	6	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	0	L	0	0	0	L	0	0
				R4	0	0	B	D	0	0	B	D	0	0
				R5	3	3	3	L	0	0	6	L	3	3
				R6	0	3		F	3	3		F	3	3
GRAND TOTAL	I-V		100	R1	3		A	D	0	0				
				R3	0		25	L	25	16				
				R4	6		B	D	0	0				
				R5	70		75	L	41	25				
				R6	22			F	34	34				

Table A-27 (continued)

Region 6: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
Top Ten	I	13	3	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	3	L	3	0	0	L	0	0
				R4	0	0	B	D	0	0	B	D	0	0
				R5	6	3	10	L	10	6	3	L	3	0
				R6	6	0		F	0	0		F	0	0
	II	0	3	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	0	L	0	0	0	L	0	0
				R4	0	0	B	D	0	0	B	D	0	0
				R5	0	0	0	L	0	0	3	L	0	0
				R6	0	3		F	0	0		F	3	3
	III	6	3	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	6	L	6	3	3	L	3	3
				R4	0	0	B	D	0	0	B	D	0	0
				R5	3	3	0	L	0	0	0	L	0	0
				R6	3	0		F	0	0		F	0	0
	IV	6	0	R1	0	0	A	D	0	0	A	D	0	0
				R3	0	0	0	L	0	0	0	L	0	0
				R4	0	0	B	D	0	0	B	D	0	0
				R5	6	0	6	L	3	3	0	L	0	0
				R6	0	0		F	3	3		F	0	0
	V													
Top Ten Total	I-V		34	R1	0		A	D	0	0				
				R3	0		13	L	13	6				
				R4	0		B	D	0	0				
				R5	22		22	L	16	10				
				R6	13			F	6	6				

Table A-28

Wind direction quadrants, Region 6.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS				REGION: 6
		NE	NW	SE	SW	Variable
1 - 2	2	1		1		
3 - 5	6	3	1	2		
6 - 10	3	2	1			
11 - 15	4	0.5	1	2.5		
16 - 20	8	3.5	3.5		1	
>20	9	3.5	3.5	2		
Totals		13.5	10.0	7.5	1	0

REGION 7: Baffin Bay

Storm Track Description and Frequency

27% I. Storm organizes to lee of Northern Canadian Rockies (Northern Alberta/British Columbia) and

- 18% a) tracks NE across northern prairies/N.W.T. and Hudson Bay to Baffin Island.
- 9% b) tracks east across prairies and Hudson Bay, then recurves northwards across N. Quebec to Baffin Island.

18% II. Storm organizes to lee of Southern Canadian Rockies (Southern Alberta) and

- a) tracks east and then NE across Manitoba/Northern Ontario and Hudson Bay to Baffin Island.
- 6% b) tracks east across Great Lakes and NE across Central Quebec (3%) to Davis Strait or to the St. Lawrence River Valley, sparking a coastal redevelopment (3%) which crosses Nova Scotia/Newfoundland to the Labrador Sea and Davis Strait.

15% III. Storm organizes to lee of American Rockies (near Colorado) and

- 12% a) tracks east and NE across the Great Lakes to James Bay/Hudson Bay/N. Quebec and Baffin Island (9%) or Central Quebec to Labrador/Labrador Sea (3%).
- 3% b) tracks NE west of Great Lakes across Hudson Bay to Baffin Island.

REGION 7: Baffin Bay (Cont'd)

15% IV. Storm organizes over the Yukon or Arctic and

12% a) tracks east-south eastwards across Northern Hudson Bay and continues to Baffin Island (9%) or meanders (3%).

3% b) tracks SE across Manitoba/James Bay and redevelops, continuing NE across Central/Northern Quebec to Baffin Island.

27% V. Other

12% a) Storm organizes over/near Great Lakes/St. Lawrence River Valley and tracks NE across Labrador to the Davis Strait (9%) or NNE across Quebec to Baffin Island (3%).

9% b) Storm develops in Gulf of Mexico and tracks NE along east coast and across the Maritimes (6%) to the Davis Strait and Greenland or tracks west of the Appalachians and across the Great Lakes/Quebec to Baffin Island (3%).

3% c) Storm develops from extratropical remnants of tropical storm/hurricane and tracks north across Maritimes/Labrador to Baffin Island.

3% d) Storm organizes in Davis Strait well to the north of the main baroclinic zone, via the "instant occlusion" mode of development.

Note: About 12% of storms eventually took coastal route.

Table A-29

Region 7: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
OCT 11/50	5	Ia	+975	-18.5	+ 1.9
OCT 15/56	9	Ia	-973	-10.3	-10.3
NOV 3/59	31	Va	968(L)	-27.1	- 6.1
OCT 27/60	12	Ia	-994	- 1.0	0.0
SEP 5/62	2	IVa	983(L)	- 4.6	- 4.6
NOV 25/62	2	Vb	+977	-32.5	+13.1
OCT 2/63	1	Vb	+967	-22.2	+ 2.9
NOV 19/65	9	IIa	+989	-16.3	-10.1
OCT 7/66	24	Ib	958(L)	-23.8	-23.8
NOV 1/66	12	Va	+982	-36.7	+ 1.9
NOV 6/66	31	Vb	+990	-13.5	+10.6
SEP 22/67	12	Ia	+983	-23.2	+18.9
NOV 7/67	27	IIIa	+978	-12.5	- 3.9
JUL 15/68	21	Ia	+978	-12.3	0.0
OCT 5/68	12	IVa	+999	-13.7	+11.3
NOV 17/69	24	Ia	+978	-27.1	+14.0
OCT 13/70	12	IIIa	+995	-23.4	+11.9
OCT 20/70	8	Ve	+994	-17.9	+ 6.5
NOV 25/70	4	IIa	966(L)	-14.4	- 7.4
AUG 13/71	18	IVb	+969	-11.4	+ 4.8
NOV 20/71	27	IIIa	977(L)	-16.4	-16.4
OCT 6/72	27	IVa	+988	0.0	+ 8.3
OCT 19/72	9	Ib	-988	-28.6	+ 5.0

Table A-29 (continued)

Region 7: Storm Type Summary

DATE	RANK	TYPE	±PPP	ΔP_{MAX}	ΔP_{EVENT}
SEP 26/74	12	IVa	988(L)	-12.4	- 3.9
OCT 3/74	6	Va	+998	-23.1	+23.0
OCT 16/74	18	IIIa	978(L)	-21.4	-21.4
OCT 30/74	21	Va	982(L)	-17.2	- 0.9
NOV 24/74	31	Vd	+998	I.0	I.0
OCT 7/75	20	Ib	-989	(- 4.9)	0.0
SEP 10/76	27	IIa	978(L)	-13.8	- 0.9
NOV 23/77	6	IIIb	+987	-22.0	+ 3.9
OCT 1/78	31	IIb	+984	-32.6	+ 5.9
OCT 9/78	24	IIb	984(L)	- 9.7	- 9.7
OCT 20/81	19	IIa	968(L)	-16.6	- 9.9

Table A-30

Region 7: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
ALL STORMS	I	18	9	R5	0	3	A	D	3	0	A	D	3	0
				R6	3	6	3	L	0	0	6	L	3	0
				R7	15	0	B	D	3	0	B	D	3	0
							15	L	0	0	3	L	0	0
								F	12	3		F	0	0
	II	12	6	R5	0	0	A	D	0	0	A	D	0	0
				R6	3	3	0	L	0	0	3	L	3	0
				R7	9	3	B	D	0	0	B	D	0	0
							12	L	9	0	3	L	0	0
								F	3	0		F	3	3
	III	12	3	R5	3	0	A	D	0	0	A	D	0	0
				R6	6	0	6	L	6	0	0	L	0	0
				R7	3	3	B	D	0	0	B	D	0	0
							6	L	0	0	3	L	0	0
								F	6	0		F	3	0
	IV	12	3	R5	0	0	A	D	0	0	A	D	0	0
				R6	3	3	3	L	3	0	0	L	0	0
				R7	9	0	B	D	0	0	B	D	0	0
							9	L	3	0	3	L	0	0
								F	6	0		F	3	0
	V	27		R5	3		A	D	0	0				
				R6	9		0	L	0	0				
				R7	15		B	D	0	0				
							27	L	6	3				
								F	20	6				
GRAND TOTAL	I-V	100		R5	9		A	D	6	0				
				R6	35		20	L	15	0				
				R7	56		B	D	6	0				
							80	L	18	3				
								F	56	12				

Table A-30 (continued)

Region 7: Storm Statistical Summary

CATEGORY	STORM TRACK			STORM POSITION AT EVENT TIME			PRESSURE CHARACTERISTICS							
		(a)	(b)		(a)	(b)	(a)				(b)			
TOP TEN	I	6	3	R5	0	0	A	D	3	0	A	D	0	0
				R6	0	3	3	L	0	0	0	L	0	0
				R7	6	0	B	D	0	0	B	D	3	0
							3	L	0	0	3	L	0	0
								F	3	0		F	0	0
	II	6	0	R5	0	0	A	D	0	0				
				R6	3	0	0	L	0	0				
				R7	3	0	B	D	0	0				
							6	L	3	0				
								F	3	0				
	III	0	3	R5	0	0					A	D	0	0
				R6	0	0					0	L	0	0
				R7	0	3					B	D	0	0
											3	L	0	0
												F	3	0
	IV	3	0	R5	0	0	A	D	0	0				
				R6	0	0	3	L	3	0				
				R7	3	0	B	D	0	0				
							0	L	0	0				
								F	0	0				
	V	12		R5	0		A	D	0	0				
				R6	6		0	L	0	0				
				R7	6		B	D	0	0				
							12	L	0	0				
								F	12	3				
TOP TEN TOTAL	I-V		32	R5	0		A	D	3	0				
				R6	12		6	L	3	0				
				R7	20		B	D	3	0				
							27	L	3	0				
								F	20	3				

Table A-31

Wind direction quadrants, Region 7.

STORM RANKING	Totals	WIND DIRECTION QUADRANTS				REGION: 7
		NE	NW	SE	SW	Variable
1 - 2	3		2		1	
3 - 5	2					2
6 - 10	6	1	1	2.5	0.5	1
11 - 15	6	1		2.5	0.5	2
16 - 20	3	1	1			1
>20	14	3	3	5		3
Totals		6	7	10	2	9

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