Weather, Ice and Sea Conditions Relative to Arctic Marine Transportation

N. Parker and J. Alexander
Arctic Weather Centre
Atmospheric Environment Service, Western Region

Institute of Ocean Sciences
Department of Fisheries and Oceans
Sidney, B.C. V8L 4B2

1983

Canadian Technical Report of Hydrography and Ocean Sciences No. 26

Fisheries and Oceans   Pêches et Océans

Canada

Canadian Technical Report of Hydrography and Ocean Sciences

These reports contain scientific and technical information of a type that represents a contribution to existing knowledge but which is not normally found in the primary literature. The subject matter is generally related to programs and interests of the Ocean Science and Surveys (OSS) sector of the Department of Fisheries and Oceans.

Technical Reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report will be abstracted in Aquatic Sciences and Fisheries Abstracts. Reports are also listed in the Department's annual index to scientific and technical publications.

Technical Reports are produced regionally but are numbered and indexed nationally. Requests for individual reports will be fulfilled by the issuing establishment listed on the front cover and title page. Out of stock reports will be supplied for a fee by commercial agents.

Regional and headquarters establishments of Ocean Science and Surveys ceased publication of their various report series as of December 1981. A complete listing of these publications and the last number issued under each title are published in the *Canadian Journal of Fisheries and Aquatic Sciences,* Volume 38: Index to Publications 1981. The current series began with Report Number 1 in January 1982.

Rapport technique canadien sur l'hydrographie et les sciences océaniques

Ces rapports contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles mais que l'on ne trouve pas normalement dans les revues scientifiques. Le sujet est généralement rattaché aux programmes et intérêts du service des Sciences et Levés océaniques (SLO) du ministère des Pêches et des Océans.

Les rapports techniques peuvent être considérés comme des publications à part entière. Le titre exact figure au-dessus du résumé du chaque rapport. Les résumés des rapports seront publiés dans la revue Résumés des sciences aquatiques et halieutiques et les titres figureront dans l'index annuel des publications scientifiques et techniques du Ministère.

Les rapports techniques sont produits à l'échelon régional mais sont numérotés et placés dans l'index à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page de titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

Les établissements des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports depuis décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques,* la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du Rapport n° 1 en janvier 1982.

Canadian Technical Report of Hydrography and Ocean Sciences No. 26

1983

WEATHER, ICE AND SEA CONDITIONS RELATIVE TO ARCTIC MARINE TRANSPORTATION

by

N. Parker and J. Alexander

Arctic Weather Centre

Atmospheric Environment Service, Western Region

Institute of Ocean Sciences

Department of Fisheries and Oceans

Sidney, B.C. V8L 4B2

Cat. No. Fs. 97-18/26 ISSN 0711-6764

Correct citation for this publication:
Parker, N., and J. Alexander. Weather, Ice and Sea Conditions Relative to Arctic Marine Transportation. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 26: xii + 211 p.

ABSTRACT

Parker, N., and J. Alexander. Weather, Ice and Sea Conditions Relative to Arctic Marine Transportation.
Can. Tech. Rep. Hydrogr. Ocean Sci. No. 26:xii + 211 p.

This study presents an overview of climatic factors pertinent to marine transportation through the Northwest Passage. The subjects of wind, visibility, temperature, ice and sea state in an arctic environment are treated as completely as time permitted. The final section places special emphasis on these climatic factors along the Northwest Passage from Bering Strait to southern Davis Strait.

Keywords: Arctic, Northwest Passage, climatic factors, marine transportation

RÉSUMÉ

Parker, N., and J. Alexander. Weather, Ice and Sea Conditions Relative to Arctic Marine Transportation.
Can. Tech. Rep. Hydrogr. Ocean Sci. No. 26:xii + 211 p.

Les auteurs presentent une vue d'ensemble des facteurs climatiques qui ont rapport au transport marin par le passage du Nord-Quest. Ils traitent du vent, de la visibilité, de la témperature et de l'état de la mer et de la glace dans un environnement arctique, de façon aussi complète que le permet le temps. La dernière section couvre spécialement les facteurs climatiques présents de long du passage du Nord-Ouest, du détroit de Bering à la partie meridionale du détroit de Davis.

Mots-clès: Arctique, passage du Nord-Ouest, facteurs climatiques, transport marin

ACKNOWLEDGEMENTS

The management of AES	- for providing the authors with the opportunity and time to prepare this report.
Mr. A.S. Mann	- Head, Scientific Services Division (Western Region) for providing guidance and constructive criticism in addition to considerable help with the initial chart preparation and collation.
Mr. W.D. Hume	- Head, Special Projects and Satellite Office (Western Region) who not only reviewed the paper but, along with Mr. Mann, provided advice and encouragement.
Mr. W.E. Markham	- Director, Ice Branch (Central Services Directorate) who made two extensive reviews with special attention to the sections on ice.
Mr. M.O. Berry	- Chief, Applications and Impact Division for arranging for reviews of the initial and second drafts.
Mr. V.R. Swail and other members of Climatological Applications Branch.	- for providing the above-mentioned review.
Mr. P.J. Kociuba	- for providing a review of the original draft.
Ms. Hilda Gutzmann	- Secretary, Scientific Services Division (Western Region) for the many hours spent at the word processor.
Dr. L.F. Giovando, R.H. Herlinveaux and Ms. S.D. Ball	- Institute of Ocean Sciences, Sidney, B.C.-- editorial and typing services.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
ACKNOWLEDGEMENTS		iv
LIST OF TABLES		viii
LIST OF FIGURES		x
1.	INTRODUCTION	
1.1	The Northwest Passage	1
2.	METEOROLOGY OF THE ARCTIC	
2.1	General Climatology of the Arctic	3
2.2	Major Storm Tracks of the Arctic	6
3.	WIND	
3.1	Introduction	12
3.2	Geostrophic Versus Surface Winds	12
3.3	Local Wind Effects	16
4.	VISIBILITY	
4.1	Introduction	23
4.2	Fog	23
4.3	Ice Crystals	23
4.4	Blowing Snow	23
4.5	Precipitation	24
4.6	Other Phenomena	24
5.	TEMPERATURE	
5.1	Introduction	25
5.2	Mean Temperatures	25
5.3	Extreme Temperatures	31
5.4	Atmospheric Stability and Inversions	33
5.5	Wind Chill	34
5.6	Blizzards	45
6.	ICE	
6.1	Introduction	49
6.2	Ice Physics and Structures	49
6.3	Icebergs	50
6.4	Ice Islands	52
6.5	Ice Motion	52

TABLE OF CONTENTS (Cont'd)

		Page
7.	SEA STATE	
7.1	Introduction	54
7.2	Waves	54
7.3	Freezing Spray	57
7.4	Storm Surges	58
8.	DETAILED REGIONAL MARINE CLIMATES	
8.1	Introduction	62
8.2	Eastern Arctic Marine Area	63
8.2.1	Winds	63
8.2.2	Waves	88
8.2.3	Visibilities	90
8.2.4	Freezing Spray	93
8.2.5	Ice	93
8.3	Central Arctic Marine Area	100
8.3.1	Winds	100
8.3.2	Waves	118
8.3.3	Visibilities	120
8.3.4	Freezing Spray	121
8.3.5	Ice	130
8.3.6	Ice Ridges	131
8.4	Beaufort Sea Marine Area	132
8.4.1	Winds	132
8.4.2	Waves	148
8.4.3	Visibilities	148
8.4.4	Freezing Spray	149
8.4.5	Ice	149
8.5	Beaufort Sea Coastal Weather	158
8.5.1	Introduction	158
8.5.2	Wind	158
8.5.3	Temperatures	170
8.5.4	Precipitation	170
8.5.5	Visibility	170
8.5.6	Blowing Snow	174
8.6	Western Alaskan Waters Marine Area	175
8.6.1	Winds	175
8.6.2	Waves	194
8.6.3	Visibilities	194
8.6.4	Freezing Spray	195
8.6.5	Ice	195

TABLE OF CONTENTS (Cont'd)

		Page
9.	SCENARIOS	
9.1	Introduction	199
9.2	The Alaskan Route	199
9.3	The Northwest Passage Route	199
9.4	Beaufort Sea Production Area	200
9.5	Weather Impact on Marine Accidents	200
10.	OBSERVATIONAL AND FORECASTING SYSTEMS	
10.1	Introduction	202
10.2	Support for Routine Operations	202
10.2.1	Forecast Services	202
10.2.2	Basic Data Requirements	203
10.2.3	Communications	203
10.3	Support for Emergency Operations	204
10.3.1	Forecast Services	204
10.3.2	Basic Data Requirements	204
10.3.3	Communications	204
11.	AREAS OF FURTHER STUDIES	205
12.	REFERENCES	207

LIST OF TABLES

		Page
3.1	Influence of various factors on the observed wind.	13
3.2	Percent frequency of wind by direction for Johnson Point	20
5.1	Percent frequency of occurrence of comfort classes by month. . .	42
5.2	Percent frequency of occurrence of comfort classes by month. . .	43
5.3	Percent frequency of occurrence of comfort classes by month. . .	44
5.4	Absolute percentage frequency of occurrence of blizzard conditions	46
5.5	Mean and extreme durations of observed blizzard conditions . . .	47
5.6	Expected maximum duration of blizzard conditions (hrs)for various return periods	48
7.1	Ice accumulation (cm) per 24 hours from freezing spray	58
8.1	Gridpoint wind speed percent frequency by month for GP1.	71
8.2	Gridpoint wind speed percent frequency by month for GP2.	71
8.3	Gridpoint wind speed percent frequency by month for GP3.	72
8.4	Gridpoint wind speed percent frequency by month for GP4.	72
8.5	Gridpoint wind speed percent frequency by month for GP5. . . .	73
8.6	Gridpoint wind speed percent frequency by month for GP6.	73
8.7	Percent frequency of wind speed by class for Marine Area M 9 . .	85
8.8	Percent frequency of wind speed by class for Marine Area M10 . .	85
8.9	Percent frequency of wind speed by class for Marine Area M11 . .	85
8.10	Percent frequency of wind speed by class for Marine Area M12 . .	86
8.11	Percent frequency of wind speed by class for Marine Area M13 . .	86
8.12	Percent frequency of wind speed by class for Marine Area M14 . .	86
8.13	Percent frequency of wind speed by class for Marine Area M15 . .	87
8.14	Percent frequency of wind speed by class for Marine Area M16 . .	87
8.15	Percent frequency of wind speed by class for Marine Area M17 . .	87
8.16	Waves - Percent frequency by height for Marine Area M 9.	88
8.17	Waves - Percent frequency by height for Marine Area M10.	88
8.18	Waves - Percent frequency by height for Marine Area M11.	88
8.19	Waves - Percent frequency by height for Marine Area M12.	89
8.20	Waves - Percent frequency by height for Marine Area M13.	89
8.21	Waves - Percent frequency by height for Marine Area M14.	89
8.22	Waves - Percent frequency by height for Marine Area M15.	89
8.23	Waves - Percent frequency by height for Marine Area M16.	90
8.24	Waves - Percent frequency by height for Marine Area M17.	90
8.25	Percent frequency of visibilities for Marine Area M 9	90
8.26	Percent frequency of visibilities for Marine Area M 10	91
8.27	Percent frequency of visibilities for Marine Area M 11	91
8.28	Percent frequency of visibilities for Marine Area M 12	91
8.29	Percent frequency of visibilities for Marine Area M 13	91
8.30	Percent frequency of visibilities for Marine Area M 14	92
8.31	Percent frequency of visibilities for Marine Area M 15	92
8.32	Percent frequency of visibilities for Marine Area M 16	92
8.33	Percent frequency of visibilities for Marine Area M 17	92

LIST OF TABLES (Cont'd)

		Page
8.34	Gridpoint wind speed percent frequency by month for GP10	108
8.35	Gridpoint wind speed percent frequency by month for GP9	108
8.36	Gridpoint wind speed percent frequency by month for GP8	109
8.37	Gridpoint wind speed percent frequency by month for GP7	109
8.38	Percent frequency of wind speed for Marine Area M 4	117
8.39	Percent frequency of wind speed for Marine Area M 5	117
8.40	Percent frequency of wind speed for Marine Area M 6	117
8.41	Percent frequency of wind speed for Marine Area M 7	118
8.42	Percent frequency of wind speed for Marine Area M 8	118
8.43	Percent frequency of wind speed for Marine Areas M 4-M 8	119
8.44	Percent frequency of visibilities for Marine Areas M 4-M 8	120
8.45	Mean and extreme duration of observed blizzard conditions	122
8.46	Absolute percentage frequency of blizzard conditions	123
8.47	Expected maximum duration of blizzard conditions (hrs) for various return periods	123
8.48	Range of pressure ridge heights	131
8.49	Gridpoint wind speed percent frequency by month for GP13	132
8.50	Gridpoint wind speed percent frequency by month for GP12	143
8.51	Gridpoint wind speed percent frequency by month for GP11	143
8.52	Percent frequency of wind speed for Marine Area M 3	148
8.53	Percent frequency of wave heights for Marine Area M 3	148
8.54	Percent frequency of visibilities for Marine Area M 3	148
8.55	Summary of summer ice conditions	150
8.56	Percent frequency wind speed ranges by month for Tuktoyaktuk	169
8.57	Percent frequency wind speed by month for Inuvik	169
8.58	Canadian Normals - Monthly average and extreme temperatures	171
8.59	Mean monthly rainfall	172
8.60	Mean monthly snowfall	172
8.61	Greatest 24-hour snowfall	173
8.62	Greatest 24-hour rainfall	173
8.63	Tuktoyaktuk percent frequency for visibility ranges	174
8.64	Percent frequency of blowing snow for inuvik	174
8.65	Gridpoint wind speed percent frequency by month for GP16	183
8.66	Gridpoint wind speed percent frequency by month for GP15	183
8.67	Gridpoint wind speed percent frequency by month for GP14	184
8.68	Percent frequency of wind speed for Marine Area M 2	188
8.69	Percent frequency of wind speed for Marine Area M 1	188
8.70	Percent frequency of wave heights for Marine Area M 2	194
8.71	Percent frequency of wave heights for Marine Area M 1	194
8.72	Percent frequency of visibilities for Marine Area M 1	194
8.73	Percent frequency of visibilities for Marine Area M 2	195

LIST OF FIGURES

		Page
1.1	Geographical key map of place names	2
2.1	Approximate first and last sunrise and sunset	4
2.2	Mean tracks of low pressure centres-Jan Feb Mar 1944-1951	8
2.3	Mean tracks of low pressure centres-Apr May Jun 1944-1951	9
2.4	Mean tracks of low pressure centres-Jul Aug Sep 1944-1951	10
2.5	Mean tracks of low pressure centres-Oct Nov Dec 1944-1951	11
3.1	Hand extracted geostrophic surface winds vs reported surface winds	15
3.2	Streamlines and velocity field around a fixed cyclindrical barrier	18
3.3	Streamlines showing tendency for enhanced anticyclonic flow around a peninsula or island	19
5.1	January mean temperatures	26
5.2	May mean temperatures	27
5.3	July mean temperatures	28
5.4	September mean temperatures	29
5.5	Mean date of beginning of winter	30
5.6	Mean date of end of winter	32
5.7	Temperature extremes and means, Arctic Bay and Pond Inlet	35
5.8	Temperature extremes and means, Resolute A and Clyde	36
5.9	Temperature extremes and means, Cape Parry and Point Barrow	37
5.10	Temperature extremes and means, Sachs Harbour and Holman	38
5.11	Temperature extremes and means, Cape Lisburne and Barter Island	39
5.12	Temperature/wind-chill index	40
6.1	Ocean currents over arctic marine areas	51
7.1	Shoaling effect on wave heights	56
7.2	Principle of wave refraction	56
7.3	The Ekman Spiral	60
8.1	Eastern arctic marine area	64
8.2	Gridpoint wind roses - annual	65
8.3	Gridpoint wind roses - January	66
8.4	Gridpoint wind roses - May	67
8.5	Gridpoint wind roses - July	68
8.6	Gridpoint wind roses - September	69
8.7	Direction and speed of maximum wind by month for GP1-6	70
8.8	Duration for yearly maximum for wind speed at GP1-4	74
8.8a	Duration for yearly maximum for wind speed at GP5-6	75
8.9	Return period for maximum wind speed by month for GP1-4	76
8.9a	Return period for maximum wind speed by month for GP5-6	77
8.10	Return period for wind speed events of specific duration for GP1-4	78
8.10a	Return period for wind speed events of specific duration for GP5-6	79
8.11	July wind roses for Marine Areas M 9-17	81
8.12	August wind roses for Marine Areas M 9-17	82

LIST OF FIGURES (Cont'd)

Page

8.13 September wind roses for Marine Areas M 9-17 83
8.14 October wind roses for Marine Areas M 9-17 84
8.15 Median concentration of old ice - May 21-Jul 2 94
8.16 Median concentration of old ice - Jul 16 - Aug 27. 95
8.16a Median concentration of old ice - Sep 10 - Oct 22. 96
8.17 Worst ice conditions - May 21 - Jul 2. 97
8.18 Worst ice conditions - Jul 16 - Aug 27 98
8.18a Worst ice conditions - Sep 10-Oct 22 99
8.19 Central Arctic Marine Area 101
8.20 Gridpoint wind roses - annual. 102
8.21 Gridpoint wind roses - January 103
8.22 Gridpoint wind roses - May 104
8.23 Gridpoint wind roses - July. 105
8.24 Gridpoint wind roses - September 106
8.25 Direction and speed of maximum wind by month for GP7-10. 107
8.26 Duration for yearly maximum wind speed at GP7-10 110
8.27 Return period for maximum wind speed by month for GP7-10 111
8.28 Return period of wind speed events for specific duration for GP7-10 112
8.29 July wind rose for Marine Area M 4 113
8.30 August wind roses for Marine Areas M 4-08. 114
8.31 September wind roses for Marine Areas M 4-08 115
8.32 October wind roses for Marine Areas M 4-08 116
8.33 Median concentration of old ice - May 21 - Jul 2 124
8.34 Median concentration of old ice - Jul 16 - Aug 27. 125
8.34a Median concentration of old ice - Sep 10 - Oct 22. 126
8.35 Worst ice conditions - May 21 - Jul 2. 127
8.36 Worst ice conditions - Jul 16 - Aug 27 128
8.36a Worst ice conditions - Sep 10 - Oct 22 129
8.37 Beaufort Sea Marine Area 133
8.38 Annual wind roses for Gridpoints 11-13 134
8.39 January wind roses for Gridpoints 11-13. 135
8.40 May wind roses for Gridpoints 11-13. 136
8.41 July wind roses for Gridpoints 11-13 137
8.42 September wind roses for Gridpoints 11-13. 138
8.43 Direction and speed of maximum wind by month for GP11-13 139
8.44 Duration for yearly maximum wind speed at GP11-13. 140
8.45 Return period for maximum wind speed by month for GP11-13. . . . 141
8.46 Return period for wind speed events of specific duration for GP11-13. 142
8.47 July wind rose for Marine Area M 3 144
8.48 August wind rose for Marine Area M 3 145
8.49 October wind rose for Marine Area M 3. 146
8.50 September wind rose for Marine Area M 3. 147

LIST OF FIGURES (Cont'd)

Page

8.51 Median concentration of old ice - May 21 - Jul 2 152
8.52 Median concentration of old ice - Jul 16 - Aug 27. 153
8.52a Median concentration of old ice - Sep 10 - Oct 22. 154
8.53 Worst ice conditions - May 21 - Jul 2 155
8.54 Worst ice conditions - Jul 16 - Aug 27 156
8.55 Worst ice conditions - Sep 10 - Oct 22 157
8.56 Map of northcoast of Yukon showing prominent mountain ranges . 159
8.57 Wind roses for Komakuk Beach, Y.T. 160
8.58 Wind roses for Shingle Point, Y.T. 161
8.59 Wind roses for Inuvik, NWT - Jan, Mar, May, Jul. 163
8.59a Wind roses for Inuvik, NWT - Sep & Nov 164
8.60 Wind roses for Tuktoyaktuk, NWT - Jan, Mar, May, Jul 165
8.60a Wind roses for Tuktoyaktuk, NWT - Sep & Nov. 166
8.61 Roses of maximum wind speed by direction for Tuktoyaktuk, N.W.T. - Jan, Mar, May, Jul. 167
8.61a Roses of maximum wind speed by direction for Tuktoyaktuk, N.W.T. - Sep & Nov 168
8.62 Western Alaska waters marine areas 176
8.63 Annual wind roses for Gridpoints 14-16 177
8.64 January wind roses for Gridpoints 14-16. 178
8.65 May wind roses for Gridpoints 14-16. 179
8.66 July wind roses for Gridpoints 14-16 180
8.67 September wind roses for Gridpoints 14-16. 181
8.68 Direction and speed of maximum wind by month for GP14-16 182
8.69 Duration for yearly maximum for wind speed at GP14-16. 185
8.70 Return period for maximum wind speed by month for GP14-16. . . . 186
8.71 Return period of wind speed events for specific duration for GP14-16. 187
8.72 June wind rose for Marine Area M 1 189
8.73 July wind roses for Marine Areas M 1 and M 2 190
8.74 August wind roses for Marine Areas M 1 and M 2 191
8.75 September wind roses for Marine Areas M 1 and M 2. 192
8.76 October wind roses for Marine Areas M 1 and M 2. 193
8.77 Edge of pack ice for western Alaska waters marine area - May 16 - Jul 15. 196
8.78 Edge of pack ice for western Alaska waters marine area - Jul 16 - Sep 15 197
8.79 Edge of pack ice for western Alaska waters marine area - Sep 16 - Oct. 31 198

1. INTRODUCTION

1.1 THE NORTHWEST PASSAGE

The name "Northwest Passage" brings forth thoughts of ice, cold, hardship, and adventure. In today's context, however, it represents a viable means of resource transportation to southern markets. A number of alternate routes through the islands of the Arctic Archipelago are increasingly being studied. The one which appears to be destined to become a main transportation corridor stretches from the Beaufort Sea to Baffin Bay via Prince of Wales Strait and Parry Channel.

It is this route plus its westward extension through the Bering Strait that this paper addresses. An attempt has been made to combine information from various disciplines to give the reader an overview of weather, ice and sea conditions. In addition, a detailed geostrophic wind climatology for the route has been included. In Figure 1.1, a geographical key map of place names is included for reference throughout this paper.

Although the document is intended as a working paper for internal Environment Canada applications, it is hoped that it will also be useful for the new Arctic Meteorologist. Consequently, more detail has been presented on local winds and wave theory than might normally have been required. The geostrophic wind climatology may be useful for engineers but should be applied only with an understanding of the limitations of such statistics. For the meteorologist or oceanographer it may be useful for estimating the frequency and extent of blowing snow, extreme wind chills, extended periods of onshore flow, surface currents, ice drift, etc.

For some areas such as the southern Beaufort Sea there is a considerable amount of information available. For other areas such as western Parry Channel, records are either lacking or sparse leading to considerable difficulty in drawing meaningful conclusions. Time constraints prevented the examination and incorporation of all available information and the authors have relied heavily on the work of others, especially that of W.E. Markham and J.B. Maxwell.

The preparation of this paper resulted in the assembly of a considerable amount of data in Western Region. It is hoped that this information will provide a foundation for future work.

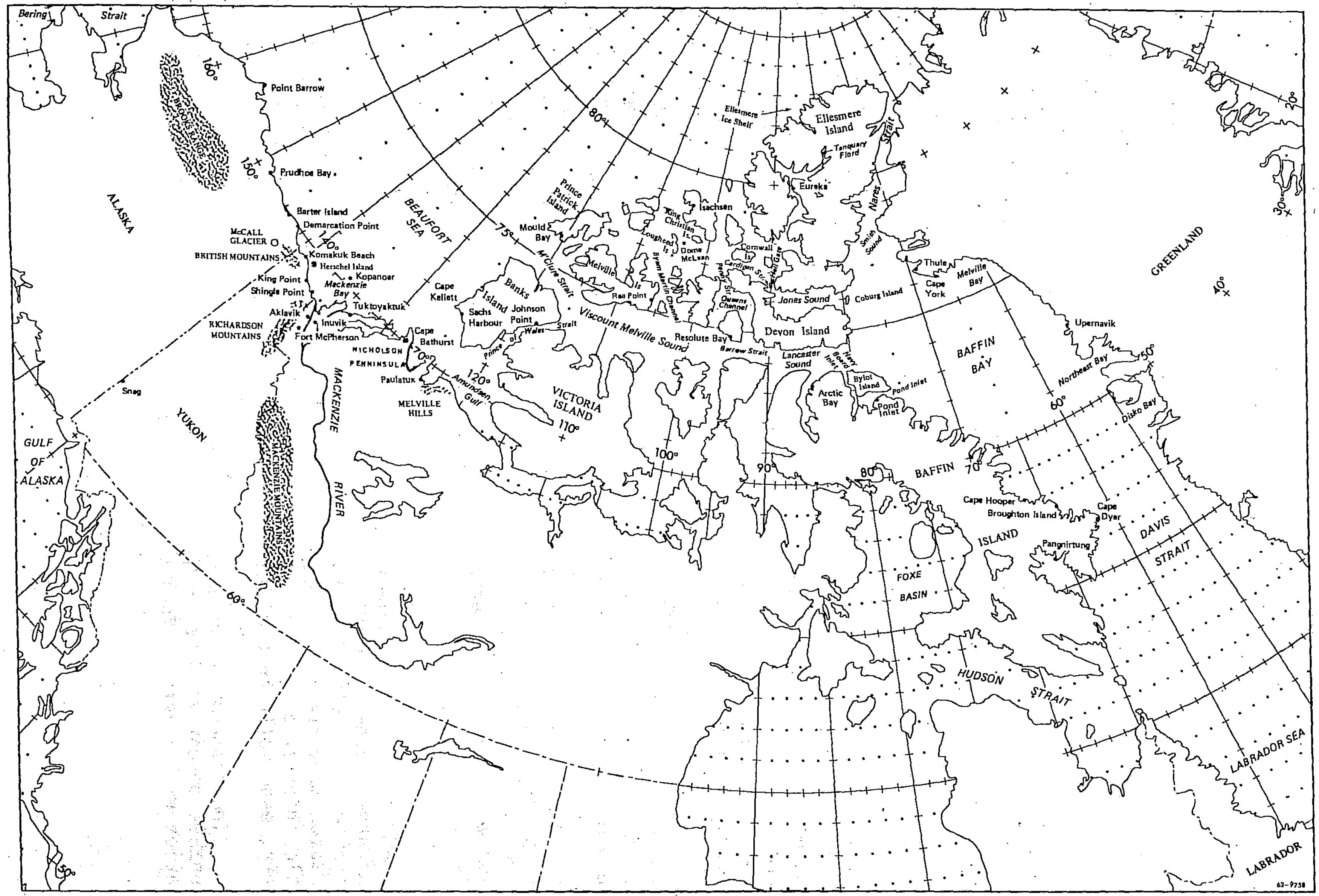


Figure 1.1 Geographical key map of place names.

2. METEOROLOGY OF THE ARCTIC

2.1 GENERAL CLIMATOLOGY OF THE ARCTIC

The climate of the Canadian Arctic is the result of interactions between highly variable incoming solar radiation, large expanses of ice-covered seas and very marked topographical features. The driving force for the atmosphere is, of course, the sun and the unequal energy distribution across the planet. Equatorial regions receive a much larger amount of solar energy than polar areas. The day-to-day variations in the weather are the result of the atmosphere attempting to reach a thermal equilibrium by transferring heat from warmer to colder areas. This process is complicated by the rotation of the earth and variation in surface type and roughness. Land masses offer a wide variation in friction ranging from high values over mountains to low values over the oceans. In addition, the oceans, while offering a nearly uniform surface, also transport considerable heat to the Arctic by way of the major ocean currents. Over northern regions the large number of physical characteristics are collectively known as the "arctic environment".

Because geography plays an important role in determining the climate of a given area it is important to first have some knowledge of the major geographic features of the Arctic before examining a few of these characteristics.

In the far eastern extremities lies Greenland. Its outer rim consists of rugged valleys and fiords while beyond 160-320 kilometres inland the ice sheet rises to 1500 to 2000 metres reaching over 3000 metres near its centre. Moving westward, mountainous terrain extends northward from Labrador through Baffin Island to northern Ellesmere Island. The ranges of eastern Baffin Island contain some of the highest and most rugged mountains in the Canadian Arctic. A series of east-west breaks interrupt this barrier, the most notable being Hudson Strait, and Lancaster and Jones Sounds. Numerous fiords and ice-covered valleys cut deeply into the ranges, and a few actually penetrate them.

West of these mountains lies what is commonly known as the Arctic lowlands. Elevations are generally less than 600 metres and the landscape tends to be relatively flat with a few notable exceptions. For example, Melville Island has peaks over 900 metres while the southwest section of the island contains a plateau rising to over 600 metres which, like the eastern mountains, is deeply cut by fiords and valleys.

Southwest of these lowlands are the Mackenzie and Richardson mountains which extend westward to merge with the British Mountains of the northern Yukon and the Brooks Range of Alaska. The lowlands, however, do extend along the north coast of the Yukon as a narrow strip of land only three kilometres wide at Demarcation Point. West of Barter Island the lowlands expand to become the Arctic coastal plain.

The mountainous terrain of Alaska continues westward into Siberia with the Bering Strait providing a narrow but very significant break.

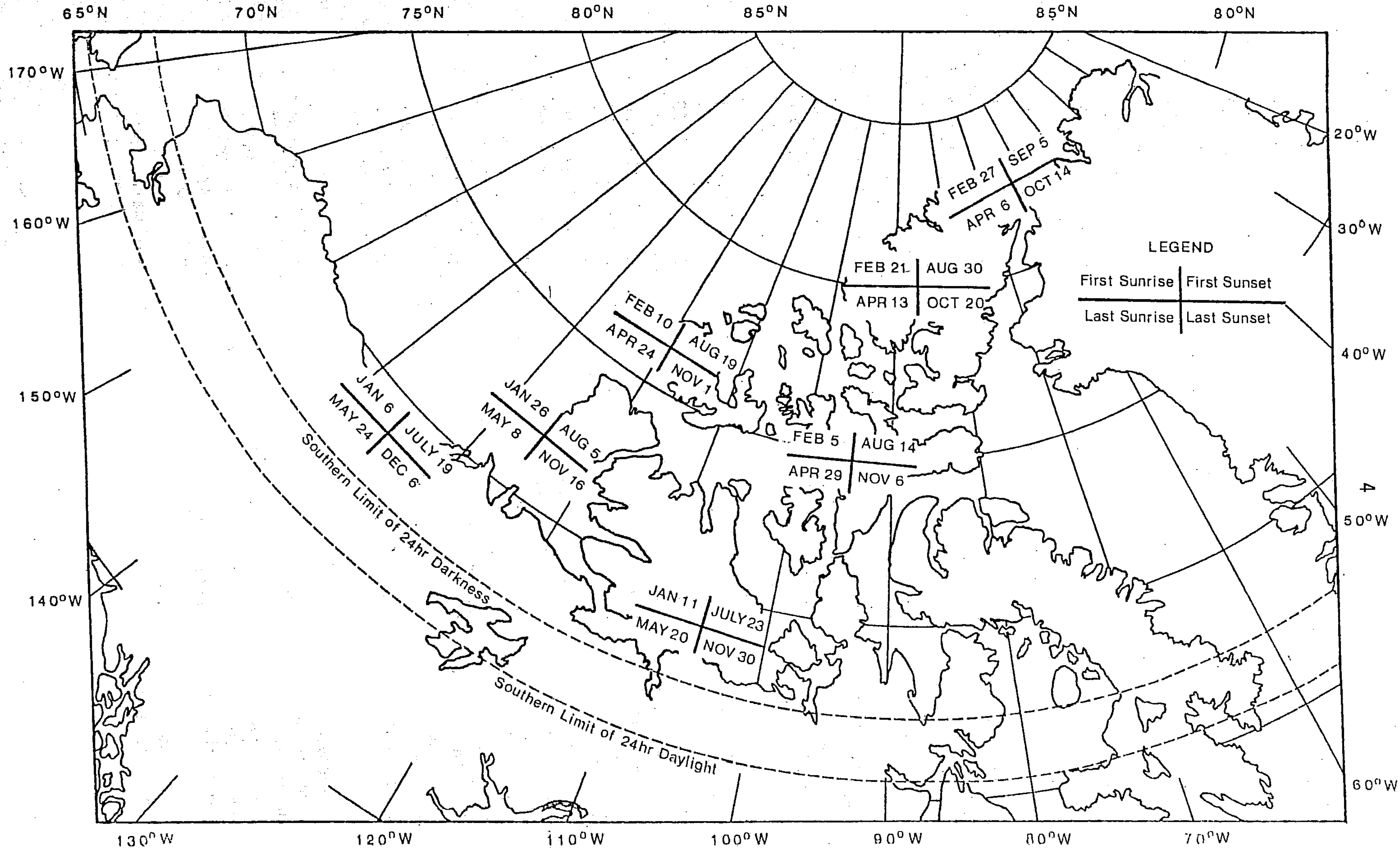


Figure 2.1 Approximate first and last sunrise and sunset.

Returning now to the "arctic environment" the extended periods of light and darkness are possibly one of the better known characteristics. Figure 2.1 shows approximate dates for the first and last sunrise and sunset at a number of arctic stations. Prolonged darkness can become very depressing. The journals of the early explorers never failed to speak of "the return of the sun" and one can almost feel their spirits rise with it.

The arctic is often referred to as a land of ice and snow; however during the short summer, most of the lowlands become snow-free. This snow-free period varies from an average of 131 days at Aklavik to 84 days at Mould Bay to 71 days at Isachsen. The presence of the ice and snow plays a large role in the overall climatology since such surfaces are very effective in reflecting incoming solar energy. The albedo or the percentage of incident solar energy which a surface can reflect is dependent upon surface colour, texture, and the sun angle. Typical albedo values are 80-90% for snow, 19% for dry pastures and 13-18% for sand (Landsberg, 1968). Water is unique for at low sun angles it becomes very reflective while at high sun angles it effectively absorbs energy. Albedo values for water range from a low of 4% at 47° sun angle to 65% at 5° sun angle.

A significant amount of the available energy is thus simply reflected back into space and a portion of that which is absorbed goes into melting snow and ice. This leaves a small amount to increase the air temperature.

The latitudinal variations of temperature show, not unexpectedly, a decrease in the annual mean temperatures with increasing latitude. However, if the extremes are considered, the coldest values are found to occur over the mainland. This is because, although the arctic ocean and waters of the Archipelago are ice covered during the winter, there is still an upward heat flux which has a modifying effect on the air. In Canada, the coldest reading was recorded in the southwestern Yukon where the temperature at Snag fell to -62.7°C. This is over 320 kilometers south of the arctic circle. However, it must be kept in mind that there are little temperature data available from the interior of larger arctic islands where similar values may occur. From the data available, the coldest temperature recorded in the Archipelago is -53.9°C, a record shared by Mould Bay, Isachsen and Eureka.

Another distinctive feature of arctic climatology is the low annual precipitation, in general below 200 mm. A number of factors combine to justify the term "Polar Desert" often used to describe this area. Foremost is the low annual temperature, and the fact that cold air can only hold a limited amount of moisture. Areas of open water act as sources of moisture. However, except for Hell Gate, the north open water located in northern Baffin Bay and other unique areas of open water called "polynyas", the sea is ice covered for much of the year. One final but also important reason for low precipitation is that most cyclones are in their final stages of existence by the time they reach the arctic, and have already lost much of their moisture over southern latitudes through precipitation. The one region that does not fall into the "desert" category is the mountainous area of the eastern arctic. Here, higher annual temperatures, the frequency of major cyclonic activity throughout the year, and the presence of polynyas result in significantly higher annual precipitation. This is especially the case along the eastern slopes of the mountains where upslope flow becomes a significant mechanism to enhance precipitation.

A look at the annual precipitation figures for a few selected locations shows this precipitation variability. Resolute Bay, in the central arctic, receives on the average 136.2 mm of precipitation a year. Western arctic locations such as Isachsen (102.3 mm), Sachs Harbour (102.5 mm), Inuvik (260.3 mm) and Barter Island (167.4 mm) are in sharp contrast to the yearly average of 677.4 mm received at Cape Dyer located on southeastern Baffin Island. By comparison, Toronto receives an average of 789.9 mm per year, Vancouver 1068.1 mm, and Kamloops, one of southern Canada's drier areas, 268.4 mm.

For more detail on arctic climatology one can consult "The Climate of the Canadian Arctic Islands and Adjacent Waters", Vol. I by J.B. Maxwell.

2.2 MAJOR STORM TRACKS OF THE ARCTIC

Unlike the more temperate latitudes where cyclogenesis is common, systems affecting the northern regions seldom originate there but rather move into the Arctic by a number of preferred routes. Figures 2.2 through 2.5 show by season the major tracks cyclones follow to reach and move across the northern regions.

Cyclones show a general west to east progression and there is a tendency for them to spiral towards the pole. Cyclones move into Baffin Bay during all months of the year where, because of the mountainous terrain surrounding the bay, they tend to remain and eventually dissipate. Thus it is with justification that this area has become known as a graveyard for lows.

Terrain plays a dominant role in steering disturbances northward into Baffin Bay. A significant number of systems moving across the North American continent or northward along its east coast track toward southern Greenland.

Depending on a number of factors the whole system may be channeled northward into Davis Strait, or a split may occur carrying part of the low toward Iceland and the remainder northward along the west Greenland coast.

Storms in the former category tend to be the main producers of severe weather in the eastern Arctic while the split systems are generally much weaker; a result of the fact that much of the original energy remains with the parent low.

As shown in the charts, there are a number of principal tracks across the Beaufort Sea and western Archipelago. During the summer months one track runs eastward along 75°N while systems crossing Alaska and the Yukon tend to move along the mainland coast and across northern Hudson Bay. This pattern gradually breaks down in the fall. During the winter months the main track is through the Bering Sea and eastward toward northern Banks Island.

It must be kept in mind that not all systems follow these tracks, and gale force winds in the Beaufort Sea have resulted from systems tracking northwestward across the District of Mackenzie. Also certain upper level wind patterns will on occasion cause lows to move northwestward across the Labrador Sea and Foxe Basin into the archipelago, producing some of the more severe conditions experienced in the area.

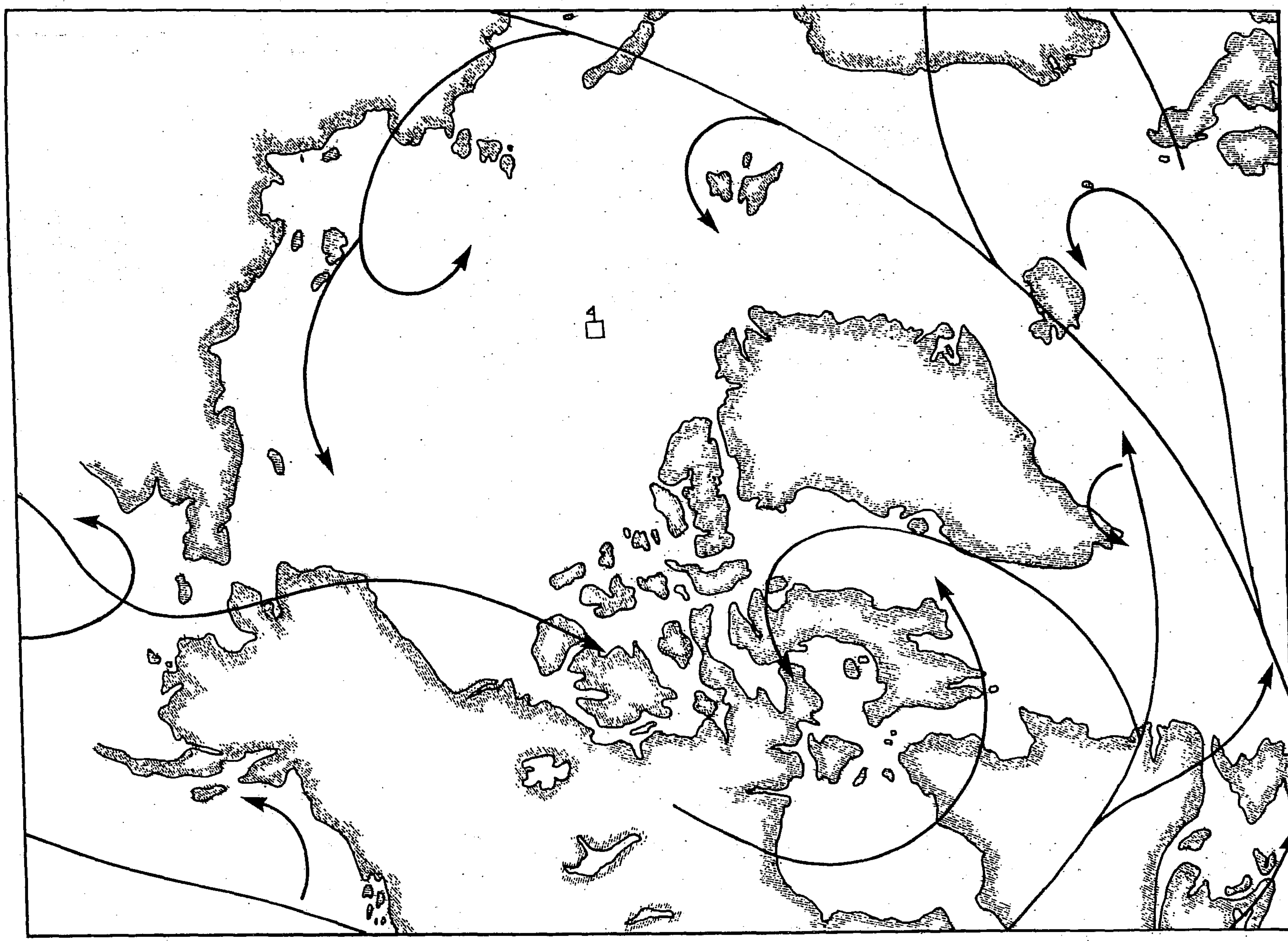


Figure 2.2 Mean tracks of low pressure centres - Jan Feb Mar 1944-1951 (after Berry, et al, 1953).

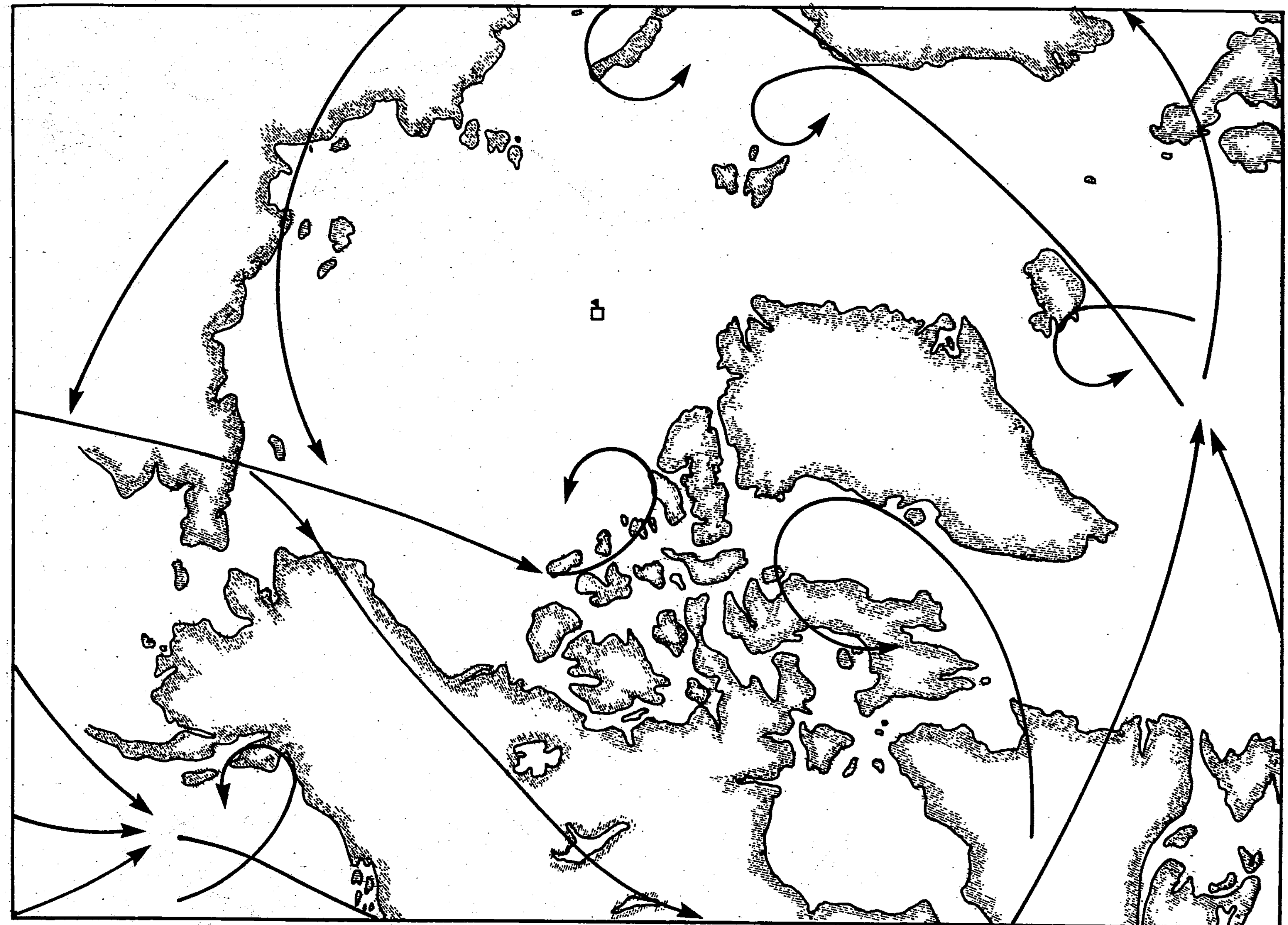


Figure 2.3 Mean tracks of low pressure centres - Apr May Jun 1944-1951 (after Berry, et al, 1953).

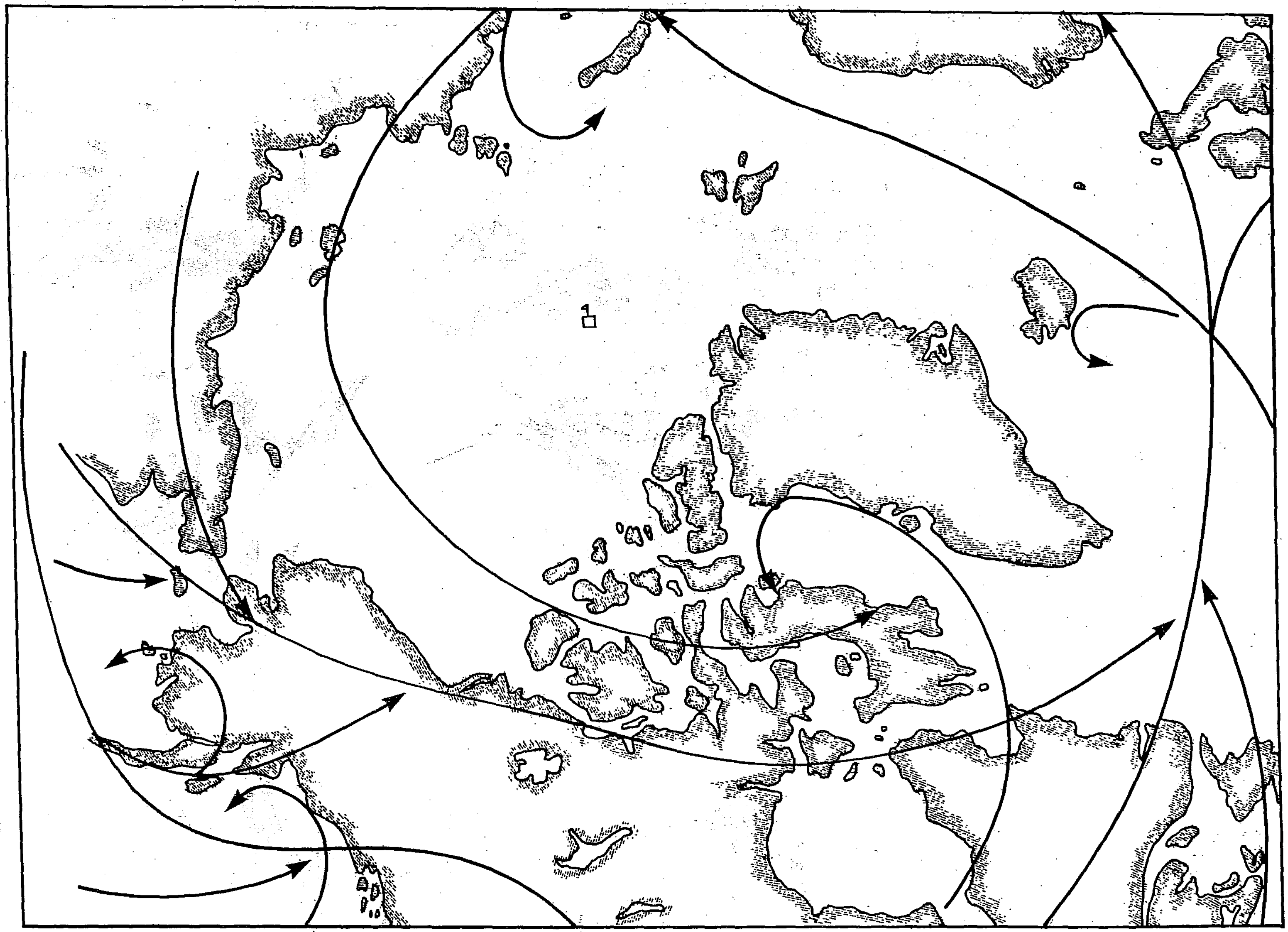


Figure 2.4 Mean tracks of low pressure centres - Jul Aug Sep 1944-1951 (after Berry, et al, 1953).

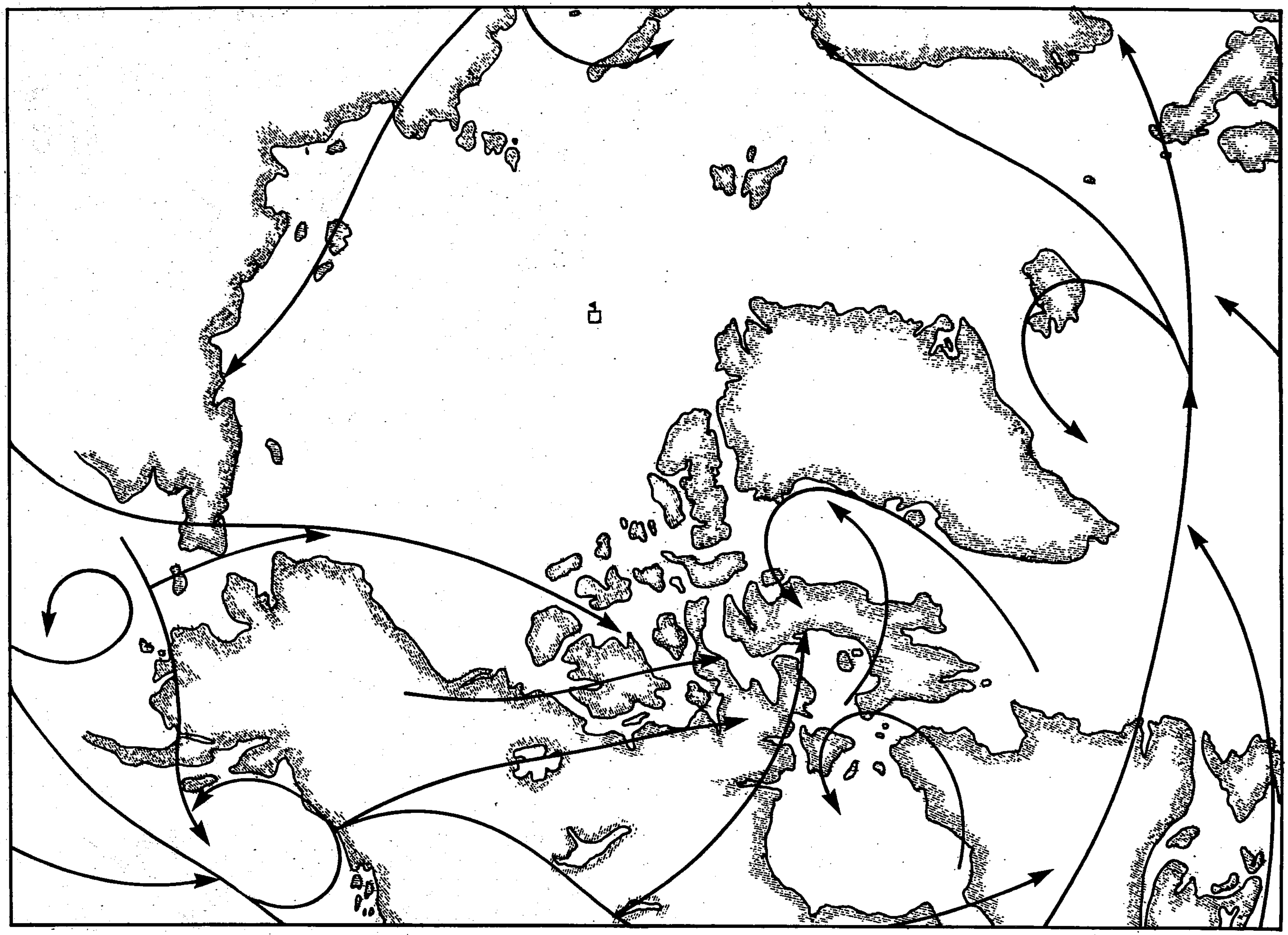


Figure 2.5 Mean tracks of low pressure centres - Oct Nov Dec 1944-1951 (after Berry, et al, 1953).

3. WIND

3.1 INTRODUCTION

The purpose of this chapter is to examine the winds over the open marine areas as well as the alterations to the wind field due to influences such as terrain, atmospheric stability and others which will be discussed subsequently.

Wind is the driving force behind many of the meteorological and oceanographic factors that influence the marine transportation area. For example, ice motion, waves, blizzards, and fog are the result of or directly affected by wind. Thus, a considerable portion of this study will be devoted to wind.

A major problem for a wind study in the Arctic marine areas is the lack of data over the sea. The few land-based stations that report on a regular basis are not representative of the wind structure over the sea due to local terrain effects. There are ship reports available at several locations but only at sporadic time intervals and mainly during the summer season. There are virtually no winter-time observations over the proposed marine transportation route.

Due to the lack of observations, a set of numerically derived wind statistics has been presented. These data are derived from mean sea level pressure maps analyzed over a regular grid of 381 km spacing at 6-hourly intervals from January 1946 to December 1978. The analyses were compiled by the Fleet Numerical Oceanographic Center (FNOC) in Monterey, California. In this study, part of the FNOC gridpoint data pertaining to the Arctic marine areas was processed and supplied by the Climatological Applications Branch, A.E.S., Downsview, Ontario (Swail, 1982). Winds were computed from the pressure fields and will be referred to as the FNOC winds.

3.2 GEOSTROPHIC VERSUS SURFACE WINDS

The FNOC winds were computer derived using the simple geostrophic wind relationship. This relationship states that the geostrophic wind speed is proportional to the gradient in the pressure pattern and is also a function of latitude. Mathematicaly, it is the wind velocity for which the Coriolis force exactly balances the horizontal pressure force. In the northern hemisphere the geostrophic wind direction is oriented parallel to the isobars with the lower pressure to the left.

Several factors act to alter the observed wind speed and direction. These are briefly discussed in Table 3.1.

Table 3.1 The influence of various factors on the observed wind.

Factor	Effect
1. Surface roughness.	Increased surface roughness or friction causes the observed wind speed to be lower than the geostrophic wind speed. In addition it causes the direction of the observed wind to deflect towards lower pressure.
2. Atmospheric Stability. Stability is proportional to the difference in temperatures between upper and lower levels. Stable low level air masses are prevalent in the Arctic during winter and over open water during the summer.	The more unstable an air mass, the closer the real wind speed approaches the geostrophic speed.
3. Curvature of the isobars.	The main effect is to reduce the observed wind in areas of cyclonic flow, i.e., around a low, and to increase the observed wind in areas of anticyclonic flow, i.e., around a high.
4. Rate of change of pressure. Lines of equal pressure tendency are called isallobars.	The gradient of the pressure tendency results in a component which blows perpendicular to the isallobars towards falling pressure. It is often not neglibile and may reach speeds of 5 m/s. (Hess, 1959).

As can be seen from the preceding discussion, the geostrophic wind speed and direction may be obtained from the pressure field but several corrections have to be made to it in order to obtain a realistic result for the surface wind. Some of these corrections are difficult to determine, even in data dense areas. Such a treatment for a large set of pressure data such as the FNOC set was considered prohibitively time-consuming (if not impossible) for this study. Alternatively, an examination of the FNOC geostrophic winds at one grid point may be made in order to determine how well these represent the real surface winds where the latter are available.

Comparisons between the FNOC winds and the actual surface wind reports are difficult to obtain due to the lack of open sea observations at a single point for a considerable period of time. One statistical comparison was made by Lachapelle (1980) between Ocean Station "Bravo" in the Northwestern Atlantic and FNOC data. He found that the FNOC geostrophic winds agreed well both in direction and speed with the actual "Bravo" winds for geostrophic speeds less than about 20 metres/sec. However, for higher speed cases, the FNOC computed winds were larger than the actual reported wind speeds.

An adjustment for geostrophic wind speeds above 20 m/s will now be considered. As a part of the FNOC wind statistics, the all-time extreme geostrophic winds were computed for each grid point and each month. Forty-nine such cases were compared to geostrophic winds extracted by hand from the Arctic Weather Centre (ARWC) surface pressure maps. From this comparison it was found that the hand extracted geostrophic winds were, on the average, 2 m/s greater than the numerically computed values and direction differences averaged 2°. These values are well within the accuracy of hand extraction from hand-drawn pressure maps. Thus, for the cases examined, the hand and numerically derived geostrophic winds were in reasonably good agreement for the higher wind speeds. It now remains to compare actual surface and hand extracted geostrophic winds.

To accomplish this, three months of data were obtained for Kopanoar (70.24°N, 135.12°W) in the Beaufort Sea for July to September 1980 and for Dome Maclean (77.32°N, 103.56°W) northeast of Rea Point for December 1980 to February 1981. Kopanoar is an offshore site over open water while Dome Maclean is an offshore site on a frozen ice surface. Figure 3.1 shows the results of plotting hand extracted geostrophic and the reported surface winds. As can be seen, a considerable scatter in the points is evident. For example, a geostrophic wind speed of 30 m/s for Dome Mclean may occur for a reported wind from 10 to 22 m/s. The reason for this large range is the combination of influences such as atmospheric stability, curvature, etc. on the surface winds as discussed earlier. A similar result was found by Henry (1975) for offshore winds in Mackenzie Bay. Despite this large scatter, it was felt that an average value for the correction to the geostrophic winds could still be presented as a first-guess approximation.

From the Kopanoar and Dome Mclean cases, with winds above 15 m/s, the following results were obtained. The average ratio between the actual and geostrophic winds was calculated as 0.64 with standard deviation of 0.11 for Kopanoar and 0.52 with standard deviation 0.12 for Dome Mclean. The geostrophic wind deviated from the observed wind by 15° (standard deviation 19°) and 21° (standard deviation 21°) at Kopanoar and Dome Mclean respectively. It is noteworthy that the winter adjustments are larger for the Dome Mclean winds. This is likely due to the rougher ice surface which retards the wind speed more severely and also turns the direction more to the left. Also, the atmosphere is more likely to be stable for the Dome Mclean winter data than for the summer Kopanoar sample.

It must be emphasized that these corrections are first approximations only and that further refinements could be made based on

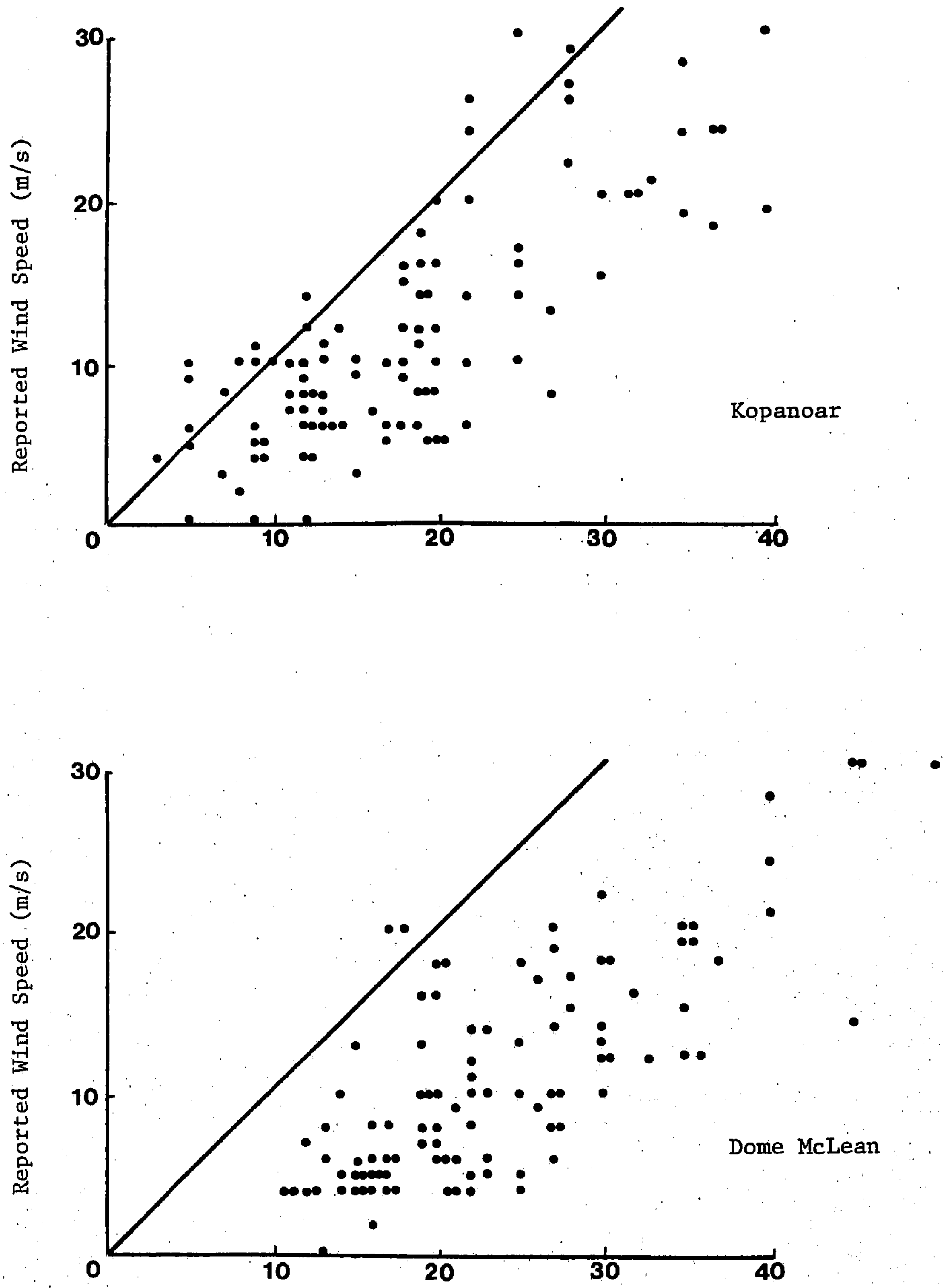


Figure 3.1 Hand extracted geostrophic surface winds vs. reported surface winds.

other effects previously discussed. In general it can be stated that for winds less than 20 m/s the FNOC wind speed will, on the average, be close to the observed wind speed. However, as speeds increase above 20 m/s a larger and larger correction will have to be applied to the FNOC data. This correction factor will likely vary from grid point to grid point and from one case to another. In addition, another correction would have to be be made to the FNOC directions which will normally be to the right of the observed wind. In the subsequent material presented in this paper, the FNOC wind statistics are presented without corrections as to speed or direction.

3.3 LOCAL WIND EFFECTS

Although grid point data provide a convenient means of using a computer for compiling wind information over a large area, as previously stated, the actual surface wind observed at any given location may show wide variations in both speed and direction. These changes can often be attributed to such factors as the effects of local topography, atmospheric stability, proximity of glaciers, and the presence or absence of open water.

The realization of the existence of local wind regimes is not new and the journals of early arctic explorers make numerous references to local winds.

The term "local" is used here in a broad sense to include such phenomena as a "chinook" type wind which may extend for 100 km along the lee slopes of a mountain range to a valley wind whose effect may be confined to a particular slope.

Some knowledge of these winds is essential, especially in the arctic, as the onset and ending can be quite abrupt both in space and time. The consequences of such rapid changes are frequently hazardous and in some cases fatal as occurred in Frobisher Bay during the winter of 1967-1968 (Parker). In this case, the rapid onset of a blizzard made it impossible for two people, who were on foot and would normally have been within sight of the settlement, to make a safe return.

Although there are any number of factors which can produce or modify local winds, the following discussion will be limited to those more common in the Arctic:

a) Wind flow around a barrier.

The influence of a barrier on local winds has been treated by a number of authors including Dickey (1961) and Wilson (1973, 1974).

A stable atmosphere (See Section 5.4) will tend to dampen or resist vertical motions. Wilson (1973, 1974) shows that, under stable atmospheric conditions, air will tend to flow around rather than over a barrier if the latter's height is over 300 m. Under very stable atmospheric conditions, not uncommon in the Arctic, this height may be as low as 100 m.

For a barrier such as a small island or individual hill, the flow will simply split with a velocity of about twice the undisturbed flow occurring on either side of the barrier (Figure 3.2).

Conditions change when a large barrier is encountered, as other, weaker forces begin to have an effect. Wilson (1974) shows that there is a theoretical maximum distance the flow will depart to the right as it has to work against the pressure gradient and thereby loses energy. On the other hand, the portion of the flow diverted to the left gains in energy and speed. This then means that there is a tendency for anticyclonic (clockwise) flow around obstacles such as islands and peninsulas and cyclonic flow (anticlockwise) flow around bays (Figure 3.3).

Dickey (1961) obtained very good results when he used this approach to explain the strong winds observed at Barter Island. The strong westerly winds observed at Cape Fanshaw on northern Bylot Island also seem to fit this theory.

(b) Wind flow through constricted areas.

Straits, such as Cardigan and Hell Gate, are well known areas of strong winds. As indicated in the preceding discussion, the height of the land on either side of the strait and the stability of the air are important in assessing how susceptible any given strait or channel will be to strong winds.

Wind records from Johnson Point (Table 3.2) indicate a channeling through Prince of Wales Strait. Also wind roses constructed from the Summary of Synoptic Meteorological Observations (SSMO) tables (Figures 8.11 to 8.14) show a tendency for east-west channeling through Lancaster Sound even though the size of the sound is much greater than the previously mentioned areas.

(c) Wind flow through mountain passes.

To the meteorologist, mountain passes and strong winds tend to be synonymous. An ideal pass for strong winds is one which cuts through a mountain range to provide a link to a relatively higher interior plain, plateau or glacier. During winter conditions, cold air forming over the interior plain will, under certain conditions, drain through the pass and if the slope is sufficient these winds can become very strong.

As with the flow through a constricted area the shape of the pass, stability of the air and general synoptic pattern are important factors in determining the strength of the wind in any given situation.

The Blow and Babbage Rivers flow through such passes over the northern Yukon and winds along portions of the Yukon coast are influenced by these valleys. This area will be examined in more detail in Section 10.6.

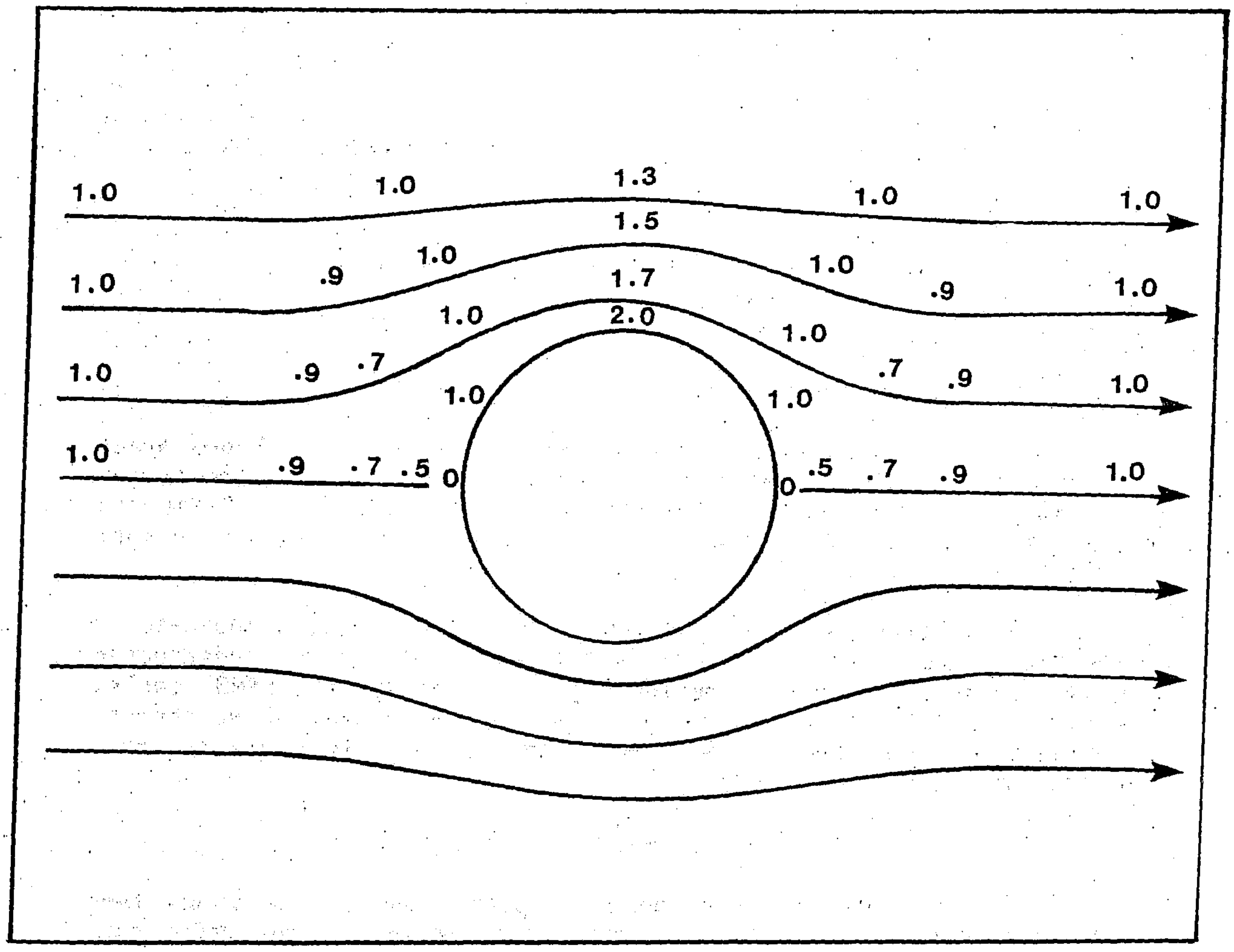


Figure 3.2 Streamlines and velocity field around a fixed cylindrical barrier (based on Dickey, 1961).

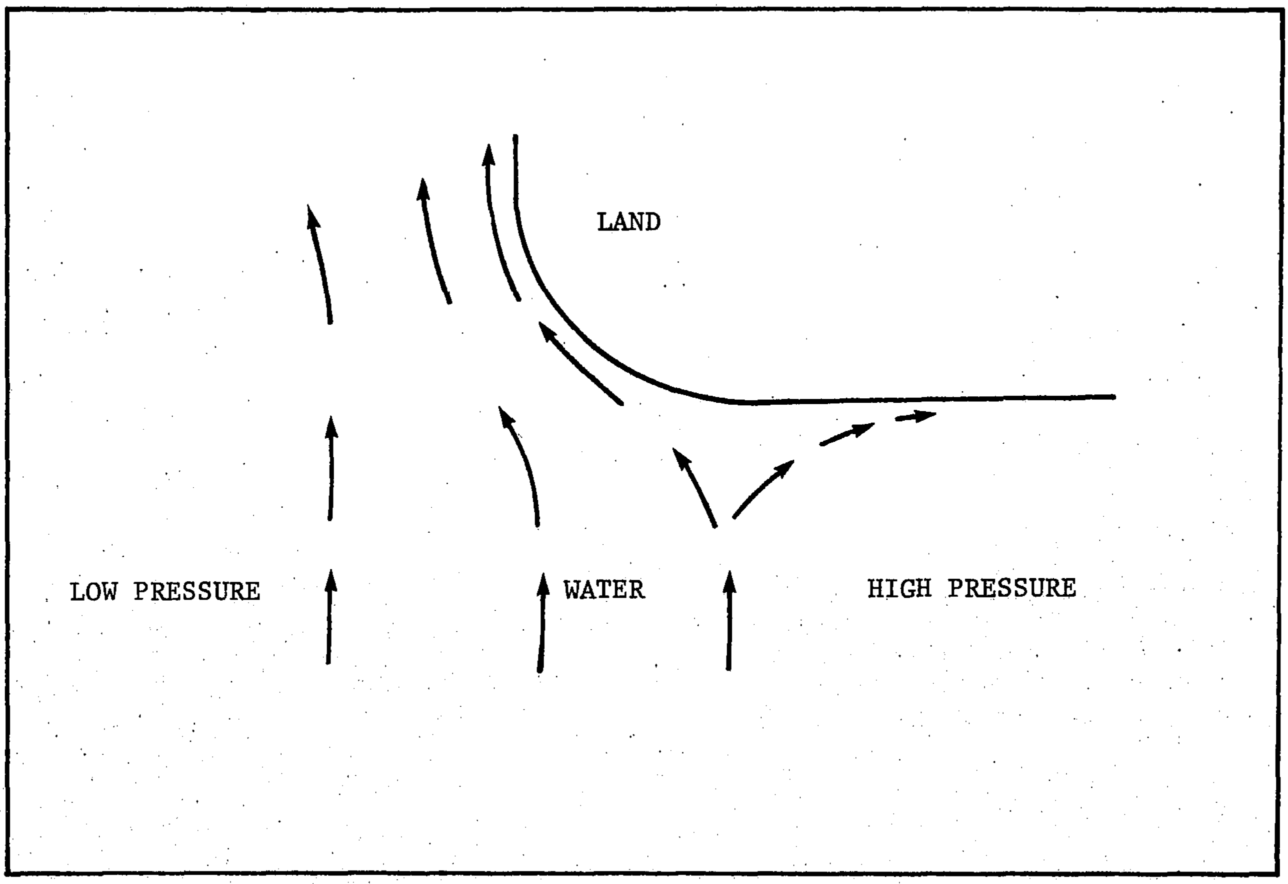


Figure 3.3 Streamlines showing tendency for enhanced anticyclonic flow around a peninsula or island.

Table 3.2 Percent frequency of wind by direction for Johnson Point, N.W.T. (period of record 1972-1976).

MONTH	DIRECTION								
	N	NE	E	SE	S	SW	W	NW	CALM
Jan.	2.6	14.7	.4	.3	1.4	14.3	22.6	29.5	14.2
Feb.	3.1	27.1	1.4	.3	1.0	11.4	16.3	25.1	14.1
Mar.	3.8	22.3	.7	.2	1.7	12.2	14.7	28.4	16.1
Apr.	2.8	44.2	2.8	.4	1.2	9.4	12.6	14.4	12.2
May.	5.9	43.5	8.8	1.4	1.6	6.4	4.7	21.5	6.1
Jun.	4.7	47.5	7.5	1.8	5.0	13.5	5.2	8.7	6.1
Jul.	5.0	26.1	1.3	.8	5.7	24.4	14.0	16.0	6.6
Aug.	5.6	32.1	3.2	1.0	4.0	12.7	13.7	16.7	11.0
Sep.	17.1	20.7	8.9	2.9	2.5	7.3	12.8	21.5	6.1
Oct.	8.4	27.6	11.8	2.9	2.5	4.6	10.5	27.1	4.6
Nov.	4.9	31.5	5.6	1.4	2.2	8.8	13.2	24.5	8.0
Dec.	3.4	23.7	2.5	2.6	2.6	12.0	18.5	25.2	10.6

(d) Katabatic winds.

The Glossary of Meteorology (1959) defines Katabatic wind as "Any wind blowing down an incline". It goes on to say "if it is warm it is called a foehn, if cold it may be a fall wind such as the bora, or a gravity wind such as a mountain wind".

A number of studies have been done on Katabatic winds associated with glaciers. N.A. Streten et al. (1971), in a study on the McCall Glacier, located in the Brooks Range of northeast Alaska, found the speed of the wind was directly related to the strength of the surface inversion and lapse rate (the change of temperature with height, 1°C/100 m) between a location outside the valley and on the mountain top. In this case the slope of the glacier was 7° and measured wind speeds were only around 5 m/s.

This is a case of a katabatic flow in the absence of other factors such as a strong pressure gradient.

The slope of the terrain plays an important part in determining the nature of these winds. F. Defant (1951) stated that a slope of 1:100 seemed to be critical, a result which is confirmed by observation. If this slope is exceeded then small initial disturbances grow exponentially with time and the flow becomes unstable and turbulent. On lesser slopes friction will dampen out these disturbances.

Fraser (1968) described the local winds that develop along the north side of the Melville Hills by using the theory of katabatic flow developed by Ball (1956). These winds are not uncommon and page 5 of his paper carries the quote "...the wind can be heard "roaring" and one can see snow churning over the slope to the southwest when calm conditions prevail at Paulatuk".

In another paper Fraser (1959) looked at the unsteady north-east winds which occur at Resolute Bay and used the theory of katabatic flow to explain them. Headley (1979) reports that in June of 1927 the R.C.M.P. station at Dundas Harbour reported "a terrific gale of hurricane force", which caused considerable damage.

There is little doubt then that strong katabatic winds are quite common in the arctic but lack of observations allows most of them to remain undetected. Of the regular reporting sites in the Arctic those in mountainous areas frequently report strong winds. Thule is well known for the strong winds which suddenly sweep across the area. In the Canadian Arctic, Cape Dyer, Broughton Island, Cape Hooper, Eureka, and Pangnirtung frequently report katabatic type winds. Although it is of particular concern to arctic marine transportation, there is little information as to how far these winds extend out to sea. Ball (1956) reports that observations made at sea near Cape Denison, Antarctica showed that the wind did not extend more than a few miles from the coast. If this is a general rule, then katabatic winds are more important in port siting and design rather than in the choice of a shipping route.

(e) Wind flow over a mountain range.

Winds over a mountain range, katabatic winds and winds through mountain passes at times blend together and may become difficult to separate. However, they frequently can be distinguished and for ease of discussion have been separated in this report.

To again quote F. Defant (1951) "In almost all mountain areas, conspicuous local winds can be observed which blow from ridges down into the leeward lowlands".

There are not a great many cases of foehn winds reported across the Arctic; however, G. Schram (1981) relates that in the summer of 1967 at Tanquary Fjord on Ellesmere Island, strong but warm northeast winds were not uncommon, at times lasting two days.

Fraser (1968) speculates that lee waves are at times responsible for the strong winds observed north of the Melville Hills.

Generally speaking, for lee waves and gusty surface winds to develop, the upper winds must be perpendicular or nearly perpendicular to the range of hills and certain conditions of atmospheric stability must exist.

These conditions are frequently met over Baffin, Devon and western Melville Islands as well as the northern mountain ranges of Alaska, the Yukon and Greenland. Satellite pictures received at the Arctic Weather Centre in Edmonton often show stationary wave clouds over these mountains which leads one to suspect that gusty winds frequently exist at or near the surface on the lee side of these ranges. When observations exist, a surface trough often shows on the lee of these mountains.

Easterly upper winds over Greenland are not uncommon, especially over the southern portions. These invariably lead to the development or intensification of a surface trough off the west coast of Greenland. This condition is then a favorable situation for foehn winds along the southwest Greenland coast.

In summary then, many types of local wind regimes can be found across the arctic. Besides the ones discussed there are several other types such as land and sea breezes which have been intentionally left out as their impact is not as great.

Of the ones discussed, the effects of channeling may have the greatest impact on the shipping route whereas depending on location, some or all of the others could affect a given port location.

4. VISIBILITY

4.1 INTRODUCTION

Due to the lack of man-made pollutants northern visibilities can be very good, but because of a number of natural phenomena, they often show considerable variation in both space and time. Of this group the most common phenomena are ice crystals, blowing snow and various types of fogs. This chapter will briefly examine each of these and comment on some of the more common optical effects observed in an arctic environment.

4.2 FOG

Fog is one of the major causes of low visibilities in the Arctic. The droplets forming the fog can be either liquid or solid, the latter being known as ice fog. For the purposes of this discussion it will suffice to say that when air is cooled below its saturation point the excess moisture can condense and form fog. This can be caused by a warm moist airmass moving over a colder surface such as Baffin Bay or the Beaufort Sea. Such fogs tend to cover large areas and will persist as long as the source of moist air continues.

It has also been observed that during the summer, fogs frequently develop over an ice pack or ice-infested waters. Wilson et al. (1953) suggested that this could be caused as a result of pools of melt water collecting on the ice surface. Such pools of water would have a low salt content and could be warmer than the sea water. If this water is further heated by solar insolation it may saturate the air and lead to the formation of fog. An example of fog over pack ice, but not the adjacent water, is shown on Page 111 of Arctic Canada From the Air (1956).

During the winter, movement of cold arctic air across open leads or polynyas can produce steam fog. If the prevailing temperature is lower than -35°C (Wilson 1973), this steam fog will frequently change to an ice fog. Ice fogs are also frequently observed near larger urban centers during the winter months and can become a serious problem with temperatures near or below -40°C.

4.3 ICE CRYSTALS

Although common during the winter months, ice crystals are seldom a serious problem as visibilities are generally better than two miles (Wilson et al., 1953). They usually occur over a wide area and surface stations frequently report a combination of ice crystals and ice fog.

4.4 BLOWING SNOW

During the winter months blowing snow is one of the main restrictions to visibility, especially throughout the central sections of the Archipelago. This area is particular susceptable to strong northerly winds due to the frequency of lows in Baffin Bay and higher pressure over the Beaufort Sea. When certain criteria of wind strength, low visibility due to blowing snow, low temperature and duration are met or exceeded, the term "blizzard" is used. Forecast regions may vary in their criteria; however, the definition used by Maxwell (1980) is for a combination of snow or blowing snow, winds of 40 km/h or greater, visibilities of 0.8 km or less, and temperatures of -12.2°C or colder to last for six hours or more.

It has been observed by the authors and other meteorologists at the Arctic Weather Centre that visibilities frequently lower due to a combination of ice crystals and ice fog prior to and following a blizzard. The time may vary from zero up to a few hours, depending on the overall synoptic situation.

A number of factors can influence the amount and duration of blowing snow; however, one of the more important is the time since the last snowfall. If all other factors remain constant, visibilities will gradually improve as the snow compacts, or if no new snow is present a strong wind may only produce drifting snow.

4.5 PRECIPITATION

Precipitation is generally light throughout much of the Arctic and by itself seldom presents a visibility problem. One exception worth noting though is during the fall when snow showers frequently develop as cold arctic air moves southward across unfrozen waters. These are generally not a major problem but, given the right conditions, can become quite heavy, occasionally lowering visibilities to less than 0.8 km.

4.6 OTHER PHENOMENA

Although not strictly a restriction to visibility no discussion of arctic visibilities would be complete without mentioning the "whiteout". It is often used inter-changeably with the term "blizzard" and although snow or blowing snow may be present they are not necessary. The Glossary of Meteorology (1959) defines whiteout as "an atmospheric optical phenomenon in which the observer appears to be engulfed in a uniformly white glow. Neither shadows, horizon, nor clouds are discernible. One's sense of depth and orientation is lost and only very dark, nearby objects can be seen".

Whiteout occurs over an unbroken snow cover and beneath a uniformly overcast sky which results in diffuse reflection and scattering from cloud and snow surface. The whiteout effect can be intensified by low sun angle.

Water sky is a more common phenomena. It refers to dark patches on the base of clouds caused by the reflection from a water surface. Unlike whiteout, this effect is useful as it can be helpful in locating large leads or an ice edge.

The opposite effect is iceblink. This is a white glare on the base of low clouds caused by reflection from an ice surface and can be of use in detecting a distant ice edge.

5. TEMPERATURE

5.1 INTRODUCTION

This chapter presents a general overview of the temperature climatology at several reporting stations either along or near the transportation corridor under consideration. Since temperature is strongly influenced by flow off water, elevation, local valleys, etc., a considerable amount of local variation is to be expected. However, for the purposes of this report, the mean temperature maps do not attempt to show this fine-scale detail. This is justified since the main emphasis here is toward the marine areas. The bulk of the material presented follows Maxwell (1980) and Burns (1973).

5.2 MEAN TEMPERATURES

In Figures 5.1 to 5.4, the mean temperature maps for January, May, July and September are displayed and are taken as being representative of the four seasons in the Arctic. These mean temperatures were based on reporting station normal values for the 1941-1970 period with marine observations also included where possible during the open-water season. The latter data had a limited impact on the results due to the few marine observations available.

The winter chart for January shows the majority of the Arctic Islands between the -30°C and -35°C isotherms. The main departure from this occurs in the east where a "warm tongue of air" extends northward through Davis Strait and Baffin Bay and across northern Baffin Island. This latter feature is a result of the frequent excursion of storms from southern latitudes accompanied by warmer airmasses. In the west, the Beaufort Sea area appears in the above -30°C area. This is a result of systems moving inland from the Gulf of Alaska accompanied by warmer air.

An examination of the May chart reveals a similar pattern. However, the intensity of the eastern "warm tongue" is diminished due to the reduction in the frequency of storms tracking through this area in the spring. The persistence of colder airmasses east of Victoria Island is evident as outlined by the -10°C isotherm.

Since July is the warmest month in the Arctic, its chart shows temperatures over the land as being warm relative to the cool air over the adjacent ice-infested waters. This cooling is evident over western Baffin Bay, western Davis Strait, Foxe Basin and to a lesser extent over the smaller water channels to the west. The warmer airmasses are still evident along the west coast of Greenland and are likely a result of surface heating at the coastal stations.

Finally, the September chart depicts the transition from summer to winter. The general build-up of colder air over the northwestern Arctic Islands is the dominant feature. However, the sea-land effects on the temperature pattern have reversed from the July situation. By September, the cooling of the large land masses is

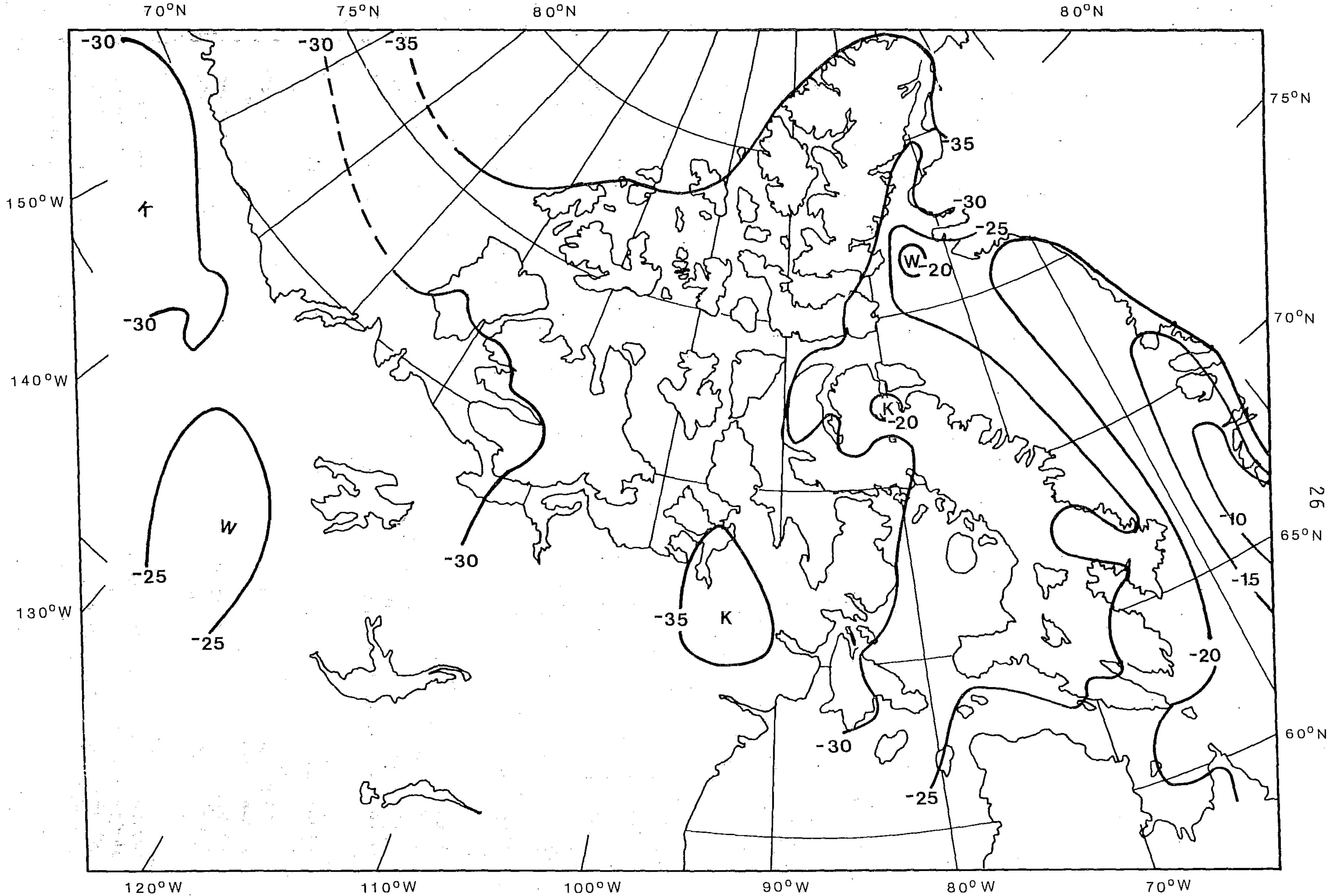


Figure 5.1 January mean temperatures. Data: 1941-1970. (After Maxwell, 1980; Burns, 1973).

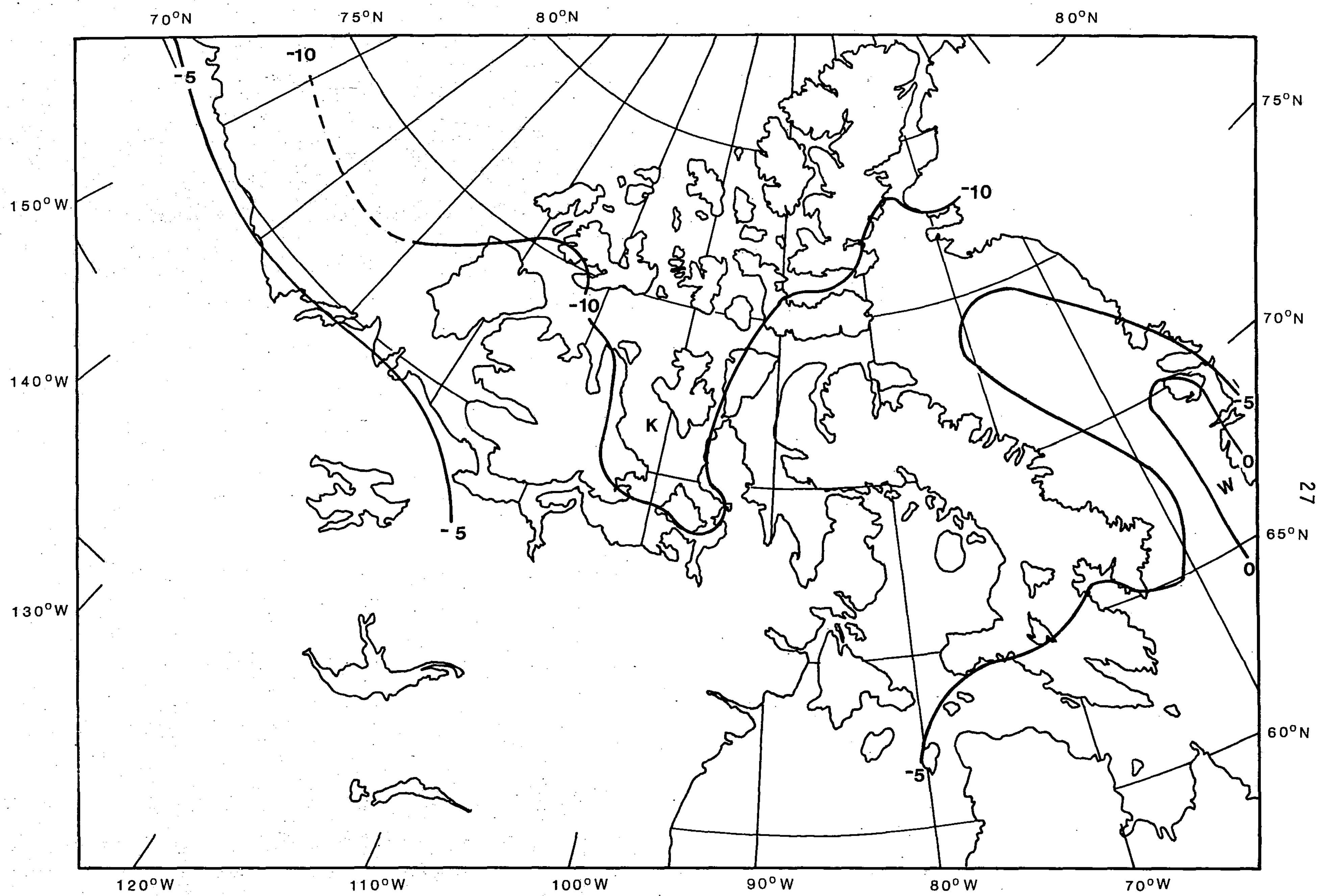


Figure 5.2 May mean temperatures. Data: 1941-1970. (After Maxwell, 1980; Burns, 1973).

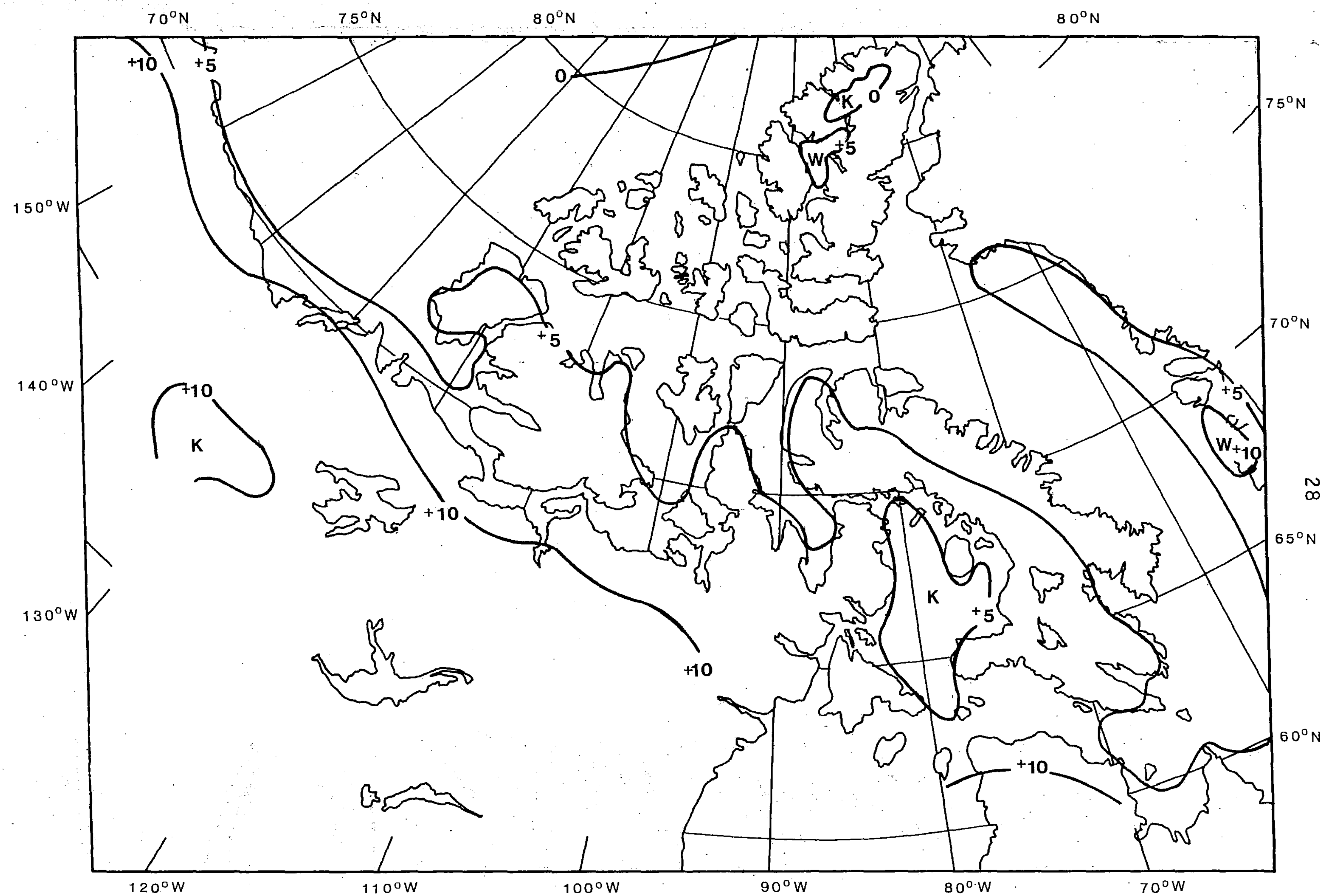


Figure 5.3 July mean temperatures. Data: 1941-1970. (After Maxwell, 1980; Burns, 1973).

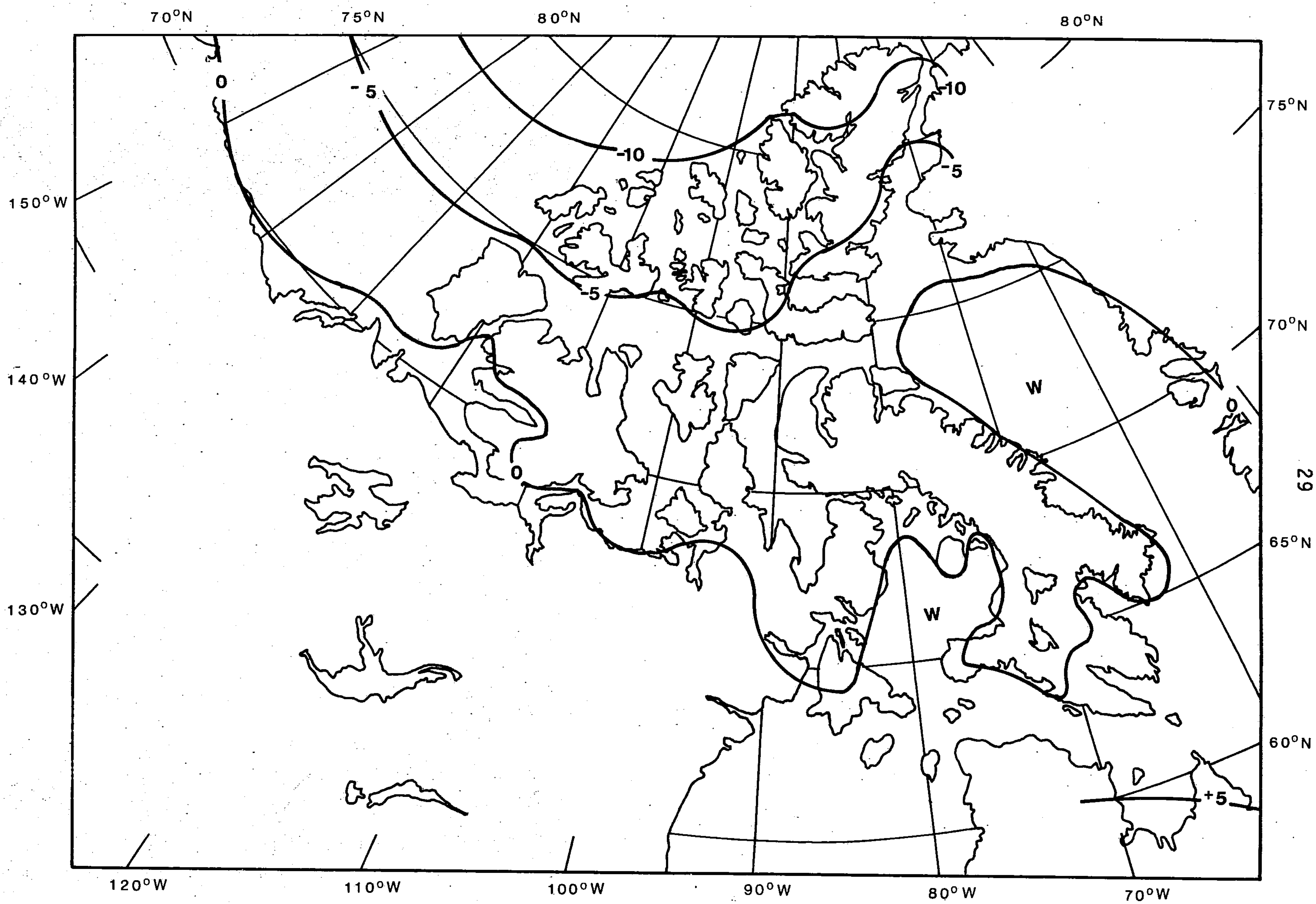


Figure 5.4 September mean temperatures. Data: 1941-1970. (After Maxwell, 1980; Burns, 1973).

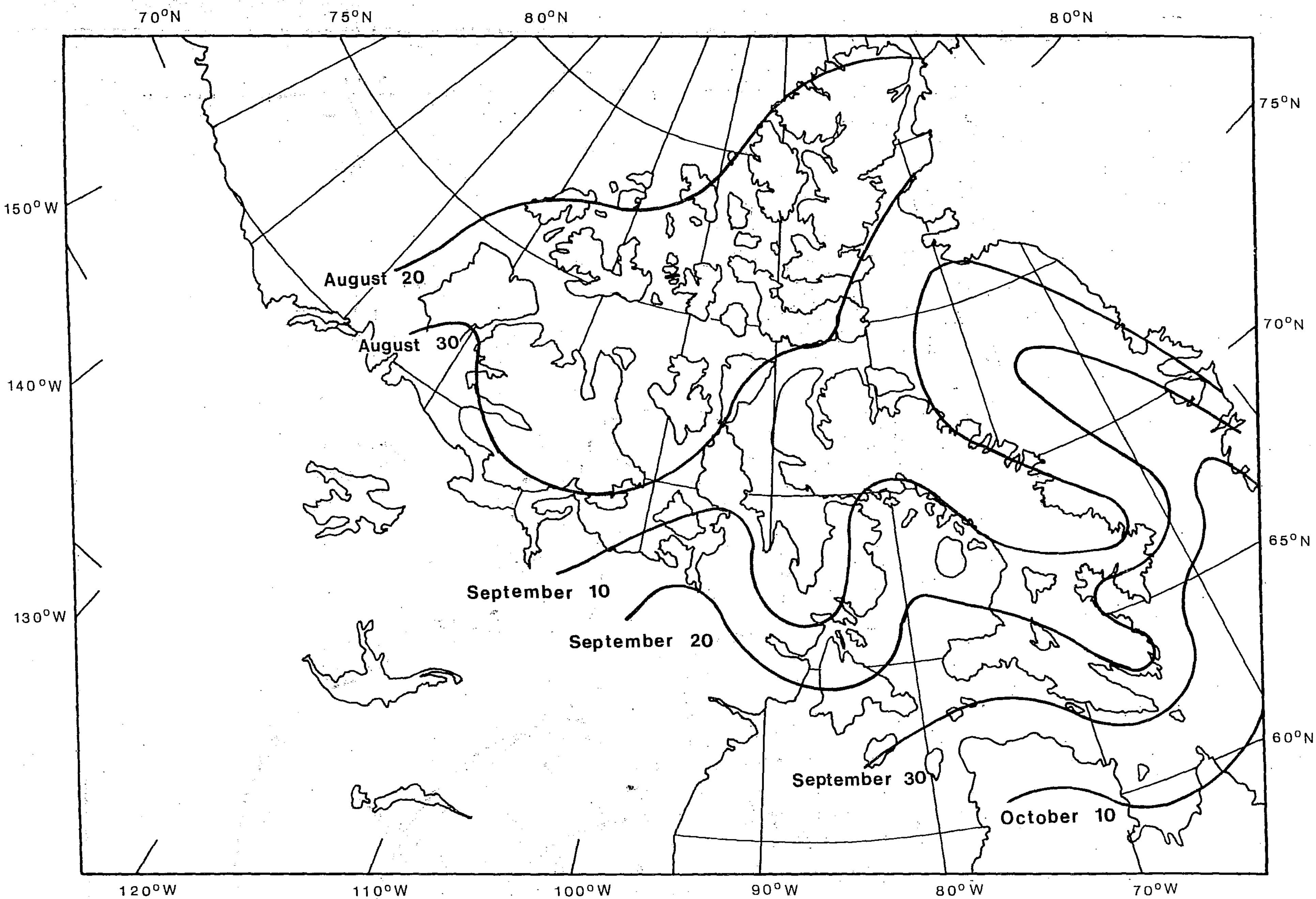


Figure 5.5 Mean date of beginning of winter (mean date when mean daily temperature drops below 0°C). Data: 1961-1970. (After Maxwell, 1980).

occurring as evidenced by the intrusion of the 0°C isotherm into Baffin Island and the northeastern parts of the mainland. The water now acts as a heat source, as clearly shown by the warmer Davis Strait, Baffin Bay, Foxe Basin and Prince of Wales Strait areas.

In Figures 5.5 and 5.6, the mean dates of the start and end of winter are shown. The start of winter is defined as the average date on which the average temperature drops below 0°C while the end refers to the average date when this temperature rises above 0°C. From the beginning of winter chart, the general progression of the dates advances from the northwest to the southeast. Delays in winter are indicated over the Foxe Basin and Davis Strait-Baffin Bay areas as a result of the open water influence in these areas. The end of winter chart is dominated by the "June 10" isopleth which plunges southeastward across the Baffin Island and northeast mainland regions. The warm air intrusions from the Pacific and Atlantic advance the end of winter dates significantly in the western and eastern Arctic respectively.

5.3 EXTREME TEMPERATURES

In Figures 5.7 to 5.11, temperature curves for several stations near the transportation corridors are shown. The upper and lower solid lines depict the record high and low temperatures respectively by month. The middle dashed line indicates the monthly averages of temperatures. All stations depict a similar pattern with the maximum average temperature in July and the minimum average in February. During the winter months the difference between the record high and low values is largest with the mean temperature line closer to the extreme low temperature line. This reflects the predominantly cold conditions that prevail with the occasional warming occurring as a result of an intrusion of a milder airmass associated with a mid-latitude storm.

During the summer the situation changes somewhat. All of the stations shown in these figures are coastal and, consequently, are strongly affected by the cold sea temperatures. As a result, the mean temperatures in summer do not venture far from the sea surface temperatures. The extreme high readings are set during spells of warm offshore winds. The low values do not drop to extremes due to the frequent fog and low cloud cover which can prevail during the calm weather coincident with the cooling conditions.

A few comments may be made regarding offshore sites. Winter temperatures would likely be similar to the shore stations with a moderation indicated near any open leads. During the summer the extreme temperatures recorded at the land stations would be modified by the cold sea surface. This would result in reduced temperature maxima and increased temperature minima for the summer season.

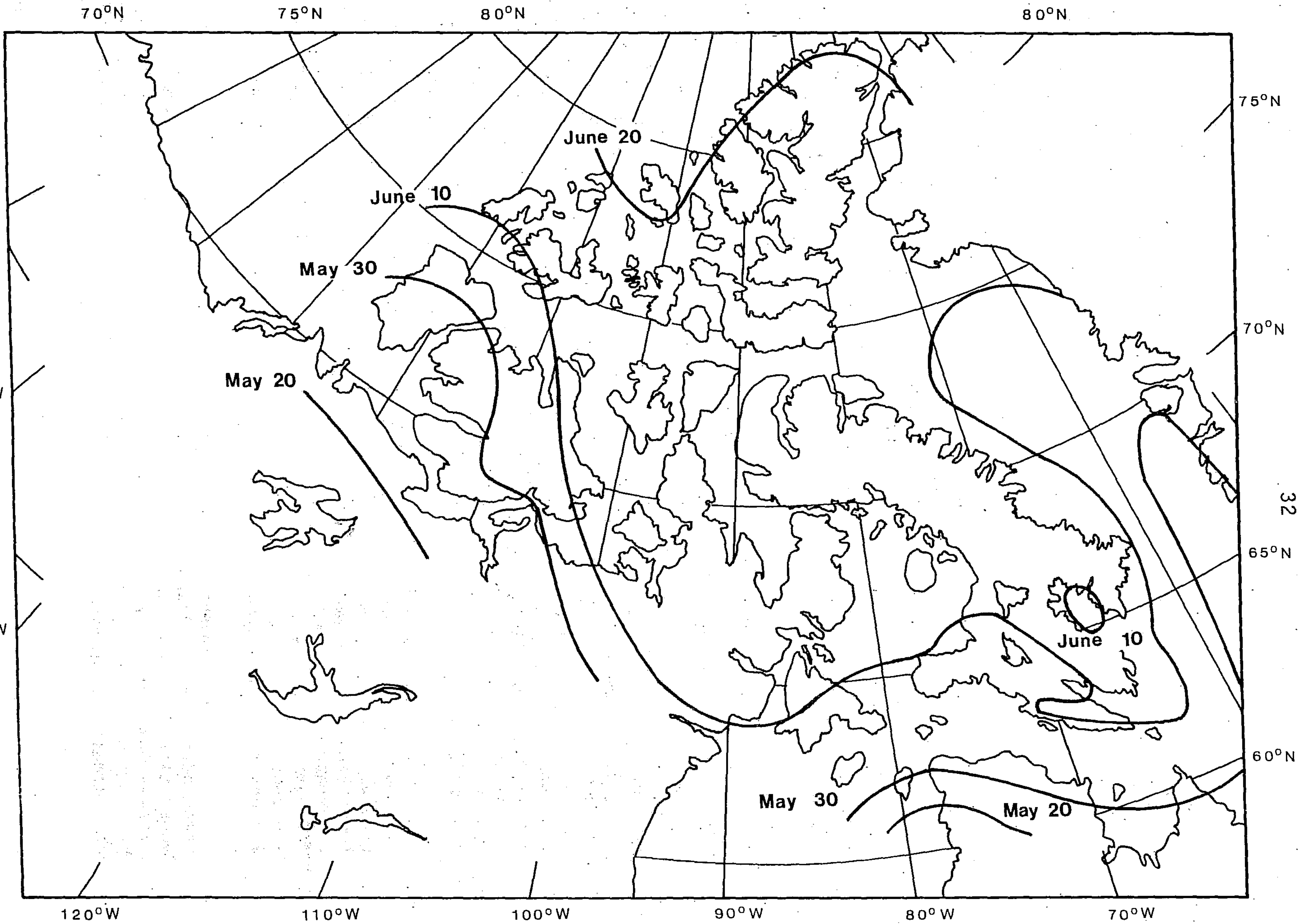


Figure 5.6 Mean date of end of winter (mean date when mean daily temperature rises above 0°C). Data: 1961-1970 (after Maxwell, 1980).

5.4 ATMOSPHERIC STABILITY AND INVERSIONS

By definition, a surface-based inversion occurs in the atmosphere when the temperature above the surface level increases with height. Such a situation is common in the Arctic during all seasons. During the winter regime the absence of sunlight allows strong radiative cooling from the surface to occur and, consequently, well developed inversions are the norm. Inversions also persist through the summer months as a result of the surface cooling by the colder ocean surfaces.

Inversions can play a significant role in several physical phenomena. A discussion of these is given in Burns (1973) and a brief examination of them will be presented here. Of particular importance for use of radar is a phenomenon known as "ducting". Ducting refers to a bending of the energy wave parallel to the earth's surface. During an inversion situation, radar and radio waves are "ducted" causing their range to be abnormally extended. With an air mass in which the temperature decreases with height, abnormal wave bending away from the earth will occur causing shortening of range.

Optical effects are observed during inversion episodes. Again the density difference of the airmass causes a refraction of light waves with the resulting images observed as being the "superior" or "looming" type of mirage. Light waves travelling from an object through a strong inversion are bent back toward the earth's surface. Thus, an object that is below the normal visible horizon "looms" above the horizon, thereby distorting the observer's perception of the distance to the object. The object may also be distorted vertically by this bending further inhibiting distance estimates.

Inversions also play a role in sound transmission. Since sound travels as a compression wave, better sound transmission may be expected within an inversion due to the denser air.

Atmospheric stability plays a strong role in dispersion of airborne pollutants. An inversion dampens vertical motions and thus vertical mixing. In doing so it acts as a trap for the dispersion of pollution. Munn et al. (1970) have compiled statistics on percentages of occurrences of inversions for Canadian radiosonde stations. During the winter months, inversions were shown to occur between approximately 60 and 75% of the time for both the early morning and late afternoon temperature soundings at stations near the proposed arctic marine transportation routes. During the summer months these frequencies dropped to 5 to 25% in the late afternoon and to 25 to 44% for the early morning soundings.

Another method of measuring the pollution potential for an area involves a combination of mixing heights and wind speeds yielding a ventilation coefficient. The mixing height is defined as the height to which a surface-heated air parcel will be mixed with the surrounding atmosphere. Thus, for a strongly heated surface in the afternoon, a parcel will ascend to greater heights thereby dispersing the pollutants more efficiently. However, the mixing height alone is not sufficient to determine whether a pollutant will disperse readily. The mean wind speed from the surface to the mixing height level is also important, since it determines how readily a pollutant is dispersed horizontally. The mixing height and mean wind speed may be multiplied to obtain a ventilation coefficient (units m^2/s). Thus, a large mixing height will imply a significant vertical dispersion of pollutants and a large mean wind speed will imply horizontal pollution dispersion. Since these factors are multiplied, either can act to increase or decrease the coefficient.

Studies by Stackpole (1967) and Gross (1970) found that values of ventilation coefficient of 6000 m^2/s or less are considered indicative of high air pollution potential. Portelli (1977) assumed that this would be a reasonable threshold value for the Canadian ventilation coefficients and presented tables and charts for all of Canada by season. Over the central Arctic Islands regions under consideration, these ventilation coefficients range from 1000 to 2000 m^2/s during spring and fall seasons. These values drop to less than 1000 m^2/s in winter and rise to 2000 to 3000 m^2/s in the summer. During all seasons, therefore, the ventilation coefficients are well below the threshold value of 6000 m^2/s required for a high pollution potential.

Thus, for activities such as power plants, vehicles or ships producing combustion products or any industrial plants there is a strong pollution potential in the Arctic environment, especially during the winter months.

5.5 WIND CHILL

As is well known to anyone living in a winter environment, it is not only the temperature that plays a role in human discomfort. Other influences are the humidity, sunshine, and wind with the latter being the most important and upon which the most emphasis will be placed here. In order to measure the combined wind and temperature effect, many indices have been derived of which the most widely accepted in Canada was developed by Sipel and Passel (1945):

$$H = (\sqrt{100\, V} + 10.45 - V)(33 - T)$$

where: V is the wind speed in m/s
T is the air temperature in °C
the assumed skin temperature is 33°C
H is the wind chill measured as the heat loss in kilocalories per square metre of exposed skin surface per hour.

Some limitations to the index are evident. No account of incoming solar radiation or cloud cover has been made. For bright sunshine, the index could be reduced by about 200 $kcal/m^2/hr$ and for a light cloud cover 100 $kcal/m^2/hr$. As well, no account of evaporation cooling from perspiration or heat loss through conduction or respiration are included. Finally, the height at which official wind speed is recorded (10 metres) is above the human activity level (1.7 metres). Following work by Davenport (1960) and Buckler (1969),

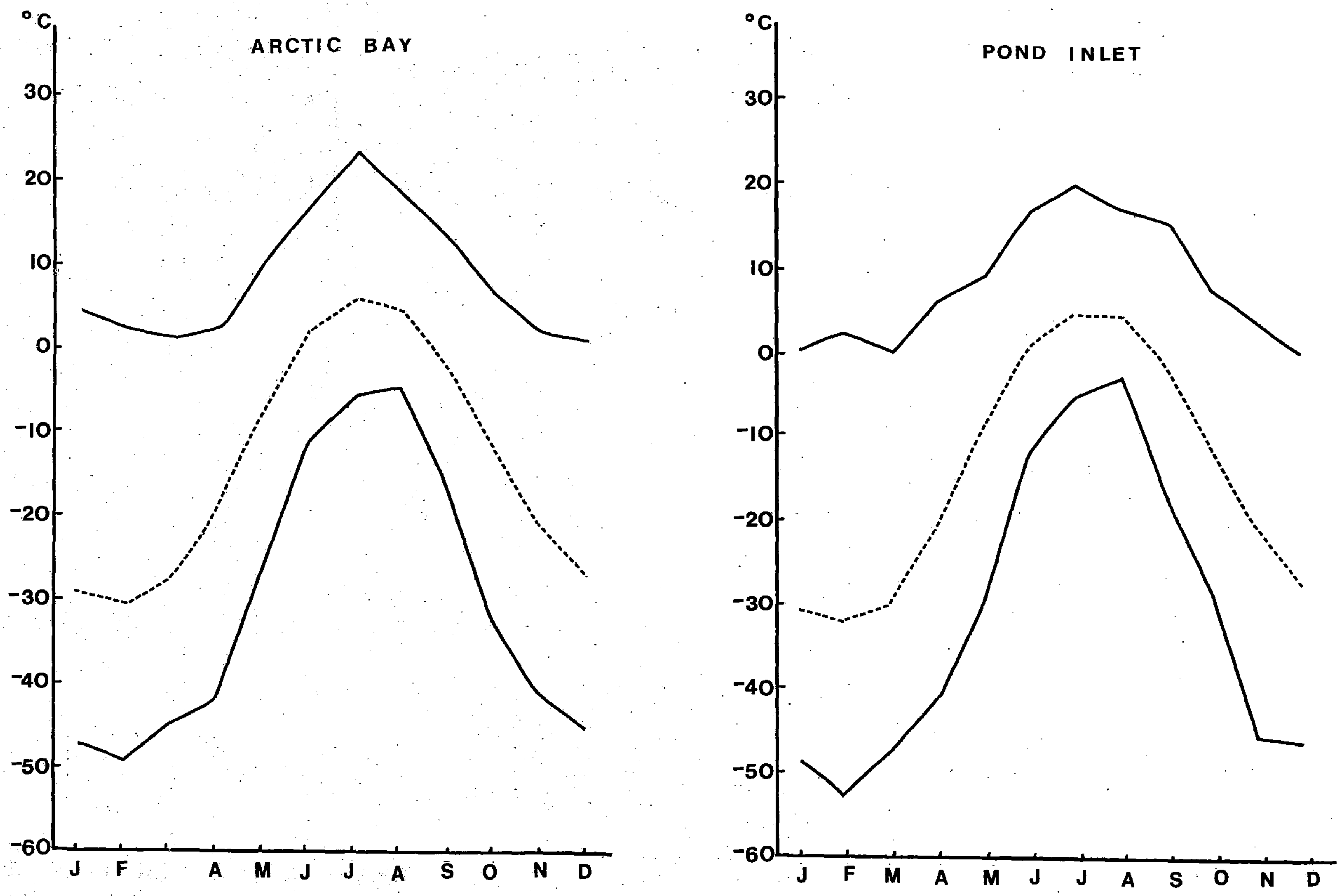


Figure 5.7 Temperature extremes and means. —— Extreme high maximum
------ Mean daily temperature
—— Extreme low minimum

(after Maxwell, 1980).

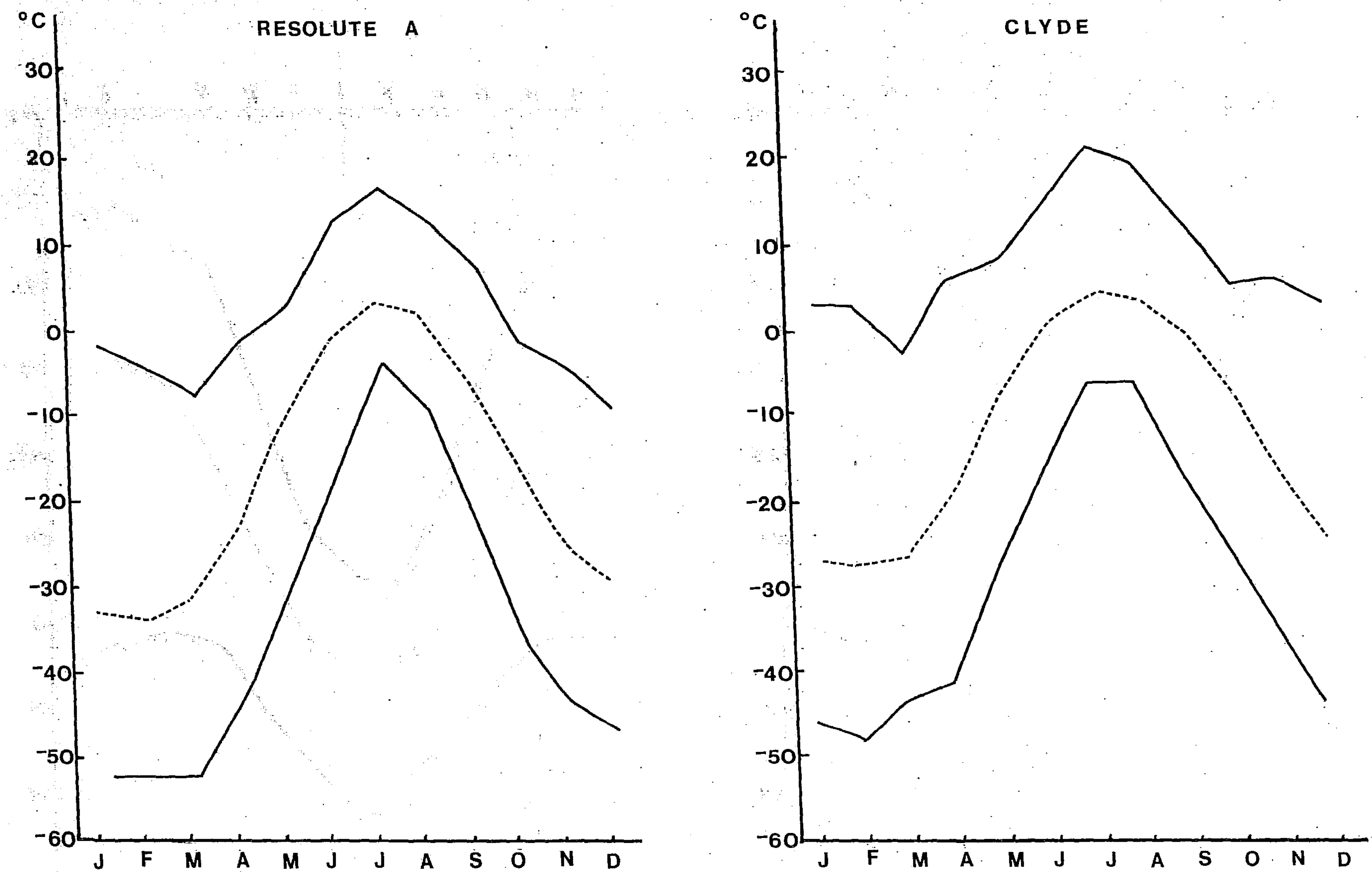


Figure 5.8 Temperature extremes and means. —— Extreme high maximum
------ Mean daily temperature
—— Extreme low minimum (after Maxwell, 1980).

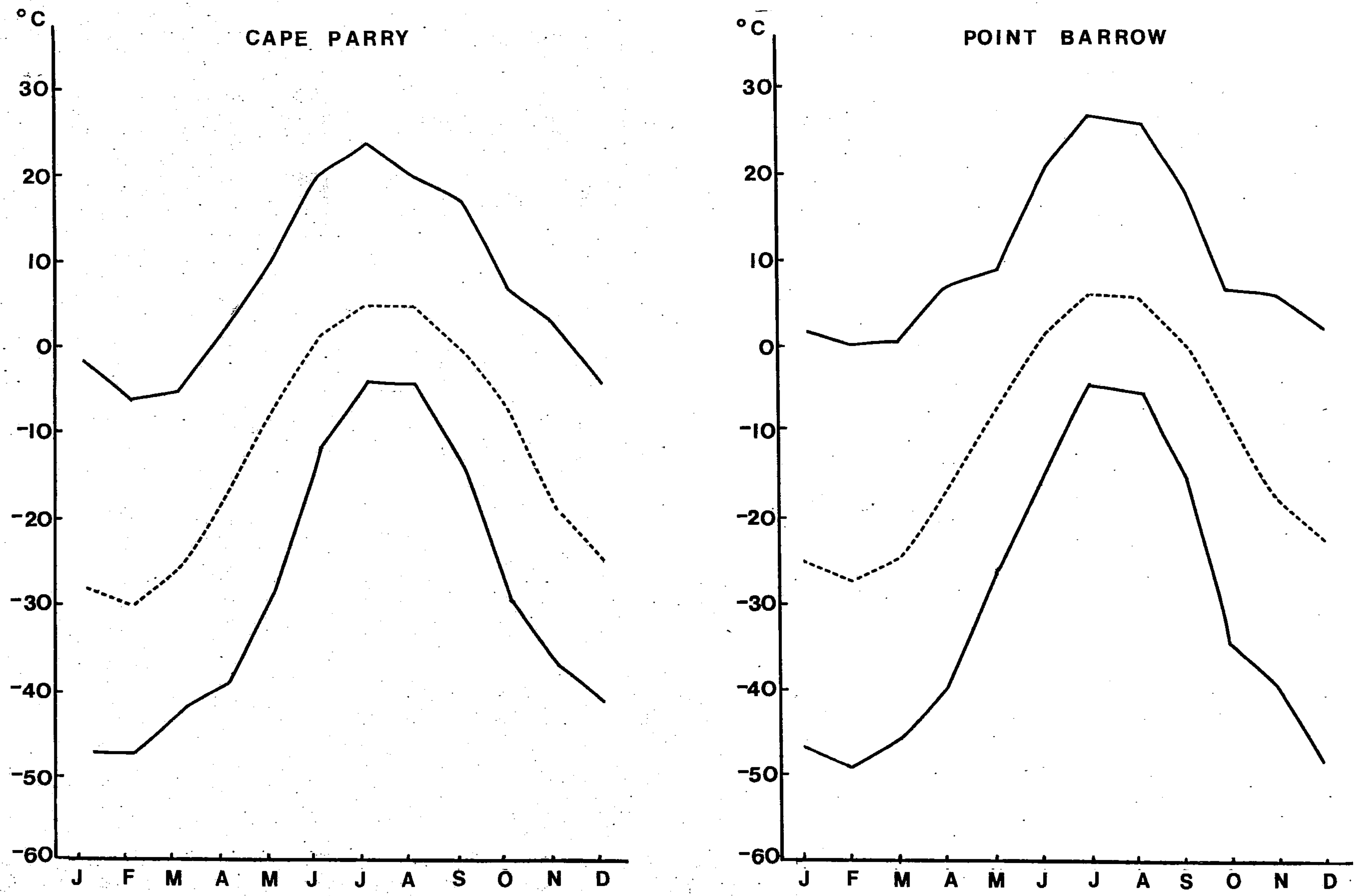


Figure 5.9 Temperature extremes and means. —— Extreme high maximum
------ Mean daily temperature
—— Extreme low minimum (after Maxwell, 1980).

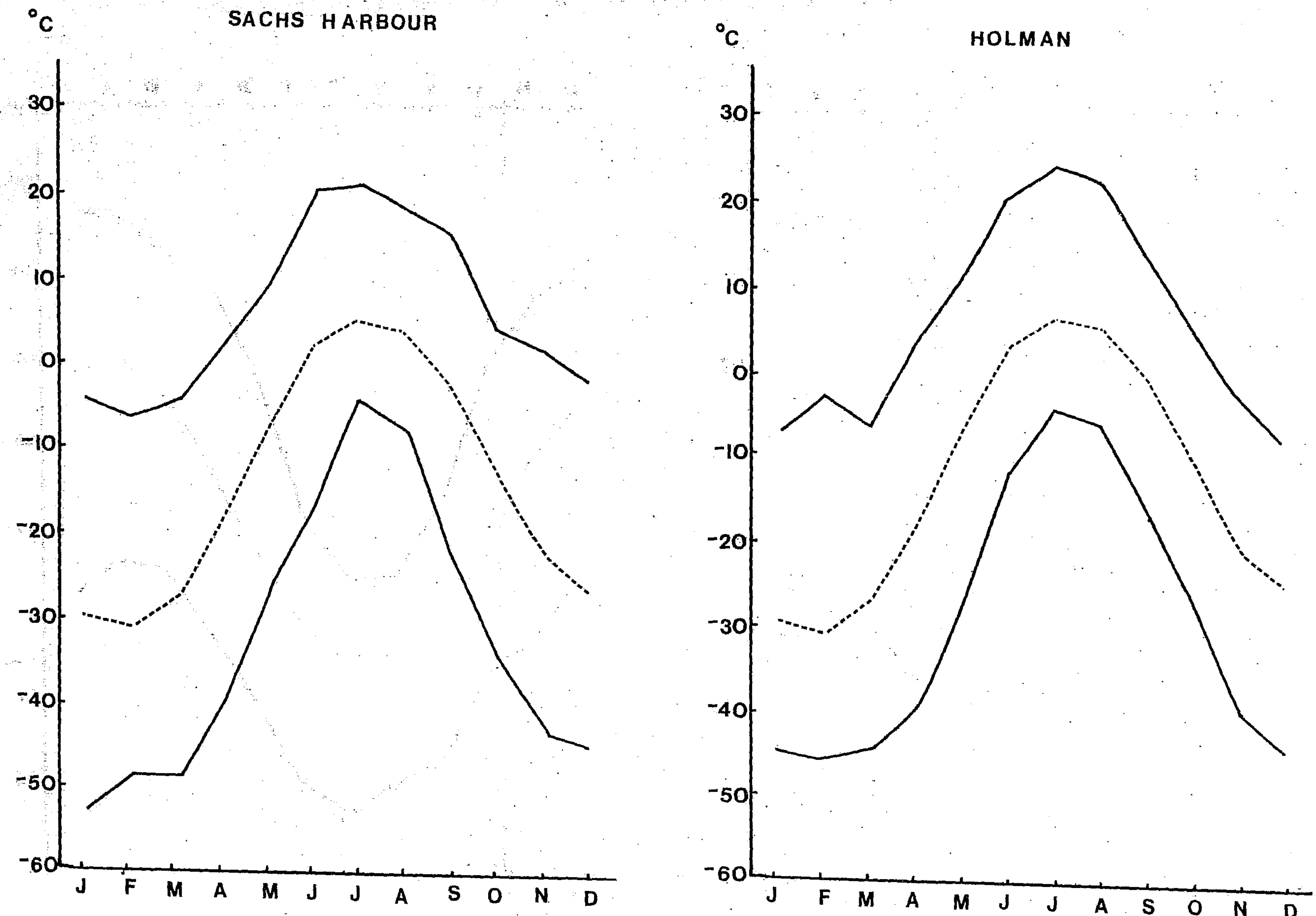


Figure 5.10 Temperature extremes and means. ——— Extreme high maximum
------ Mean daily temperature
——— Extreme low minimum

(after Maxwell, 1980).

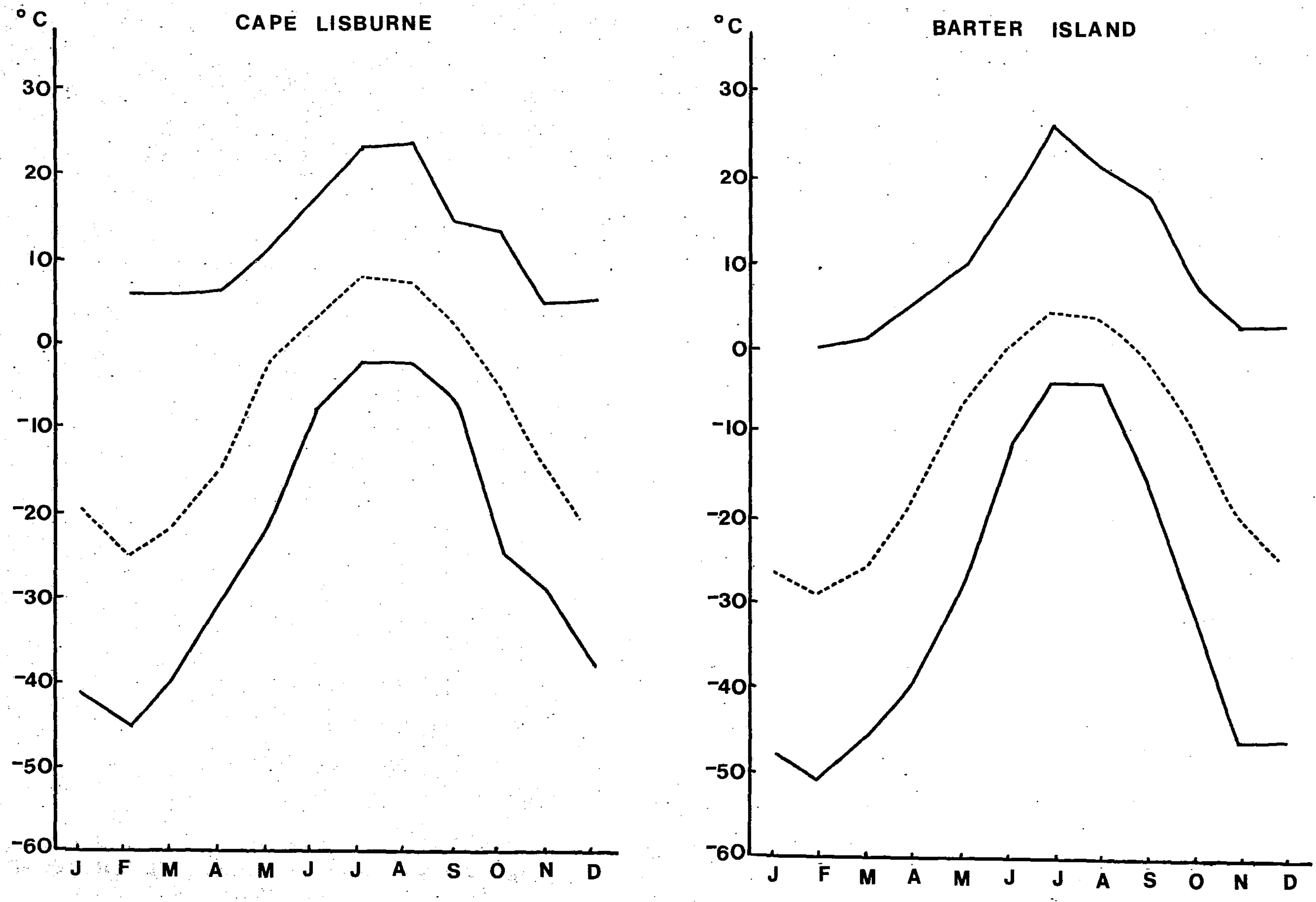


Figure 5.11 Temperature extremes and means. —— Extreme high maximum
- - - - Mean daily temperature
—— Extreme low minimum (after Maxwell, 1980).

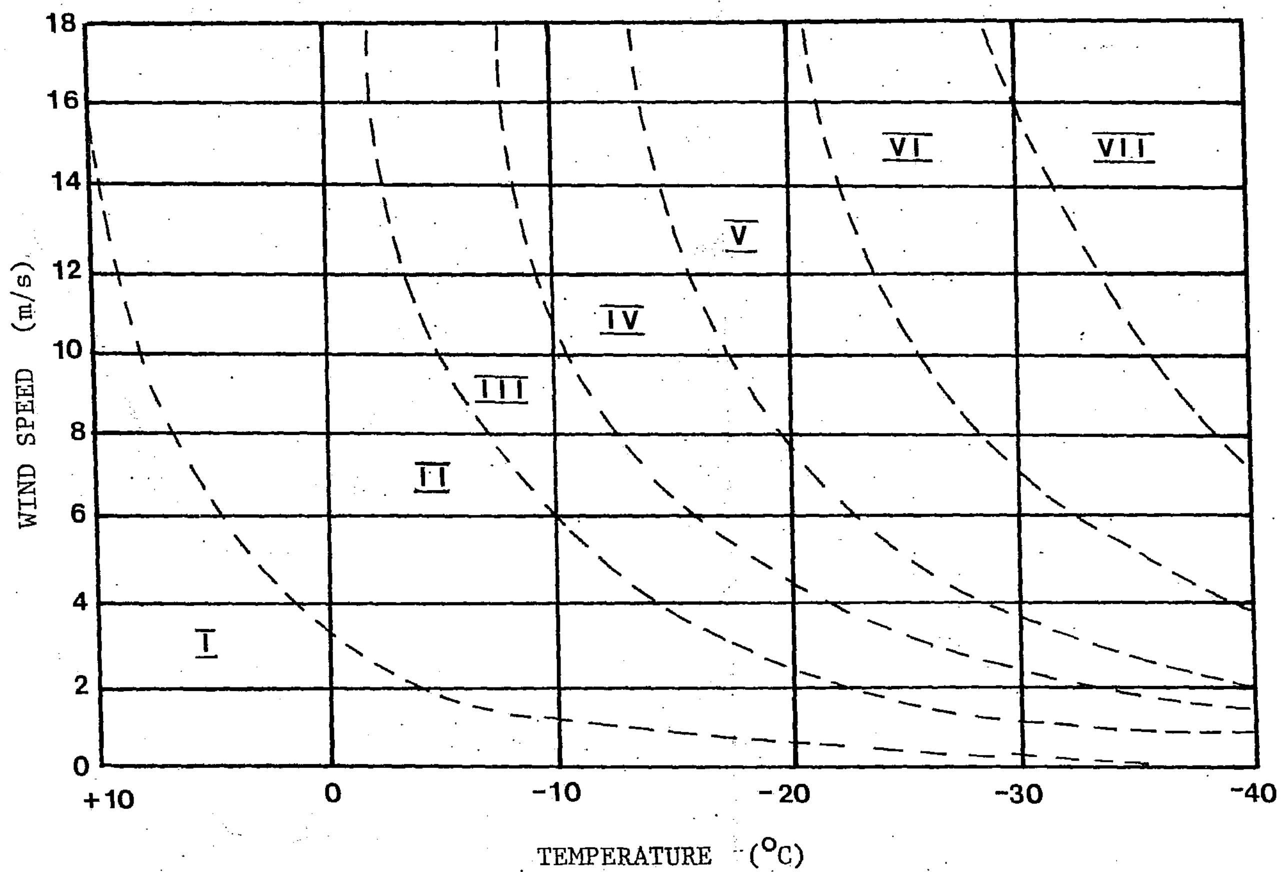


Figure 5.12 Temperature/wind chill index (after Maxwell, 1980; nomogram used by USAF at Goose Bay Air Base, revised September, 1963).

Maxwell (1980) has estimated that the effect of the height difference is to inflate the wind chills by 8 to 13 percent for temperatures from -10°C to -40°C and wind speeds 5 to 15 m/s.

A modification to the index was made by the United States Air Force at Goose Bay, Labrador in 1963. Figure 5.12 shows the nomogram used. The "comfort classes" are described below:

Class I - Comfortable with normal precaution.

Class II - Work and travel become uncomfortable unless properly clothed.

Class III - Work and travel become more hazardous unless properly clothed. Heavy outer clothing necessary.

Class IV - protected skin will freeze with direct exposure over prolonged period. Heavy outer clothing becomes mandatory.

Class V - Unprotected skin can freeze in one minute with direct exposure. Multiple layers of clothing mandatory. Adequate face protection becomes important. Work and travel alone not advisable.

Class VI - Adequate face protection becomes mandatory. Work and travel alone prohibited. Supervisors must control exposure times by careful work scheduling.

Class VII - Personnel become easily fatigued. Buddy system and observation mandatory.

Maxwell (1980) used this nomogram along with distributions of combinations of wind speeds and temperatures to derive tables for percentage frequencies of each comfort class for each month at a given station. Tables 5.1 to 5.3 show these results for several stations near the transportation route. From these tables, it can be seen that all stations exhibit the largest percentage frequencies in higher classes during January and March with the lowest classes predominating in July. The "worst" of these stations in terms of the greatest percentage frequencies in Class VI or VII are Rea Point, Resolute Bay and Isachsen. In January, percentages of times that Class VI or VII occur are 51%, 45% and 48% respectively while the March figures are 26%, 39% and 41%. A re-examination of these class descriptions indicates the severity of the conditions at these locations.

These wind chill percentages are likely applicable to a wide ranging area of the Arctic Islands and the mainland extending from northern Prince of Wales Strait to east of Resolute Bay, north to at least latitude 80°N and south into the District of Keewatin.

Table 5.1 Percent frequency of occurrence of comfort classes by month (after Maxwell, 1980).

Station: Sachs Harbour (1963-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	2	9	10	15	25	26	13
March	2	11	15	21	18	30	3
May	14	50	21	13	2		
July	40	40	*				
September	24	64	11	1			
November	3	15	18	23	27	13	*

* Indicates less than 0.5%.

Station: Rea Point A (1970-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	1	4	8	12	24	29	22
March	2	9	12	16	35	21	5
May	8	40	26	21	5		
July	48	49	*				
September	17	56	21	6			
November	1	7	11	19	28	30	4

* Indicates less than 0.5%.

Station: Resolute A (1963-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	1	5	9	14	26	30	15
March	1	8	11	14	27	26	13
May	9	39	26	19	7	*	
July	42	53	2				
September	13	58	21	7	*		
November	3	16	19	21	26	14	1

* Indicates less than 0.5%.

Table 5.2 Percent frequency of occurrence of comfort classes by month (after Maxwell, 1980).

Station: Arctic Bay (1963-1964, 1971)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	6	20	20	23	28	3	
March	6	23	24	21	23	3	
May	24	63	13	*			
July	80	15					
September	47	53					
November	18	44	19	12	7		

* Indicates less than 0.5%.

Station: Isachsen (1963-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	1	7	10	13	21	27	21
March	1	7	10	14	27	31	10
May	9	36	24	25	6		
July	34	60	4				
September	11	56	23	9	1		
November	3	17	15	19	25	20	1

* Indicates less than 0.5%.

Station: Cape Dyer A (1963-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	3	38	21	18	14	6	
March	6	21	23	26	18	6	
May	27	56	11	6	*		
July	72	22					
September	32	61	6				
November	12	44	25	14	5	*	

* Indicates less than 0.5%.

Table 5.3 Percent frequency of occurrence of comfort classes by month (after Maxwell, 1980).

Station: Coburg Island (1973-1974)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	7	22	22	25	19	5	
March	6	21	24	22	21	6	
May	25	52	18	5			
July	64	36					
September	29	66	5				
November	14	40	25	18	3		

* Indicates less than 0.5%.

Station: Clyde (1963-1972)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	5	19	20	24	27	5	
March	4	19	24	24	24	5	
May	31	53	12	4			
July	61	37					
September	37	61	2				
November	11	31	35	14	9	*	

* Indicates less than 0.5%.

Station: Cape Parry A (1960-1970)

Month	Comfort Class						
	I	II	III	IV	V	VI	VII
January	*	10	14	16	32	26	2
March	1	14	16	17	30	20	2
May	13	66	17	4	*		
July	53	23	*				
September	26	58	3	*			
November	2	27	26	16	3	*	

* Indicates less than 0.5%.

5.6 BLIZZARDS

By definition from Maxwell (1980), a blizzard is termed to exist if the following conditions exist at the same time: snow or blowing snow, winds 40 km/h or greater, visibility equal to or less than 0.8 km and temperatures below -12.2°C.

Many factors play a role in determining whether sufficient blowing snow will occur to give the reduction in visibility required to meet the blizzard definition. Snow age and compaction as well as temperature and wind all influence blowing snow occurrences. However, the wind is the most important factor assuming the temperatures are low enough. Table 5.4 shows the percentage frequencies for blizzards for several stations. As can be seen, the more exposed locations such as Resolute Bay and Rea Point experience higher blizzard frequencies than a sheltered station such as Arctic Bay. In Table 5.5, the mean and extreme durations of blizzards are presented. It should be noted that the short record length for Rea Point and Coburg Island makes the averages and extreme durations unrepresentative. Forecasting experience in the Arctic Weather Centre in Edmonton suggests that these durations should be at least as long and perhaps longer than those of Resolute Bay.

Finally, in Table 5.6, the expected maximum durations of blizzard conditions for various return periods are shown. Rea Point is not included because of the short record length.

Table 5.4. Absolute percentage frequency of blizzard conditions (after Maxwell, 1980).

Station	Period	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Arctic Bay	1953-64,71	0	0	0	0.1	0.4	0.1	0.1	0.1	0
Cape Dyer A	1959-72	0	0	0.5	2.0	4.2	3.4	1.4	0.8	*
Cape Parry A	1956-72	0	*	2.4	2.6	4.3	3.0	3.4	2.7	0.5
Clinton Point	1958-72	0	0.3	4.8	8.0	9.1	5.7	7.0	2.8	0.2
Clyde	1953-72	0	0	1.5	1.6	2.8	4.2	1.0	1.0	*
Coburg Island	1972-74	0	0.8	1.3	8.9	5.2	7.1	4.8	2.5	2.0
Holman	1953-67	0	1.0	1.2	2.2	1.6	2.7	2.0	0.8	0.1
Isachsen	1953-72	0.4	3.6	4.3	6.8	12.4	8.1	5.7	3.0	1.2
Mould Bay	1953-72	0.1	1.4	2.0	3.0	5.1	3.6	2.7	1.5	0.1
Rea Point A	1969-72	0	2.3	4.2	1.5	14.9	4.7	2.7	1.3	1.3
Resolute Bay	1953-72	*	1.7	2.6	5.1	6.4	5.5	4.7	3.0	0.6
Sachs Harbour	1955-72	0	0.9	2.6	3.2	3.0	2.0	2.0	1.4	0.2

*Implies less than 0.05%

Table 5.5. Mean and extreme durations of observed blizzard conditions (after Maxwell, 1980).

Station**	Sep		Oct		Nov		Dec		Jan		Feb		Mar		Apr		May	
	Mn	Mx	Mn	Mx	Mn	Mx	Mn	Mx	Mn	Mx	Mx	Mx	Mn	Mx	Mn	Mx	Mn	Mx
	(hrs)		(hrs)		(hrs)		(hrs)		(hrs)		(hrs)		(hrs)		(hrs)		(hrs)	
Cape Dyer A	-	-	-	-	3	9	5	28	7	43	5	22	6	22	6	21	*	2
Cape Parry A	-	-	*	1	7	47	5	46	7	48	7	52	7	45	9	57	*	30
Clinton Point	-	-	*	12	14	54	16	72	14	48	14	60	16	108	13	30	*	12
Clyde	-	-	-	-	8	24	8	24	12	36	9	36	8	36	8	24	*	6
Coburg Island	-	-	*	12	*	12	15	42	13	30	9	18	8	12	*	18	*	18
Isachsen	7	27	8	51	8	39	11	108	12	60	11	90	9	45	8	66	7	21
Mould Bay	3	3	9	36	7	33	7	24	8	87	7	27	7	24	8	27	3	3
Rea Point A	-	-	6	16	4	13	3	12	8	39	11	27	3	9	4	15	4	12
Resolute A	*	3	5	26	8	27	8	58	8	45	7	47	7	49	8	63	6	24
Sachs Harbour	-	-	7	21	6	42	10	39	7	27	8	24	7	39	10	39	*	15

* Less than 5 occurences in the given month over the period of record.
**For station periods of record, see Table 5.4.

Table 5.6. Expected maximum duration of blizzard conditions (hr) for various return periods (after Maxwell, 1980).

Station	Return Period (Yrs)					
	2	5	10	20	30	40
Cape Dyer A	21	29	35	40	43	
Cape Parry A	33	47	56	65	70	
Clinton Point	40	61	75	89	97	
Clyde	19	28	34	40	44	46
Isachsen	48	64	75	86	93	97
Mould Bay	21	34	42	50	56	59
Resolute A	32	46	55	64	70	74
Sachs Harbour	25	35	42	48	52	55

*For station periods of record, see Table 5.4.

6. ICE

6.1 INTRODUCTION

The purpose of this chapter is to present a general treatment of the movements of arctic ice along with a discussion of the origins of icebergs and ice islands and their subsequent movements in Arctic waters. A more detailed description of ice break-up, freeze-up, and seasonal distributions will be presented in subsequent chapters that deal with the regional aspects of ice cover. Much of the material of this chapter follows the excellent treatment of the subject by Markham (1981).

6.2 ICE PHYSICS AND STRUCTURES

This section presents a brief discussion of ice structure for salt water and examines its changes with age and temperature. Initial ice formation consists of needles or thin plates of pure ice. As more and more crystals are formed and the existing ones grow in size, brine becomes trapped in small cells throughout the ice. If the ice forms rapidly, more brine is trapped than if ice forms very slowly. The more brine cells present, the weaker the ice as compared to an equal thickness of fresh water ice.

With a drop in temperature, more pure ice separates from the brine in the cells. As well, the ice crystals become harder. These effects combine to make the ice stronger and harder with dropping temperatures.

Another factor that strengthens ice is its age. The denser cells of brine gradually sink through the ice leaving the ice purer and, consequently, stronger. As a result, ice which is one or more years old is stronger than newer first year ice. It is for this reason that in subsequent chapters dealing with regional ice patterns the amounts of old ice will be examined.

Once an area of ice is formed, it seldom remains in a smooth, unaltered state. Thermal forces as well as forces of wind and tide act on the ice to cause its deformation. With lowering temperatures, expansion of ice occurs. For a drop in ice temperature from -2°C to -3°C, expansion amounts for a salinity of 10% reach about one foot for every 400 feet of ice floe diameter while for a salinity of 4%, the rate is about one third this amount. Expansion ceases at about -10°C for 4% salinity ice and around -18°C for 10% salinity. Below these temperatures, ice contraction occurs. A consequence of this thermal deformation of ice floes is the formation of pressure ridges. A further and often more important influence on the ice is the wind and tide which can also result in ice ridges.

During the spring of 1975, multi-year pressure ridges and shore pile-ups were studied by Kovacs, Dickins and Wright (1975) in the landfast ice in the Tuktoyaktuk, Cape Parry and west coast of Banks Island areas. The purpose of the study was to obtain data on very large pressure ridges. One of the findings was that the average ratio of the exposed portion of the ridge to that hidden underwater was 3.25. That is, a pressure ridge with 3 meters exposed would be expected to have a 10-meter portion hidden below the surface. The largest ridge examined in the study had an exposed height of 10.5 meters with a depth below the surface of 31 meters.

It was also found in this study by examination of exposed ice faces that multi-year pressure ridges are "for all intents and purposes 'solid' ice".

Another phenomenon observed in this study was shore ice pile-ups. One particular large formation was seen to the southwest end of Cape Kellett where a 36.5-meter wide pile-up which was over 13 meters in height was recorded.

In a study by Fenco (1975) on sea-bottom scouring by ice ridges, scours up to 9 meters in depth were considered to have been caused by a ridge with below-the-surface depth of 75 meters. The largest multi-year ridge measured up to the study time had a 47-meter below surface depth. Such large ridges were expected to occur once in 100 years. It must be noted that scours at depths of 75 m are undated and may have occurred when the sea level was lower than it is today.

6.3 ICEBERGS

Icebergs originate from land-based glaciers rather than from frozen sea water. The major sources for bergs in Canadian waters are the glaciers along the west coast of Greenland, with the most productive areas extending from Smith Sound to Disko Bay. Canadian glacier sources are on Baffin, Bylot, Coburg and southern Ellesmere Islands, but their productivity in comparison to the Greenland glaciers is very small.

Through the Smith Sound to Disko Bay area, the Melville Bay region from Cape York to Upernavik is the major Greenland iceberg source, with an annual production estimated at 10,000 bergs. Northeast Bay and Disko Bay each produce approximately 5-8,000 bergs annually. Thus, there is an annual production of icebergs in Baffin Bay from 25-30,000 with some estimates as high as 40,000. The size of the bergs ranges from the growler size of 20 square metres area with a 1-metre projection above the sea to bergs 1 kilometer in length with heights over 200 metres.

Since the typical draft of a berg ranges up to three to four times its above-water height, its movement is controlled predominantly by ocean currents rather than winds. However, cases have been documented where a berg was driven by winds contrary to the current motion.

In Figure 6.1, the currents in the area of study are shown. This is a combination of work by Herlinveaux (1974) on the observed surface water movement during the summers 1954 to 1973 and summaries by

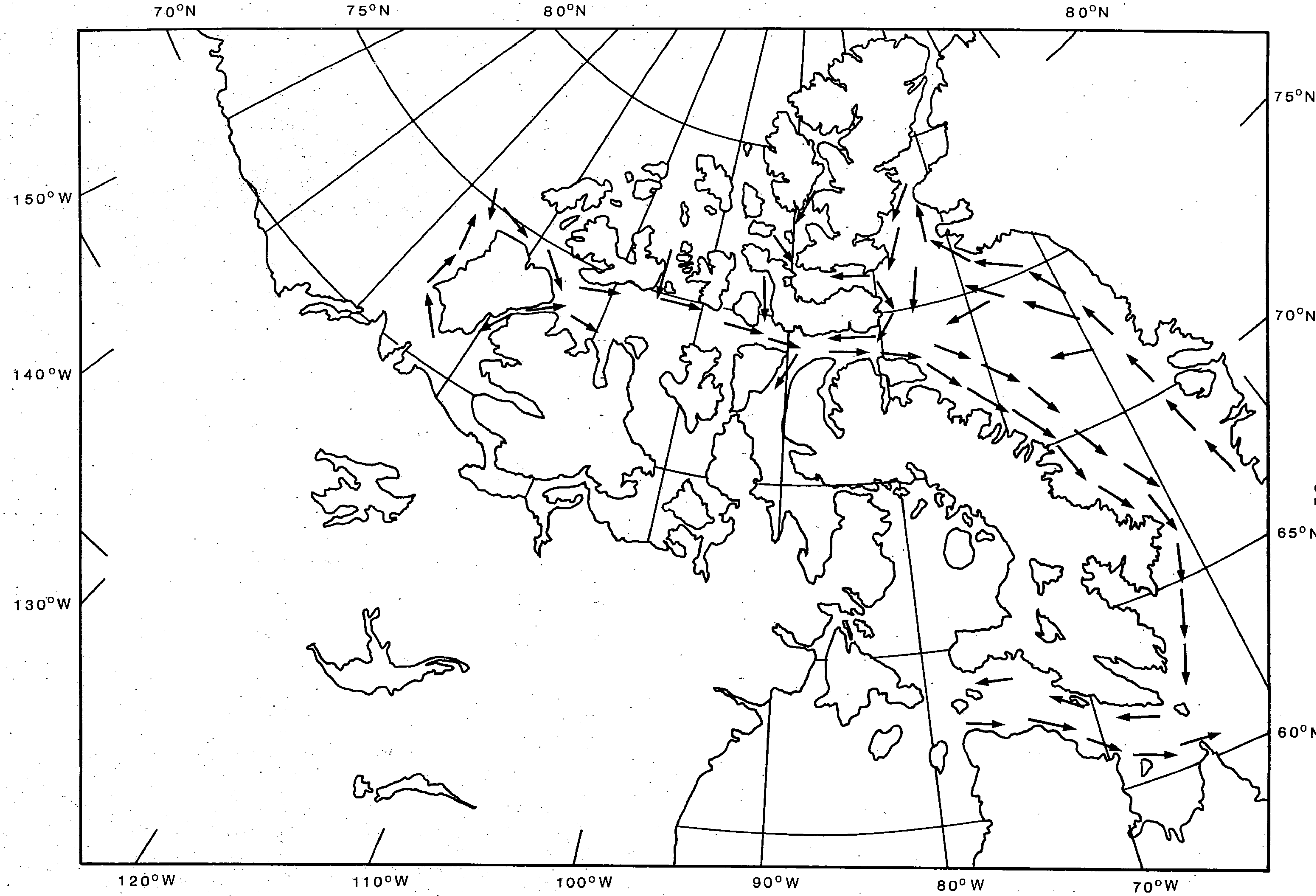


Figure 6.1 Ocean currents over arctic marine areas (after Herlinveaux 1974 and Collin 1963, as in Walker 1977).

Collin (1963) on the surface water currents found by Kiilerich (1939), Dunbar (1951), Campbell and Collin (1956), Campbell (1958), and Timofeyev (1960). Both Herlinveaux (1974) and Collin (1963) results appear in Walker (1977) and are used in Figure 6.1.

A brief examination of the Baffin Bay currents shows that these may be divided into two parts. First, there is the warm north-flowing current along the west coast of Greenland with occasional branches extending westward across the Bay. Second is the south flowing stream extending along the Baffin Island shores southward and along the Labrador coast. Icebergs originating along the west coast of Greenland will normally drift northward about 3 to 5 nautical miles per day and be carried counter-clockwise to western Baffin Bay, followed by a southward movement along the east coast of Baffin Island. A berg could also take a shorter route across Baffin Bay along a westward extending branch of the warm eastern Baffin Bay current.

Other side routes occurring less frequently than the major pathway described above are also of interest. Since part of the southward-moving western Baffin Bay current flows into Lancaster Sound as far as longitude 85° West, icebergs can move westward through the Sound although with a decreasing frequency as one moves westward. As well, bergs can travel around Bylot Island through Navy Board Inlet and Pond Inlet. A similar westward arm of this current extends into Hudson Strait and can cause bergs to loop into this area.

6.4 ICE ISLANDS

Ice islands are formed when a piece of the Ellesmere Ice Shelf located along the north coast of Ellesmere Island breaks away. At the the time of formation, ice islands can be several kilometres in horizontal extent and up to 50 metres in thickness. The main drift direction for these ice islands is southwestward along the western edge of the Arctic Islands. However, on occasion, islands have drifted eastward and then travelled through Nares Strait to Baffin Bay and southward into the eastern areas of the Arctic Islands. The main track motion toward the southwest is caused by the general clockwise drift of the North American sector of the Arctic Ocean ice pack. One island that moved along this major track was T-3. Discovered in 1946, it has since served as platform for several scientific studies and had passed through the Beaufort Sea four times as of the spring of 1979. In each case the track followed kept it well north of the Beaufort Sea oil exploration area.

6.5 ICE MOTION

In this section, an outline of the ice motions in areas along and near the transportation route will be examined. It should be stated that the main emphasis will be on the gross overall ice movements due to ocean currents. Individual floes can, of course, be moved differently by daily fluctuations in the surface winds.

In general, current directions through the northern Arctic Islands are such that the ice movements are southward as far as Parry Channel and east to Baffin Bay. Thus, in the Parry Channel area there is a west to east migration of floes. However, there is a complication in this flow due to the Coriolis force. In the Northern Hemisphere, this force acts to deflect a moving object such as an ice floe to the right of the object's path. It is for this reason that the south side of Barrow Strait is more ice congested than the north side. As well, the overall southward ice drift allows movement of floes from the King Christian Island-Cornwall Island areas south to Penny Strait and Queens Channel. A similar motion may occur from the Lougheed Island area through Byam Martin Channel. These southward movements would tend to replenish the Parry Channel ice.

At the west end of Parry Channel, in M'Clure Strait, the situation is more complex. Here, there is little general ice drift between Prince Patrick and Melville Islands and both eastward and westward movements of ice have been observed. It was in the M'Clure Strait area that both the Manhattan in 1969 and the icebreaker Franklin in 1979 encountered problems, thus supporting the fact that this is a difficult ice area.

Another main area to be considered is the Prince of Wales Strait region. Southward-drifting floes can move to the Amundsen Gulf area but the movement into the warmer southern waters causes melting generally before the southern part of Banks Island is reached.

Third is the Baffin Bay region. As a result of the general counter-clockwise current, one would expect a similar ice floe movement. Along the east Baffin Island coast, a southeastward ice movement follows the current direction. However, along the west coast of Greenland, the movement is still southeastward, contrary to the current and a result of the predominance of northerly winds. Such was not the case for icebergs, due to their deeper draft.

Another area of concern is the Beaufort Sea. The major ice floe motions here are a result of wind drag on the floes and wind-induced currents. The overall water currents are weak and consequently do not contribute significantly to the ice motion.

Finally, along the northern Alaskan coast, there is a weak east and northeast-flowing current. It is, however, not strong enough to overcome the overall westward movement of the main Arctic Ocean ice pack.

7. SEA STATE

7.1 INTRODUCTION

Energy is transferred from the atmosphere to the sea by the wind acting on the air-sea interface. In the section on storm surges, attention is focused on the mass transport of water. However, much of the wind's momentum goes into generating waves rather than directly into making currents (Stewart, 1969).

It is beyond the scope of this report to go into wave theory; however, an attempt will be made to provide some background on the conditions required for the development of waves, how they move and how they react upon reaching shallow water. This will be followed by a look at freezing spray and storm surges.

7.2 WAVES

A number of the terms commonly used when discussing sea state will be defined:

sea - this refers to waves still within the generation area.

swell - waves which are the result of distant storms or winds which have ceased to blow.

fetch - the spatial extent of the "sea"-generating area, measured in the direction of the wind.

wave length - the horizontal distance between successive wave crests.

wave heights - vertical distance of a crest above the troughs on either side.

wave period - the interval of time which elapses between the passage of two successive crests past a fixed point.

wave speed - the apparent rate at which a wave crest moves.

steepness - the ratio of wave height to wave length.

significant wave height - a hypothetical wave height which is representative of the mean of the highest one-third of all waves.

maximimum wave height - about 1.8 times the significant wave height.

Waves can result from any number of causes ranging from the wind to seismic activity to objects falling into the water. For sustained wave action over a large area wind is by far the most important cause. Except where noted the following discussion will apply to deep water waves, i.e. waves in which the depth of the water is greater than one-half the wave length.

Waves generated during periods of light winds rapidly dissipate. As wind speed increases, however, the energy supplied by the wind will exceed internal losses within the water and waves will grow.

If winds exceed about 10 kts (Fichaud 1959) waves will continue to grow, but in such a manner that the height grows much faster than the length and the wave gets steeper. This cannot continue forever and Fichaud (1959) quotes a figure of 10 to 12% as the maximum steepness a wave can attain. Any additional wind energy (supplied above that required to maintain its steepness constant) will be dissipated by the wave breaking.

At any one point in time the sea may appear as a complex pattern of troughs and crests due to the presence of a number of waves in various stages of development. This can be further complicated by swell from distant storms passing through the generation area. Each of these wave trains has its own wave length, speed, height and direction. It is the resultant of all of these waves from which the significant wave is determined. As waves move out of the generation area, those with the longest wavelength move faster, and since they also contain the most energy they tend to move over great distances. Swell waves have been recorded in the North Atlantic which must have travelled over 10,000 km (Morgan 1971).

Fetch, wind velocity and duration of wind along the fetch direction all determine the size of deep water waves. In the arctic, ice is frequently the main factor in determining fetch. An area of three-tenths or more ice cover is usually accepted as the upwind fetch boundary.

Fetch can also be limited by changes in wind direction such as that found near fronts or other areas of strong wind flow curvature. Morgan (1971) defines fetch as the distance upwind to where the wind backs or veers more than 30° from that of the datum point. For areas such as Baffin Bay where it is not uncommon to find quite intense systems, the curvature can reduce an otherwise large fetch. Over the Beaufort Sea, frontal systems and sharp trough lines frequently cross the marine areas, resulting in wind changes well above the 30° threshold. It must also be kept in mind that such systems also can alter ice conditions which, in turn, may change the fetch.

A number of methods have been developed to forecast deep water waves. The nomogram developed by Bretshneider has been widely used and is the one currently employed by the Beaufort Sea Forecast Office located in Tuktoyaktuk, N.W.T. Besides incorporation of the fetch, this method also requires the mean surface wind speed and the duration of that wind. As with most forecast methods the results can only be as good as the initial analysis and sparsity of data is often the limiting factor across the Arctic. Despite these limitations, the staff of the Beaufort Office have been reasonably satisfied with the results obtained from using the Bretschneider nomogram (Hudson 1981).

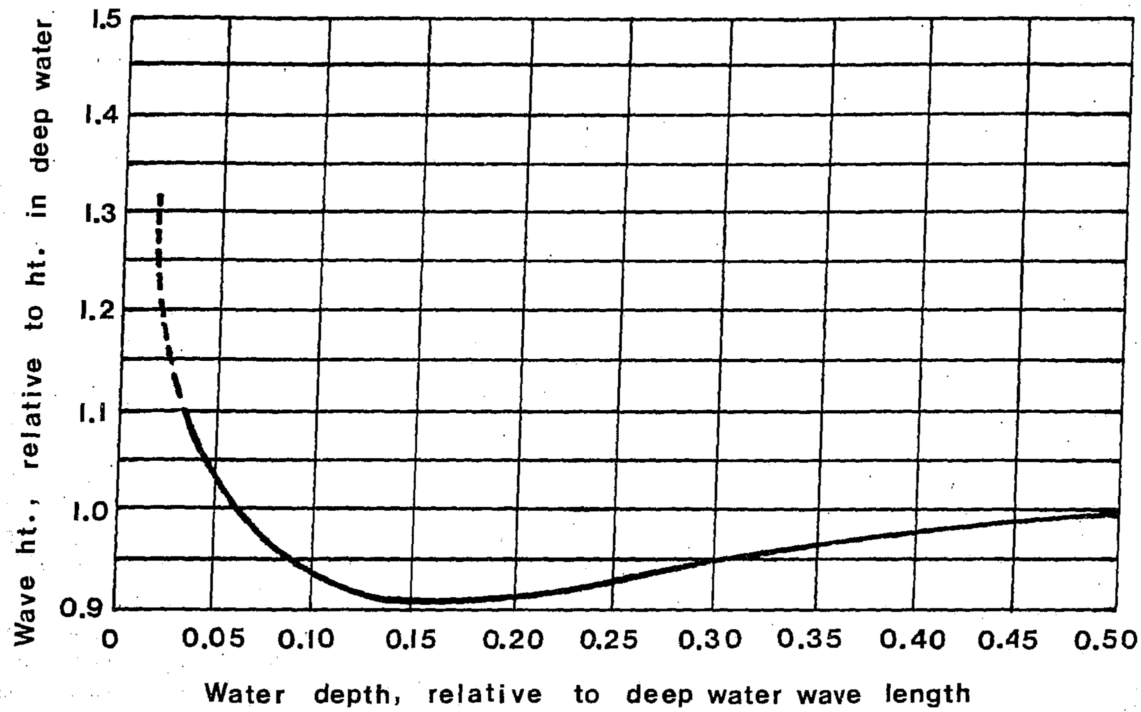


Figure 7.1 Shoaling effect on wave heights (after Oceanography for the Navy Meteorologist).

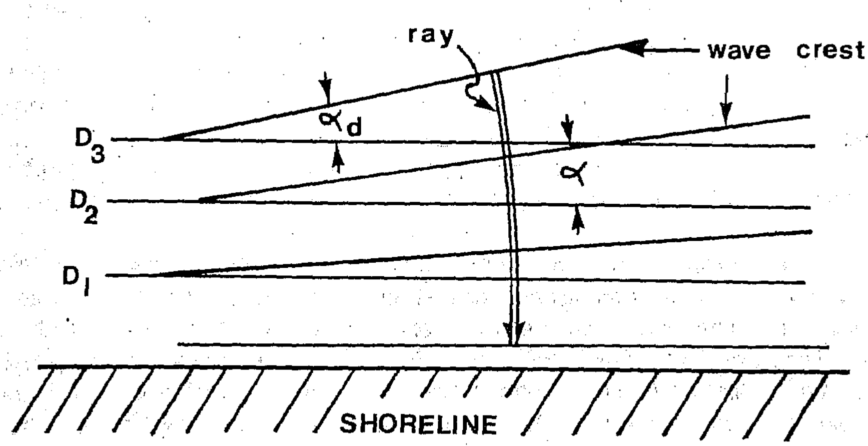


Figure 7.2 Principle of wave refraction (after Oceanography for the Navy Meteorologist).

When waves move from deep water into shallow water, a number of changes occur, including shoaling and refraction.

The following discussion on these two phenomena is largely based on the paper "Oceanography for the Navy Meteorologist" published by the U.S. Navy Weather Research Facility in Norfolk.

Shoaling affects the height of the waves but not the direction, while refraction affects both. Shoaling is comprised of two effects which oppose one another, the final result of which is illustrated in Figure 7.1. Initially, the wave height will actually decrease to about 90% of its deep water height. However, as it continues to approach the shore its height will increase until it finally breaks. This is because the wave begins to slow down as it moves into shallow water. The length of the wave also decreases, but since the period and energy is unchanged the height increases. This is because, mathematically, the energy of the crests is proportional to the square of the height and inversely proportional to the speed. As heights continue to build a point is eventually reached when the height becomes great in relation to the mean depth of water beneath the wave. This causes the wave to become unstable and it breaks. Fichaud (1959) gives this ratio of water depth to wave height as 3:2 but goes on to say some consider the ratio to be closer to 4:3.

The second effect is refraction. As a wave moves into shallower water it begins to slow. If it was initially approaching the shore at an angle αd (Figure 7.2), the portion closest to the shore will begin to move more slowly than the portion in deep water. The angle α then begins to decrease and the wave becomes more parallel to the shore. If the waves continued on until the depth was zero, then all waves would end up parallel to the shore. But, since waves break some distance from shore, there will still be some angle between the wave front and the shore.

7.3 FREEZING SPRAY

Icing on marine structures can result from fog, freezing rain or drizzle, freezing spray or by high seas which cause wave wash. Wave wash is more of a problem with smaller vessels due to their lower freeboard. The buildup of ice on a vessel can result in an elevated centre of gravity, lower speed, difficulty in maneuvering and potential stress on oil rigs. Of the various forms of icing the most common is freezing spray. It can occur when the air temperature falls below the freezing temperature of sea water and when sea surface temperatures are below about 5°C (Brower, Searby, et al. 1977).

Wise and Comiskey (1980) studied superstructure icing in Alaskan waters and revised existing nomograms to more accurately reflect observed conditions. These nomograms are the ones currently being employed by the Beaufort Sea Weather Office to forecast freezing spray.

The following table (Table 7.1) shows expected accumulation rates in centimeters per 24 hours for various combinations of air temperature and wind speed with a water temperature of 0°C.

Table 7.1. Ice accumulation (cm) per 24 hours from freezing spray. Water temperature 0°C (after Wise and Comiskey, 1980).

	Wind Speed in Knots				
Temperature Degrees C	25	30	35	40	50
0	Nil	Nil	Nil	Nil	Nil
-5	7	9	10	14	20
-10	10	14	15	17	25
-15	14	16	20	25	27

It must be kept in mind that the shape and size of the vessel will also affect the rate of ice accumulation. Another important factor to be considered in arctic waters is the amount of ice cover. Three tenths of ice cover is used as the fetch limit for wave generation and can likely be considered as the amount beyond which freezing spray would not be a problem.

Wise and Comiskey (1980) have also developed a second nomogram which replaces wind speed by a wind-wave index. This index is simply the wind times the wave height. It is recommended for use within three miles of a lee coast during conditions of cold air, strong winds, and short choppy seas that have not had time to fully develop. This may also prove useful in areas such as the Beaufort Sea where ice often limits the fetch.

7.4 STORM SURGES

A combination of wind, tide level and atmospheric pressure can produce unusually high water levels and consequently coastal flooding. This difference between the observed sea level and normal level for that particular time is called a storm surge. Values may be positive or negative.

Significant wave heights combined with the presence of ice augments the impact storm surges could have on offshore and coastal exploration or production facilities in an Arctic environment.

Fathauer (1978) produced "A Forecast Procedure for Coastal Flooding in Alaska" and much of the following discussion regarding storm surges is based on his paper.

Although a storm surge is the result of a number of factors, the wind-driven transport of sea water is the most important. Other contributing factors are tides, coastline configuration, bathymetric conditions and atmospheric pressure.

Frictional drag at the air sea interface causes water to be pushed along the surface, leading to wind-driven mass transport. In the northern hemisphere the Coriolis force acts to the right of a moving object with the result that surface currents move about 20 degrees to the right of the wind (Williams, 1962). Because each layer acts on the next layer the direction of wind-driven currents turns steadily to the right with increasing water depths.

Figure 7.3 illustrates this effect. In the shallow depths of Alaska's Arctic coastal waters, Fathauer (1978) uses a value of 45 degrees to the right of the wind for the direction of net transport.

When determining the effects of the wind it is necessary to consider the speed, duration of the period of strong winds, fetch, stability of the air and extent of ice cover. Increases in any of the first three can lead to an increase in net transport while an increase in ice cover will reduce net transport. This is because ice will reduce the amount of water in contact with the air. The effects of stability on surface winds has been discussed in a previous chapter and it will suffice to say that during periods of strong geostrophic flow, a decrease in stability will result in stronger surface wind. This condition is frequently found during the fall when cold arctic air moves across open water.

Tide tables are published for many coastal communities in the arctic and these can be used to determine the normally expected water level. Since tides in the western Arctic are generally small, their role in a storm surge is minimal. However, normal tides of six to eight metres are not uncommon in areas of the eastern Arctic and can significantly enhance or negate a storm surge.

Coastal terrain plays a significant role in most storm surges. Henry and Heaps (1976) show that variations in a surge may be considerable but follow a predictable pattern. Shallow embayments that are open in the direction of the wind and face the surge show a maximum run-up. Major promontories provide shelter and, therefore, show little run-up on their lee side. Neumann and Pierson (1966) documented the case of a hurricane moving along the northeast coast of the U.S. The storm surge generated by this system varied from less than 0.3 m to 1.2 m. At one location the surge ranged from -1.8 m to a positive surge of 0.3 m.

A lowering of atmospheric pressure will also increase water levels. For every 10 mbs atmospheric pressure drop, a 10 cm increase in water level can be expected (Fathauer 1978).

Winter surges, although less frequent than summer ones, can occur. Henry (1975) points out that even though water levels may be

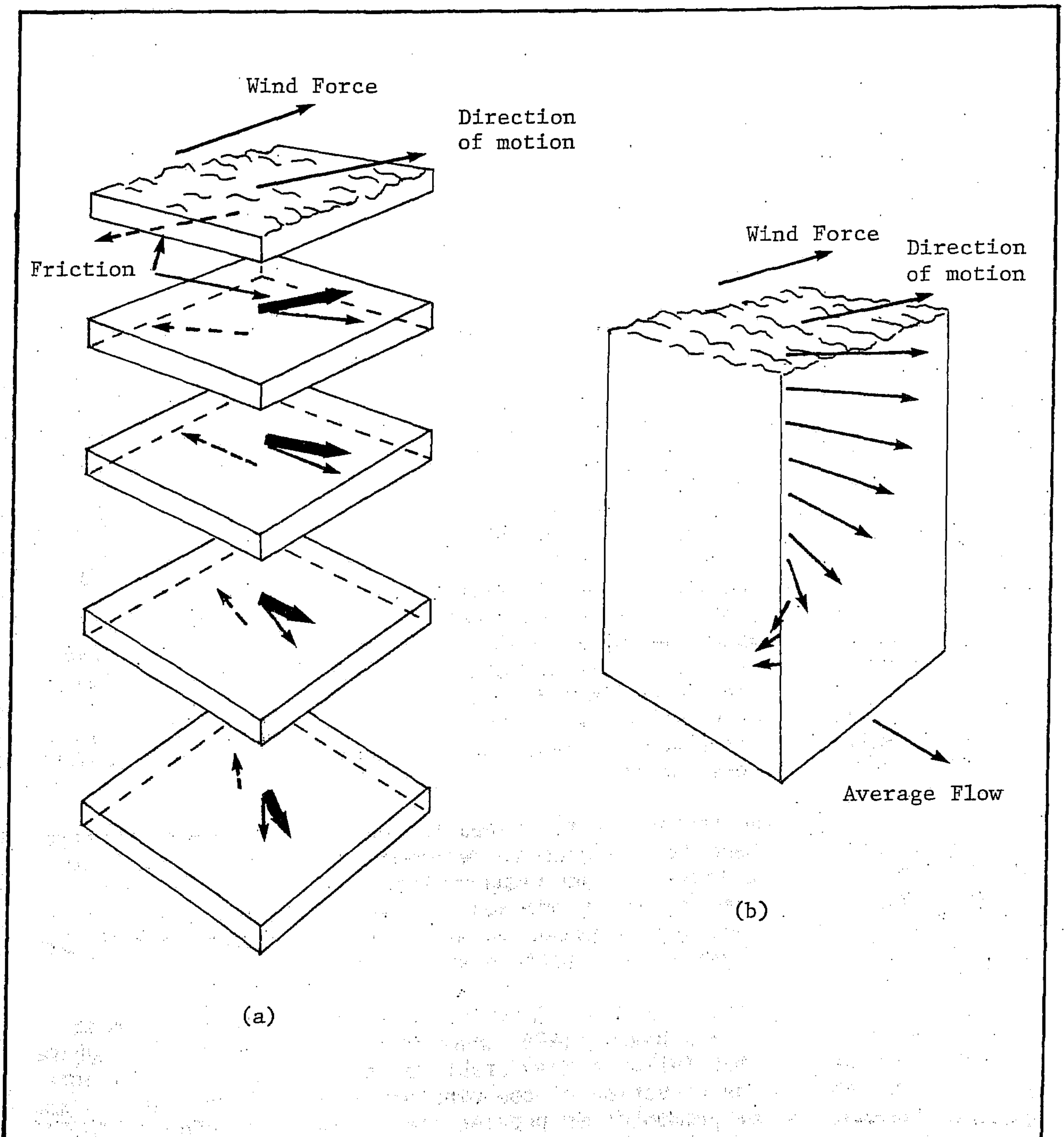


Figure 7.3 The Ekman Spiral (after Stewart, 1969). In (a) each layer drives the next lower layer. The top layer is driven by the wind with each successive layer driven by friction. The column of water in which this occurs is called the "Ekman Layer" (b).

lower they can cause considerable damage to waterline installations due to the fact large masses of ice may be carried onto the shore.

A negative storm surge occurs when mass transport is directed offshore. For example, along the Mackenzie and Yukon coasts a negative surge occurs with an easterly flow since net transport is to the right of the wind. Henry (1975) says that negative surges of up to one meter can occur at Tuktoyaktuk. The main effect of such a negative surge is to hinder vessel movement as a result of reduced water depths.

One storm and accompanying storm surge which has received considerable attention crossed the Beaufort Sea in September 1970. Wilson (1971) stated that this particular storm produced water levels at Tuktoyaktuk that were 2.5 metres above average and were accompanied by 2.5 meter waves. This same storm produced a surge of 1.2 to 1.5 metres at Shingle Point. The largest surge reported during the storm was 3.6 metres at Tent Island located at the mouth of the Mackenzie River. The previous known equivalent of this storm occurred in September, 1944 (Burns 1974), but Burns (1974) says that such storms likely occur more frequently than suspected and he estimates a seven to nine-year return period. Based on Alaskan marine data (Brower and Searby, 1977) and marine information over the Beaufort Sea since 1974, this return period seems short.

When discussing the return period of such a storm it must be kept in mind that the return period of the storm is not necessarily the same as that for the storm surge. This is because the winds resulting from any given storm are only one of the requirements necessary to produce a major storm surge. Reimnitz and Maurer (1979) suggest a 25-year return period for this storm but state that the 1970 storm surge may not have been equalled during the previous 90 to 100 years, and may not have been exceeded in several hundred years.

The preceding discussion has only touched on the problems in observing and forecasting storm surges. More information and study is necessary before good quantitative predictions can be made for northern waters.

8. DETAILED REGIONAL MARINE CLIMATES

8.1 INTRODUCTION

In this chapter, a detailed examination of the regional climates across the Northwest Passage route will be presented. Winds, waves, visibilities, freezing spray and ice will be discussed in each of the four sections, and a section on coastal weather will be included in the discussion of the Beaufort Sea.

Throughout these sections, several different types of diagrams will be included. Brief examples of interpretations of the diagrams will be presented by referencing figures in Section 8.2. In Figure 8.2, for example in the wind roses for gridpoints GP1,3,5 it can be seen that geostrophic winds from the east to north predominate on the east side of Baffin Bay. In Figure 8.7, the maximum geostrophic winds for each month are shown. For example, at GP5, in February the maximum is east-southeast at 31 m/s. In the figure dealing with durations (Figure 8.8a) 6-hour durations are defined as occurrences of the event over consecutive 6-hourly periods. In windspeed figures, such as Figure 8.8a, the maximum durations for each of the 1946 to 1978 years were obtained. From these, the maximum and minimum values are plotted in the figures. For example, in Figure 8.8a for GP6, the absolute maximum duration for winds greater than 10 m/s is 28 consecutive occurrences separated by six hours while the minimum for these yearly values is ten 6-hour periods. Sets of diagrams (Figure 8.9a) illustrating wind speed return periods, refer to the largest wind speed expected for a given return period by months. For example, for GP6 for a 10-year return period, a 24-m/s geostrophic wind would be expected in February with a 14-m/s wind for July. The remaining months would show wind speeds between these values. For the durations of wind speeds for a given return period, the number of 6-hour periods with winds greater than various criteria are indicated. For example, in Figure 8.10a for GP6, a 100-year return period for winds greater than 25 m/s would be two 6-hour periods.

Marine wind roses shown in each section are generally limited to the July to October period and are self-explanatory.

Tables of wave heights and visibilities show the percentages of occurrences of the various wave height and visibility ranges with the data being taken from SSMO ship observations. It should be noted that for the visibility reduction, due to blowing snow, statistics are presented only for the central Arctic area. For the remaining regions, blowing snow information is not shown since the data is either not available or is taken by land stations considered not representative of adjacent marine areas.

Finally, in the sections on ice coverage, extensive use of Markham (1981) has been made for the diagrams for ice concentrations in the Beaufort, central and eastern marine regions. Brower and Searby (1977) has been used for the western Alaskan area.

8.2 EASTERN ARCTIC MARINE AREA

In Figure 8.1, a map showing the eastern Arctic marine area including the gridpoint locations and marine regions is shown.

8.2.1 Winds

(i) FNOC Gridpoint Wind Results: For gridpoints GP1 to GP6, the wind roses are shown in Figures 8.2 through 8.6. Three wind rose patterns appear predominant for the six gridpoints. The first pattern appears at GP2, GP4 and GP6. For GP4 on the west side of Baffin Bay or near Lancaster Sound north and northwest winds predominate. A secondary southeast wind maximum shows up in July; a second area is the northern section of Baffin Bay as represented by point GP5. Here the north-easterlies to easterlies are evident with a shift to more southerlies in July. A final region is the eastern side of Baffin Bay as represented by points GP1 and GP3. Here the north or south directions are dominant. These three regions may be explained by reference to the synoptic weather patterns characteristic of the area. Frequently, low pressure centres track northward through Davis Strait and stall in northern Baffin Bay. To the east of these systems, southerly winds are frequent along the west coast of Greenland. West of the storms, northwesterly winds predominate while to the north of the systems northeasterlies are expected. During the summer months, there is a drop in the frequency of occurrence of these systems. This storm track and resultant wind patterns can be used to explain the wind rose patterns observed at the gridpoints described here including the shift during July. The frequent northerly winds at points GP1 and GP3 are the result of a trough of low pressure which lies along the west Greenland coast.

Figure 8.7 presents extreme wind statistics for the same gridpoints. Again, the three areas may be examined. The western points GP2, GP4 and GP6 tend to show the strongest winds as either north or southeast despite wind roses that indicate a northerly wind preference throughout most of the year. The northern point GP5 shows predominantly east to northeast for the strongest winds, in agreement with the wind rose directions. The eastern points GP1 and GP3 generally show southerly as the direction of strongest winds; also a predominant wind direction. Note that for all six gridpoints in this marine area the total absence of strong westerly winds. Such an observation is consistent with the observed weather patterns in this area.

In Tables 8.1 to 8.6, the percentage frequency of occurrence for various wind speed ranges are shown for the eastern marine area gridpoints. Again, the increased wind speeds during the winter months are evident. Gridpoints GP1, GP2 and GP6 generally have the higher percentages of winds in the higher speed ranges throughout the year.

Wind durations are shown in Figure 8.8 and 8.8a. Here points GP3 through GP6 have similar durations while GP1 and GP2 show higher values for the range 10.

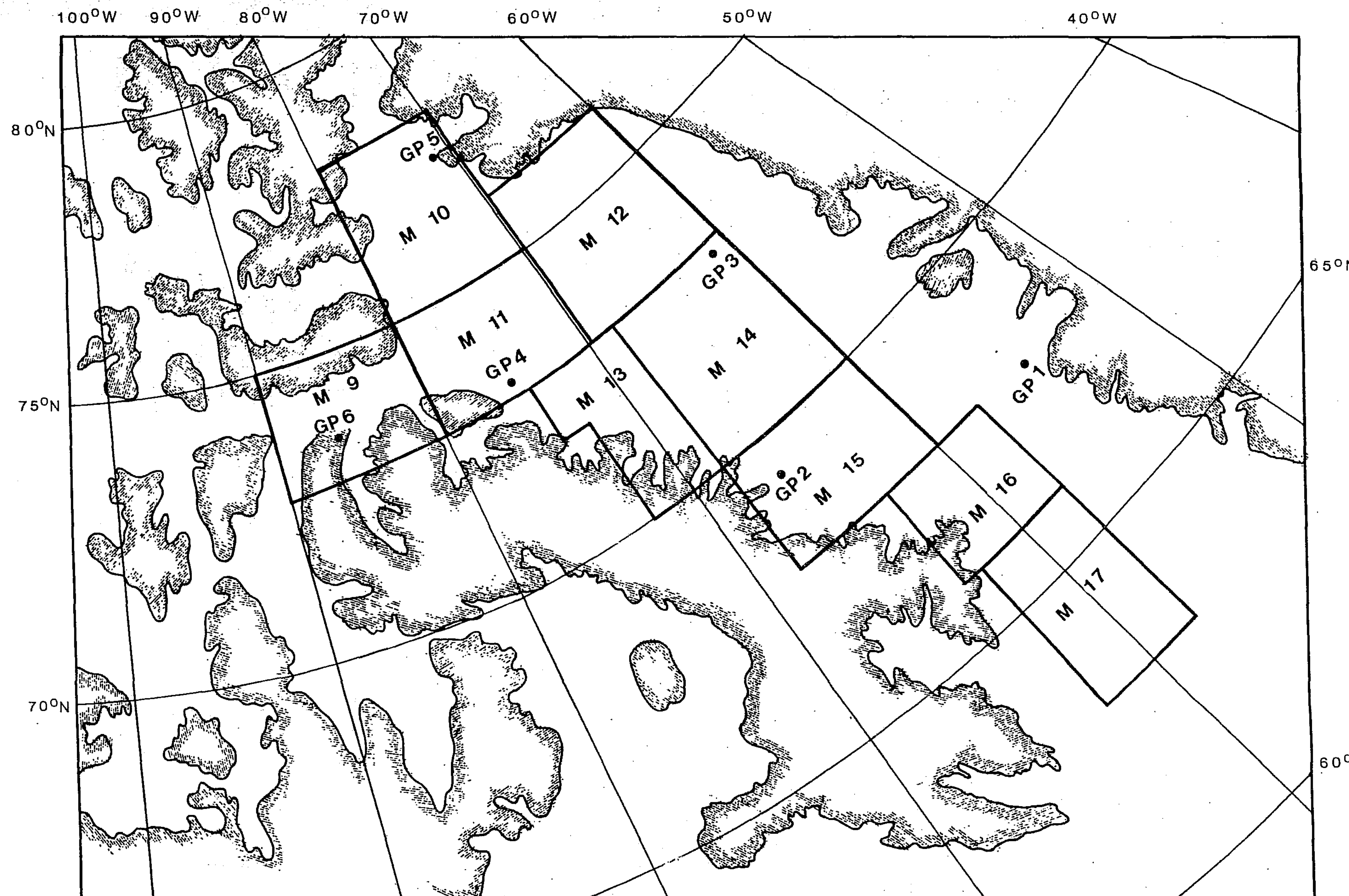


Figure 8.1 Eastern arctic marine area. Marine regions are outlined by solid lines. Gridpoints are shown as dots.

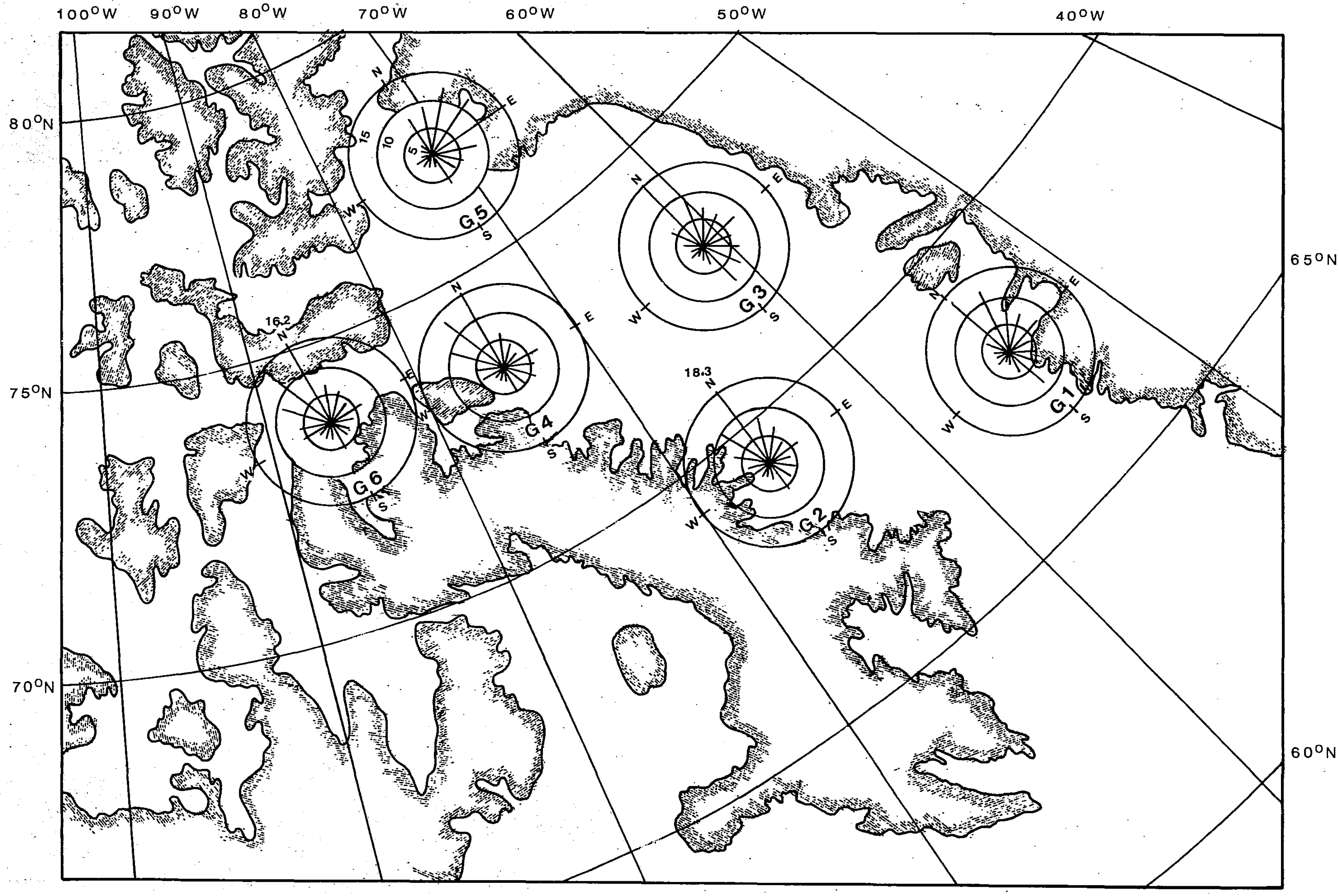


Figure 8.2 Gridpoint wind roses - annual.

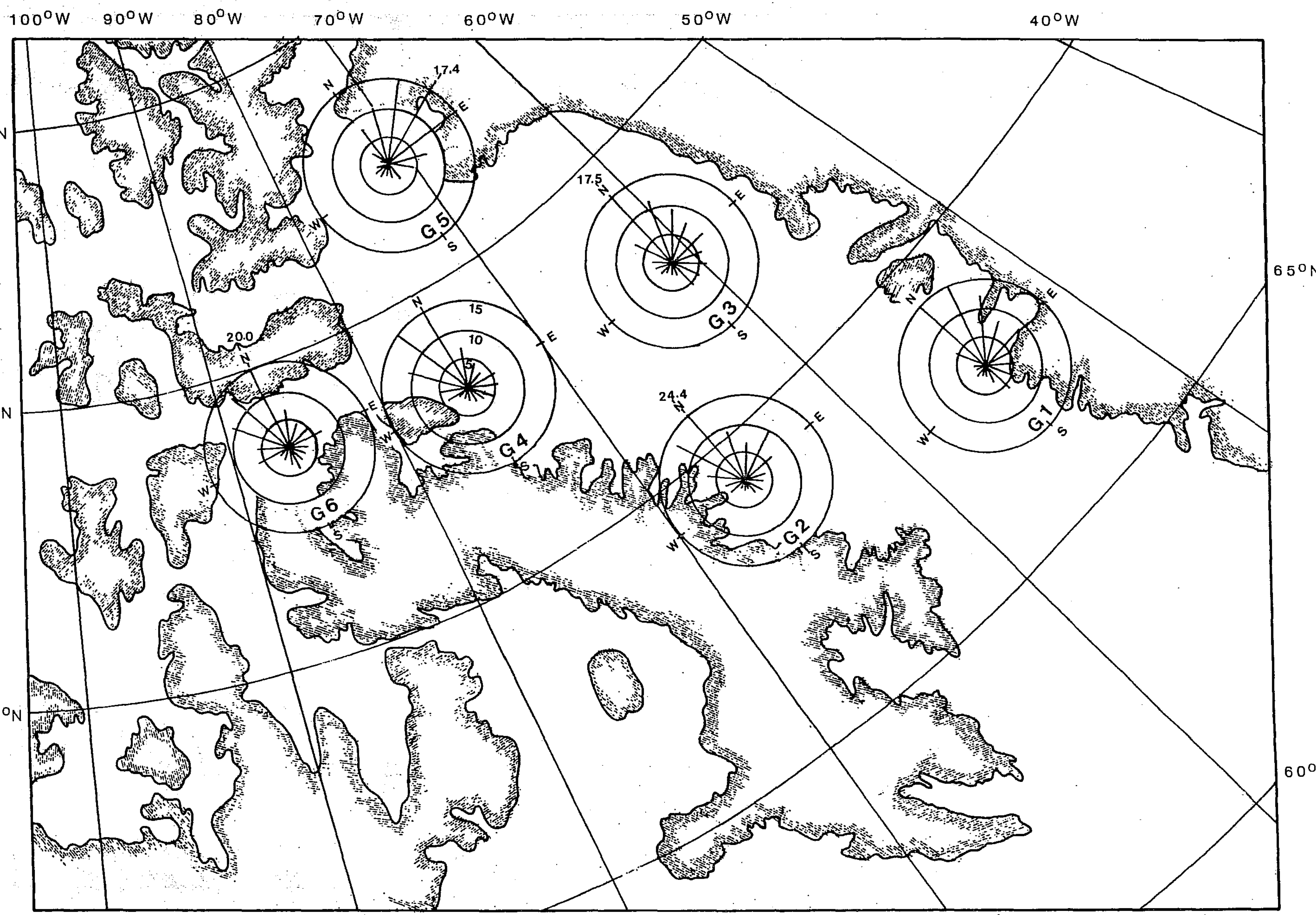


Figure 8.3 Gridpoint wind roses - January.

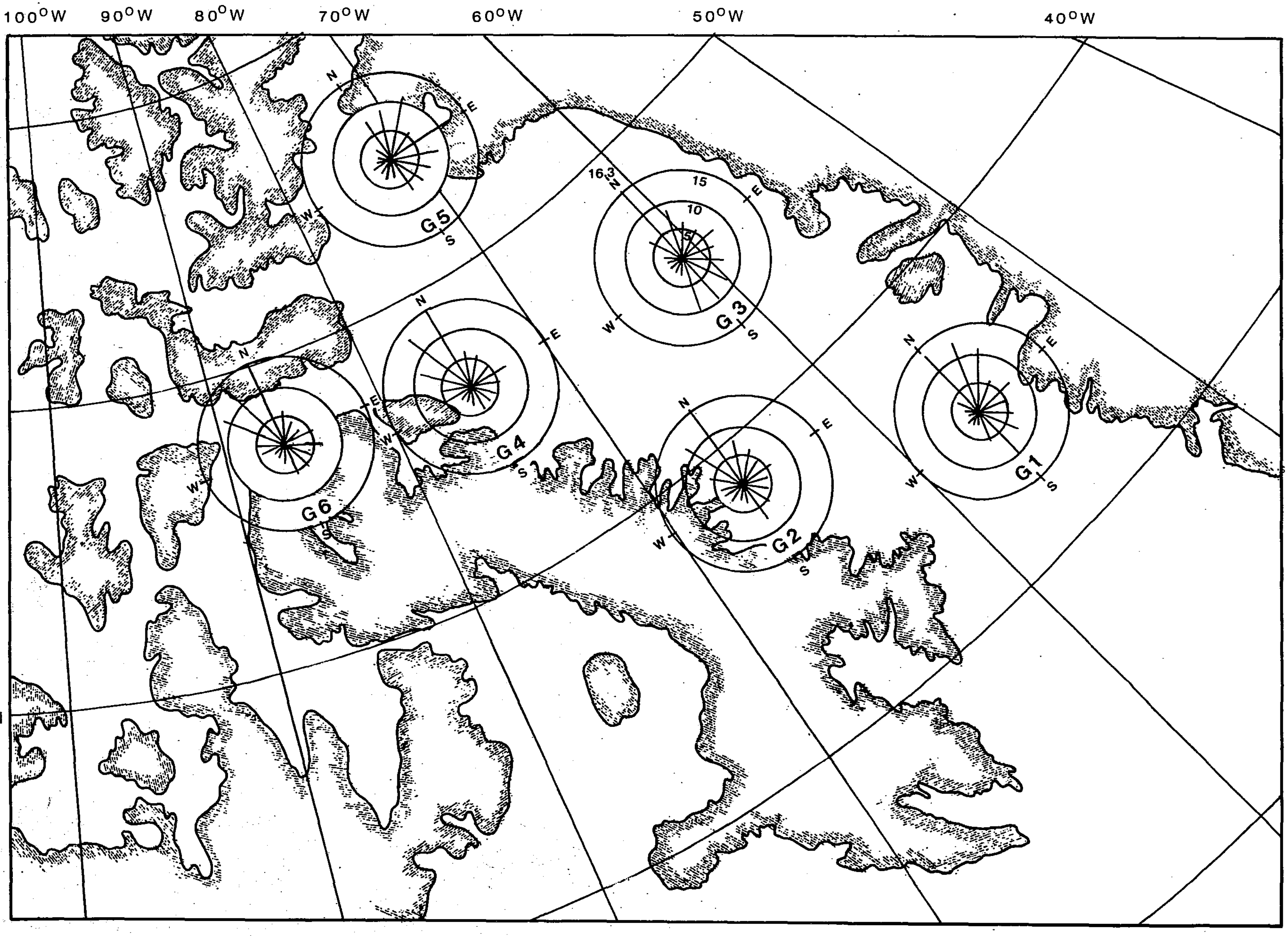


Figure 8.4 Gridpoint wind roses - May.

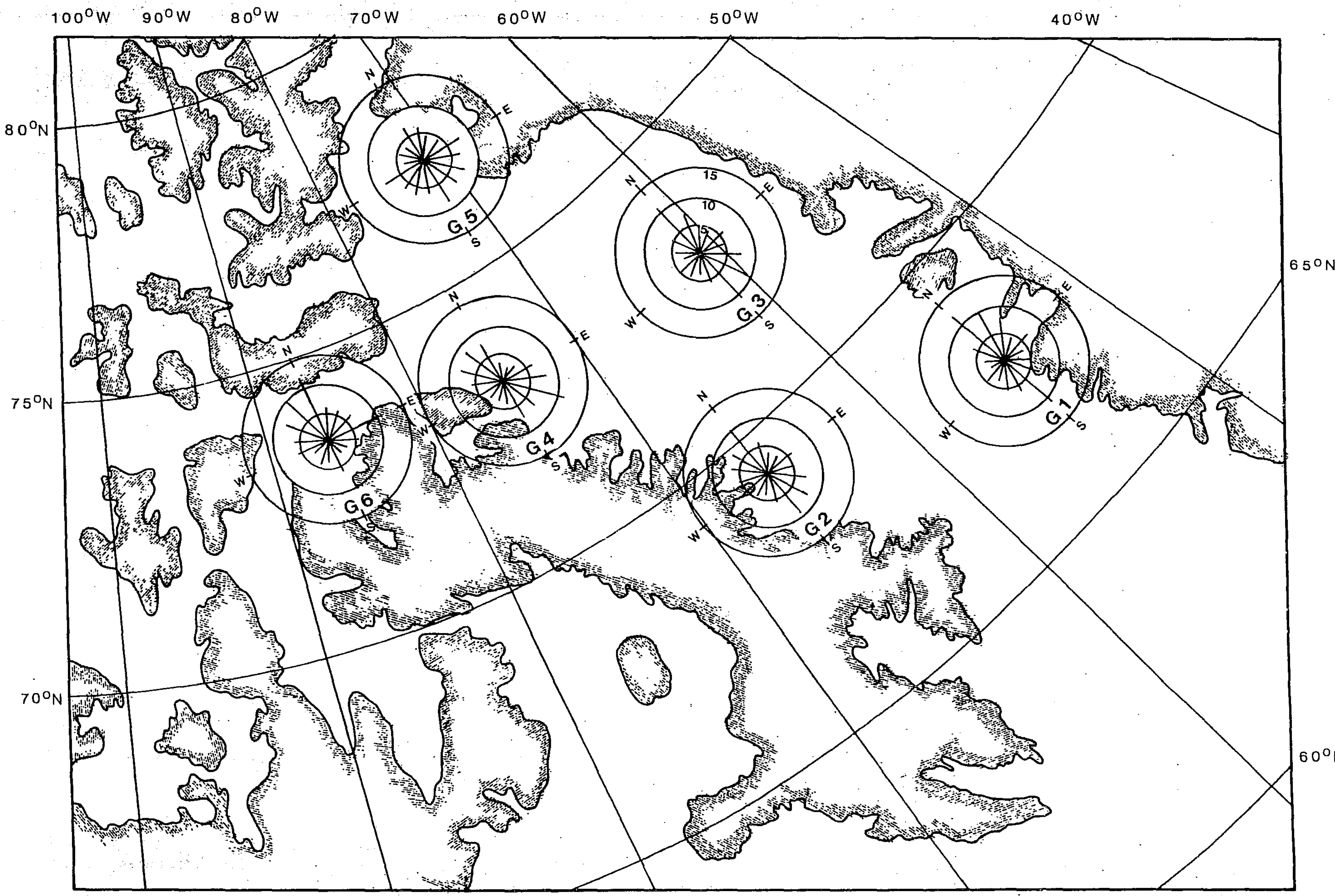


Figure 8.5 Gridpoint wind roses - July.

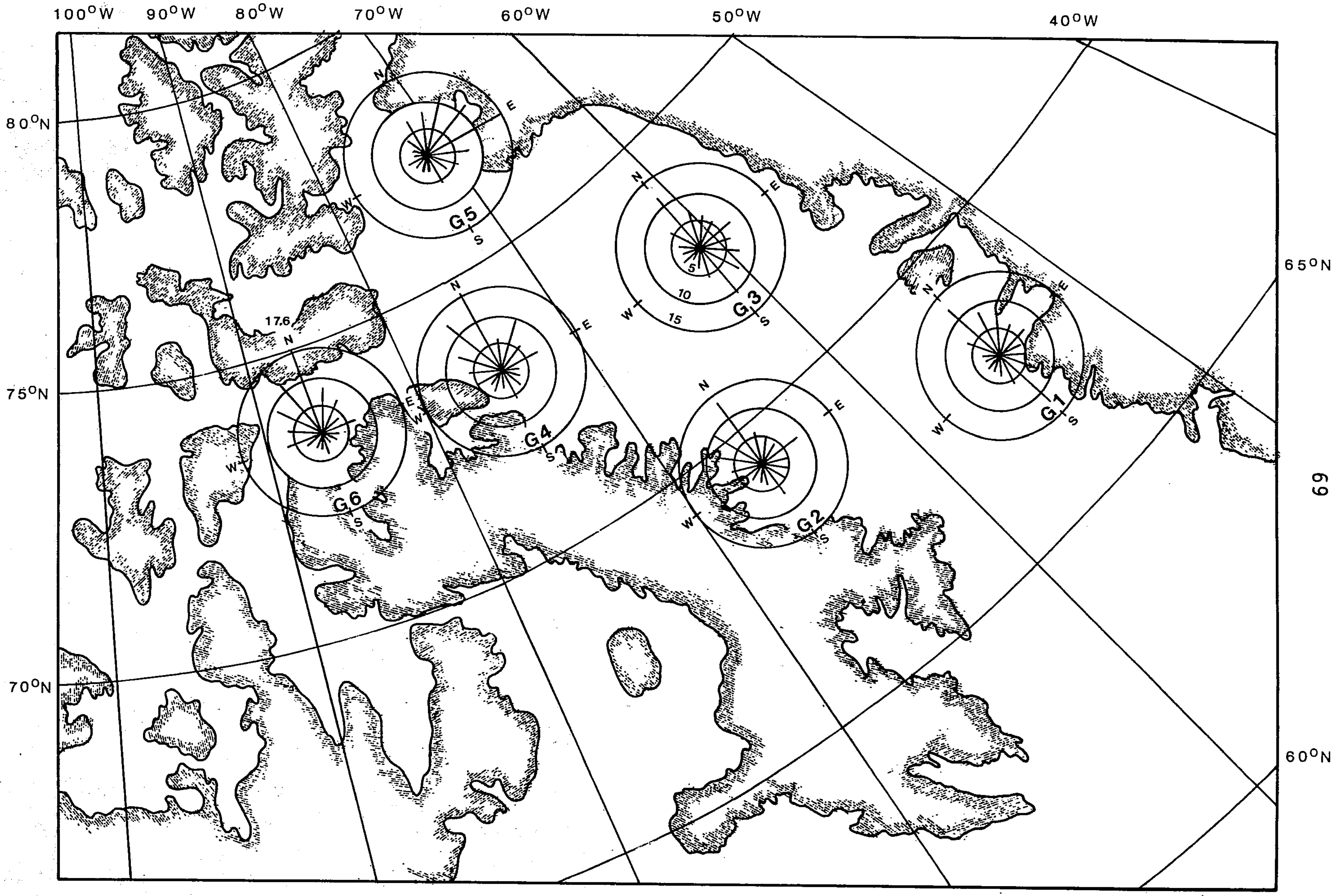


Figure 8.6 Gridpoint wind roses - September.

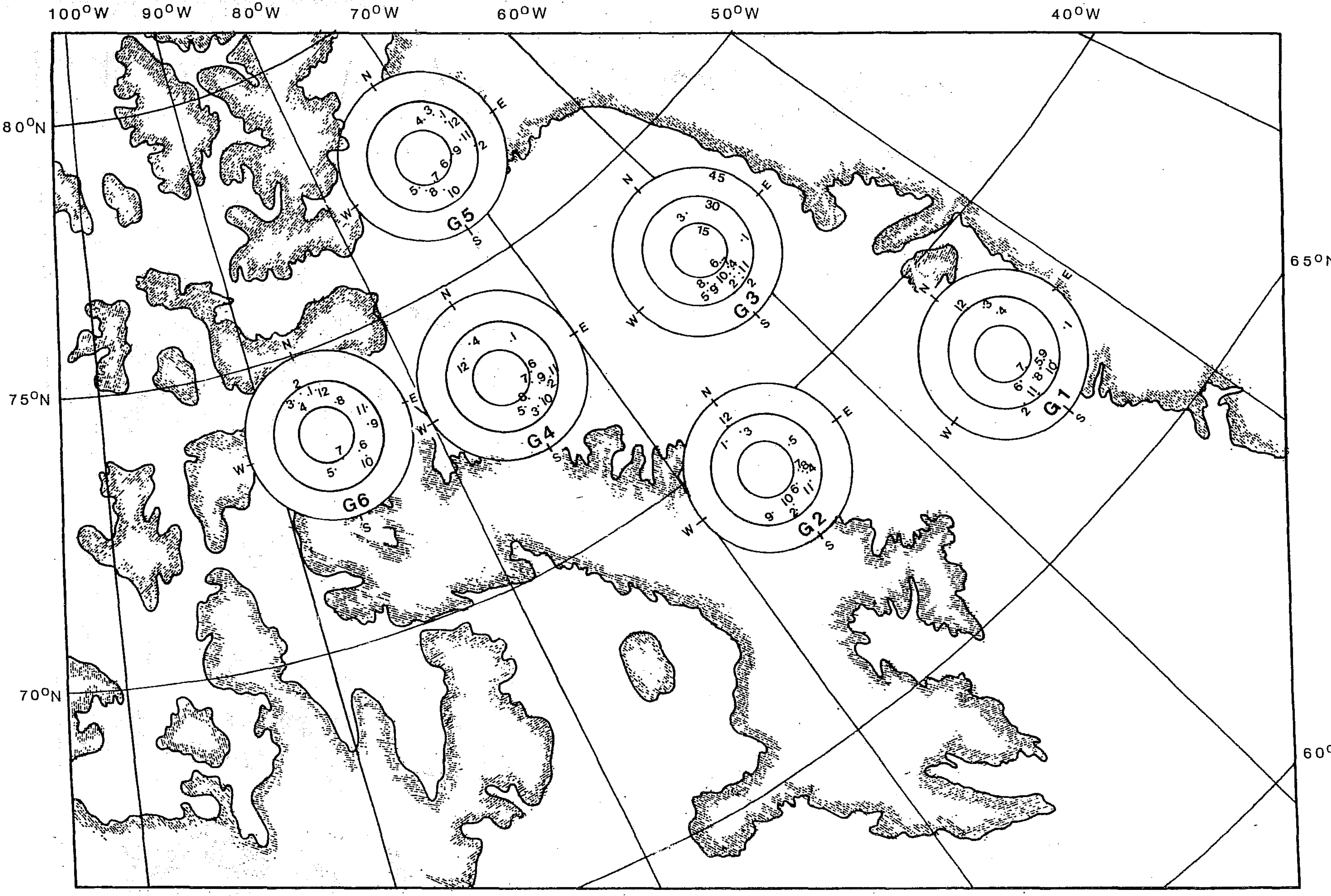


Figure 8.7 Direction and speed of maximum wind by month for Gridpoints 1-6. (Months shown by number, i.e., Jan = 1.)

Table 8.1. Gridpoint wind speed percent frequency by month.

			Gridpoint GP1		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	28.7	41.8	21.3	6.5	1.6	0.2	-	-
Feb.	31.1	43.3	19.5	5.0	0.9	0.1	0.1	-
Mar.	32.9	43.5	17.8	4.8	1.0	0.1	-	-
Apr.	38.1	45.1	14.5	2.2	0.2	-	-	-
May	50.8	41.4	7.1	0.6	0.1	-	-	-
Jun.	63.7	31.0	4.9	0.3	-	-	-	-
Jul.	70.9	26.5	2.6	-	-	-	-	-
Aug.	62.4	33.4	3.9	0.4	0.1	-	-	-
Sep.	46.8	41.1	10.2	1.8	0.2	-	-	-
Oct.	37.8	43.9	15.3	2.7	0.3	-	-	-
Nov.	34.1	41.7	18.1	4.9	1.2	0.1	-	-
Dec.	28.3	44.7	20.7	5.4	0.7	0.2	-	-
Annual	43.9	39.8	13.0	2.9	0.5	0.1	-	-

Table 8.2 Gridpoint wind speed percent frequency by month.

			Gridpoint GP2		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	24.3	44.5	23.5	6.3	1.3	0.2	-	-
Feb.	31.0	41.8	21.7	4.4	1.2	0.1	-	-
Mar.	32.7	46.7	17.1	2.7	0.7	0.1	-	-
Apr.	37.7	47.1	12.8	2.2	0.3	-	-	-
May	44.2	45.0	9.8	1.1	-	-	-	-
Jun.	56.2	38.5	5.1	0.2	-	-	-	-
Jul.	60.4	34.9	4.6	0.1	-	-	-	-
Aug.	60.1	33.9	5.4	0.6	-	-	-	-
Sep.	42.2	45.1	10.9	1.6	0.2	-	-	-
Oct.	31.6	46.5	18.7	3.0	0.2	-	-	-
Nov.	28.5	47.2	20.5	3.4	0.4	-	-	-
Dec.	29.4	42.2	20.9	6.3	1.2	0.1	-	-
Annual	39.9	42.8	14.2	2.6	0.5	-	-	-

Table 8.3. Gridpoint wind speed percent frequency by month.

			Gridpoint GP3		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	40.0	44.4	13.1	2.2	0.3	-	-	-
Feb.	46.9	41.2	9.5	2.1	0.3	-	-	-
Mar.	52.6	39.1	6.7	1.4	0.2	-	-	-
Apr.	53.1	39.8	6.6	0.4	-	-	-	-
May	60.7	33.5	5.1	0.8	-	-	-	-
Jun.	70.3	26.5	3.2	-	-	-	-	-
Jul.	74.1	23.4	2.4	0.1	-	-	-	-
Aug.	70.4	25.7	3.7	0.2	-	-	-	-
Sep.	57.6	35.0	6.1	1.1	0.2	-	-	-
Oct.	43.6	44.1	10.7	1.4	0.2	-	-	-
Nov.	42.9	44.3	10.9	1.7	0.2	-	-	-
Dec.	45.6	40.1	11.9	2.1	0.3	-	-	-
Annual	54.9	36.4	7.5	1.1	0.2	-	-	-

Table 8.4. Gridpoint wind speed percent frequency by month.

			Gridpoint GP4		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	34.7	44.2	17.8	3.1	0.3	-	-	-
Feb.	41.0	42.1	14.1	2.5	0.3	-	-	-
Mar.	47.2	41.0	10.4	1.3	0.1	0.1	-	-
Apr.	53.5	39.0	6.9	0.5	0.1	-	-	-
May	53.6	39.2	6.3	0.8	0.1	-	-	-
Jun.	64.1	31.4	4.3	0.2	-	-	-	-
Jul.	68.3	28.5	3.1	0.1	-	-	-	-
Aug.	65.4	30.4	3.8	0.4	-	-	-	-
Sep.	49.4	41.1	8.5	0.8	0.2	-	-	-
Oct.	39.5	45.6	12.7	2.1	0.1	-	-	-
Nov.	40.9	45.0	12.0	1.9	0.1	0.1	-	-
Dec.	39.6	46.7	11.8	1.7	0.3	-	-	-
Annual	49.8	39.5	9.3	1.3	0.1	-	-	-

Table 8.5. Gridpoint wind speed percent frequency by month.

			Gridpoint GP5		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	34.2	43.7	18.2	3.8	0.2	-	-	-
Feb.	39.0	43.7	14.3	2.7	0.2	0.1	-	-
Mar.	43.8	43.6	10.9	1.6	0.2	-	-	-
Apr.	50.3	42.7	6.5	0.4	0.1	-	-	-
May	57.1	37.2	5.2	0.5	-	-	-	-
Jun.	67.3	31.2	1.3	0.1	-	-	-	-
Jul.	72.9	25.5	1.6	0.1	-	-	-	-
Aug.	69.0	28.3	2.5	0.2	-	-	-	-
Sep.	49.7	42.5	7.4	0.4	-	-	-	-
Oct.	39.3	47.7	11.6	1.3	0.1	-	-	-
Nov.	38.2	48.5	11.6	1.4	0.2	-	-	-
Dec.	39.9	46.1	12.5	1.3	0.2	-	-	-
Annual	50.1	40.0	8.6	1.1	0.1	-	-	-

Table 8.6. Gridpoint wind speed percent frequency by month.

			Gridpoint GP6		(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	28.6	43.0	22.8	5.0	0.5	-	-	-
Feb.	29.5	47.0	18.3	4.3	0.8	0.1	-	-
Mar.	36.9	43.7	16.7	2.4	0.3	-	-	-
Apr.	38.2	49.7	10.9	1.0	0.2	-	-	-
May	45.4	44.2	9.2	1.2	-	-	-	-
Jun.	47.2	44.7	7.4	0.7	0.1	-	-	-
Jul.	52.1	42.1	5.6	0.1	-	-	-	-
Aug.	51.5	41.5	6.7	0.3	-	-	-	-
Sep.	39.0	45.7	12.9	1.9	0.4	-	-	-
Oct.	29.7	47.9	18.2	3.7	0.6	-	-	-
Nov.	33.0	47.8	15.9	3.0	0.3	0.1	-	-
Dec.	33.3	46.5	16.6	3.1	0.4	0.1	-	-
Annual	38.8	45.3	13.4	2.2	0.3	-	-	-

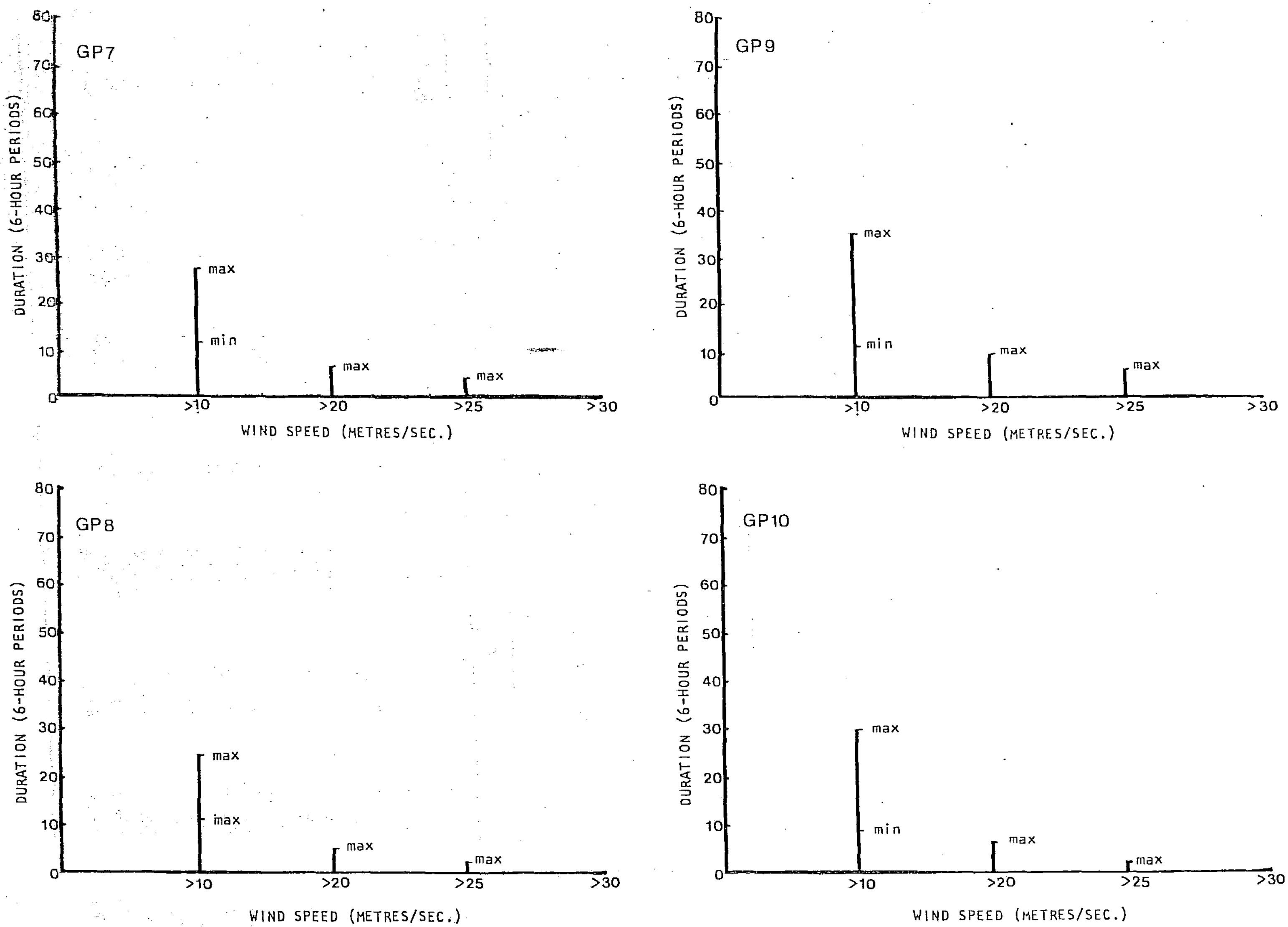


Figure 8.8 Duration (No. of 6-hr periods) for yearly maximum wind speed at Gridpoints 1-4. (The extreme event for any given year lies at or between the Max and Min points).

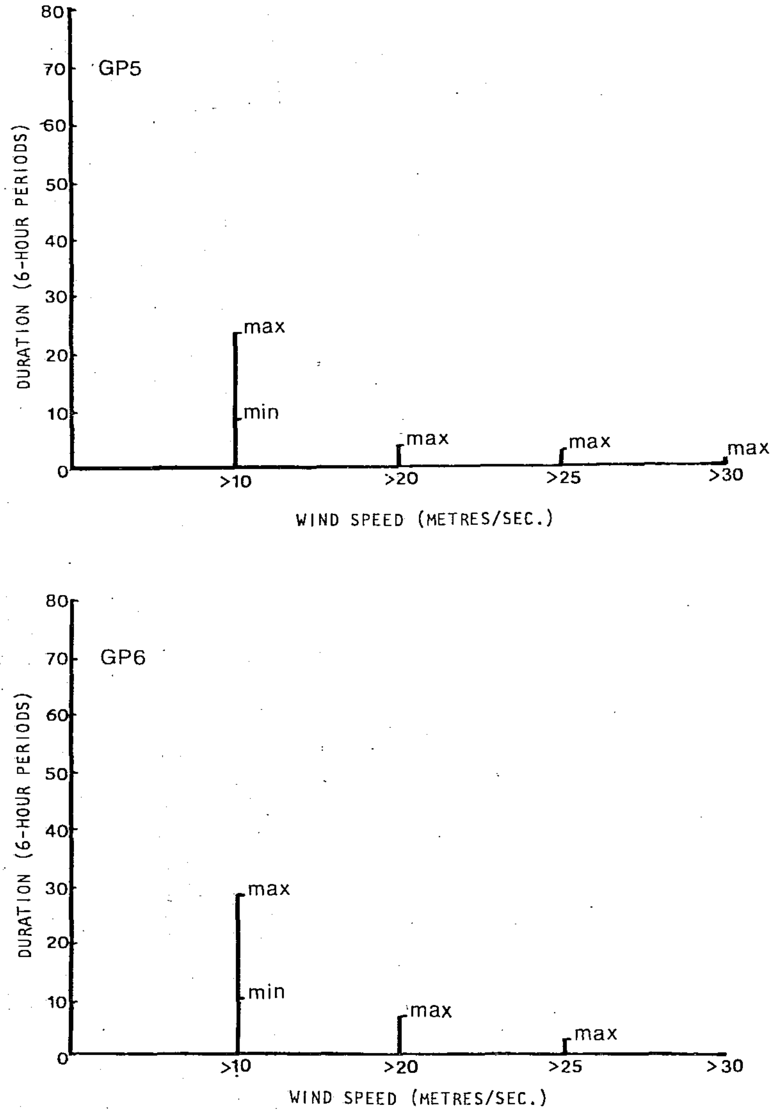


Figure 8.8a Duration (No. of 6-hr periods) for yearly maximum wind speed at Gridpoints 5-6. (The extreme event for any given year lies at or between the Max and Min points).

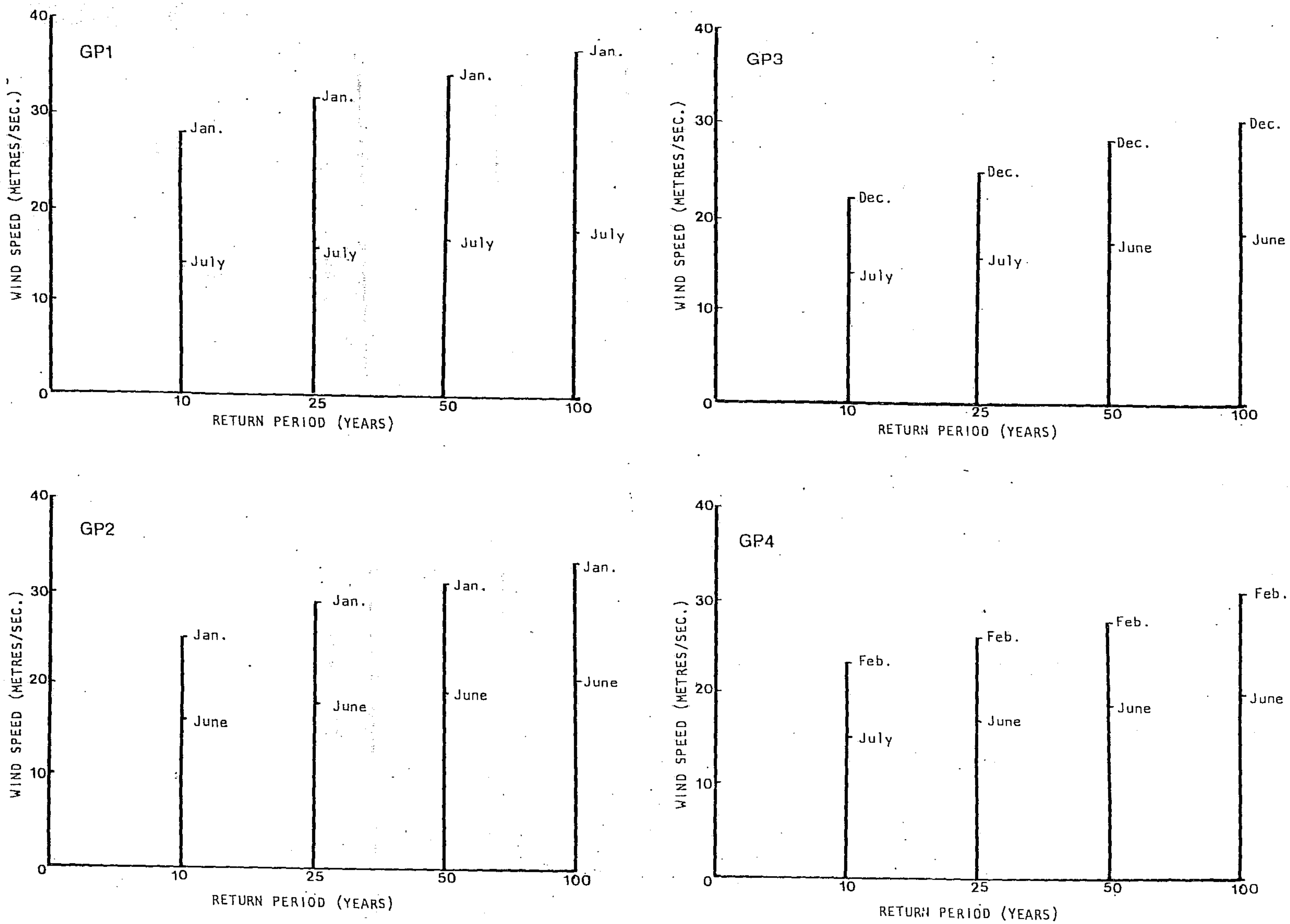


Figure 3.9 Return period for maximum wind speed by month for Gridpoints 1-4. (All values lie at or between the two points).

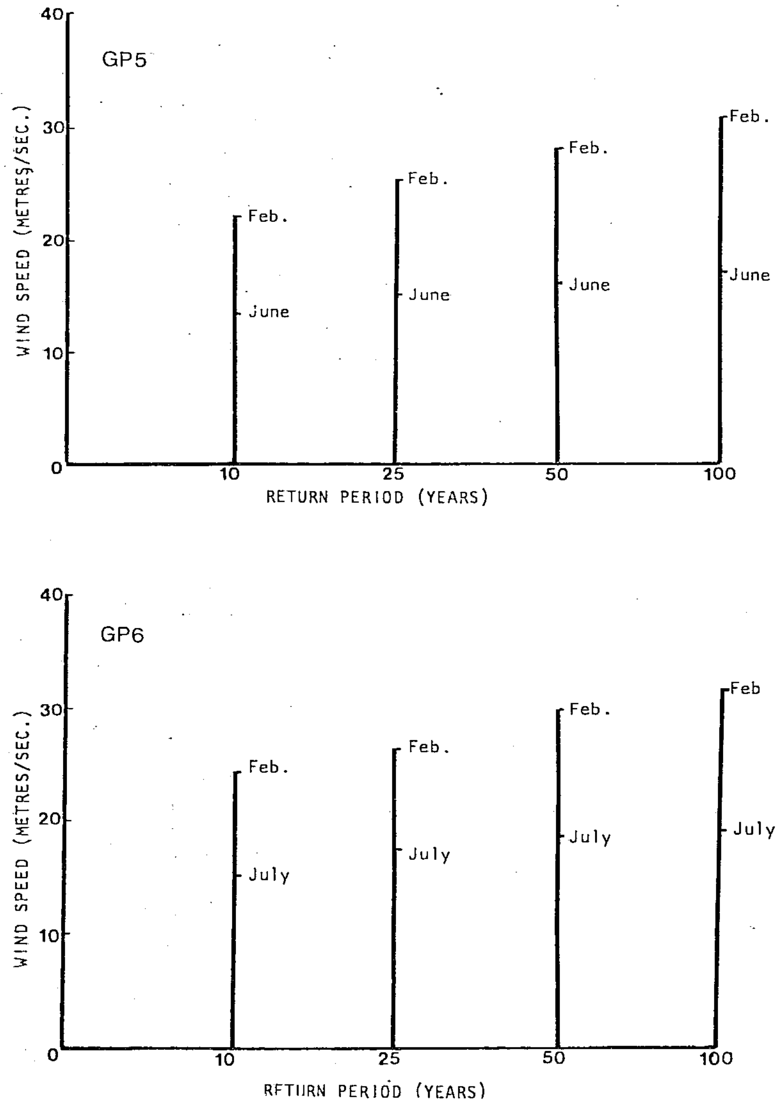


Figure 8.9a Return period for maximum wind speed by month for Gridpoints 5-6. (All values lie at or between the two points).

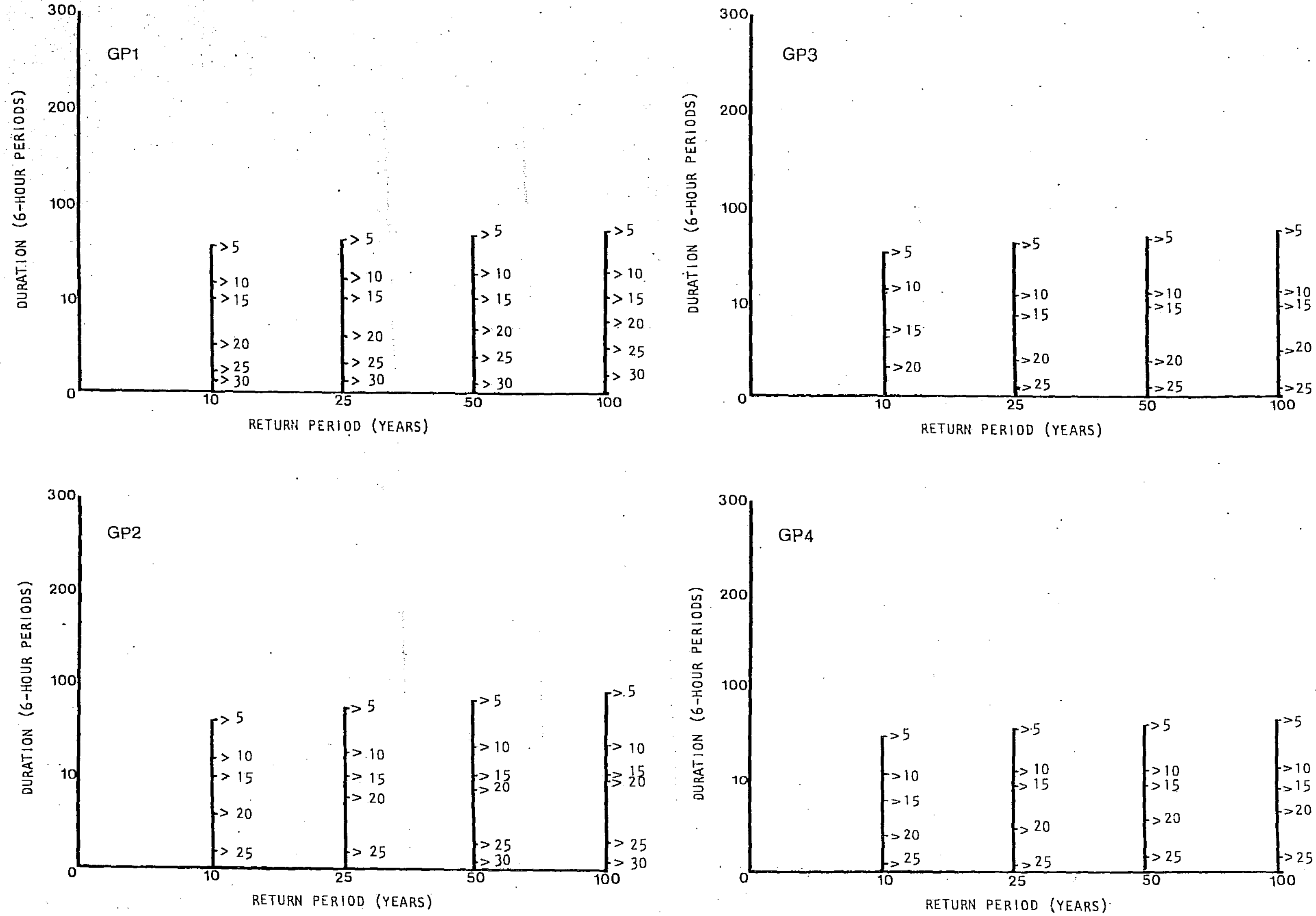


Figure 8.10 Return period for wind speed events of specific duration for Gridpoints 1-4.

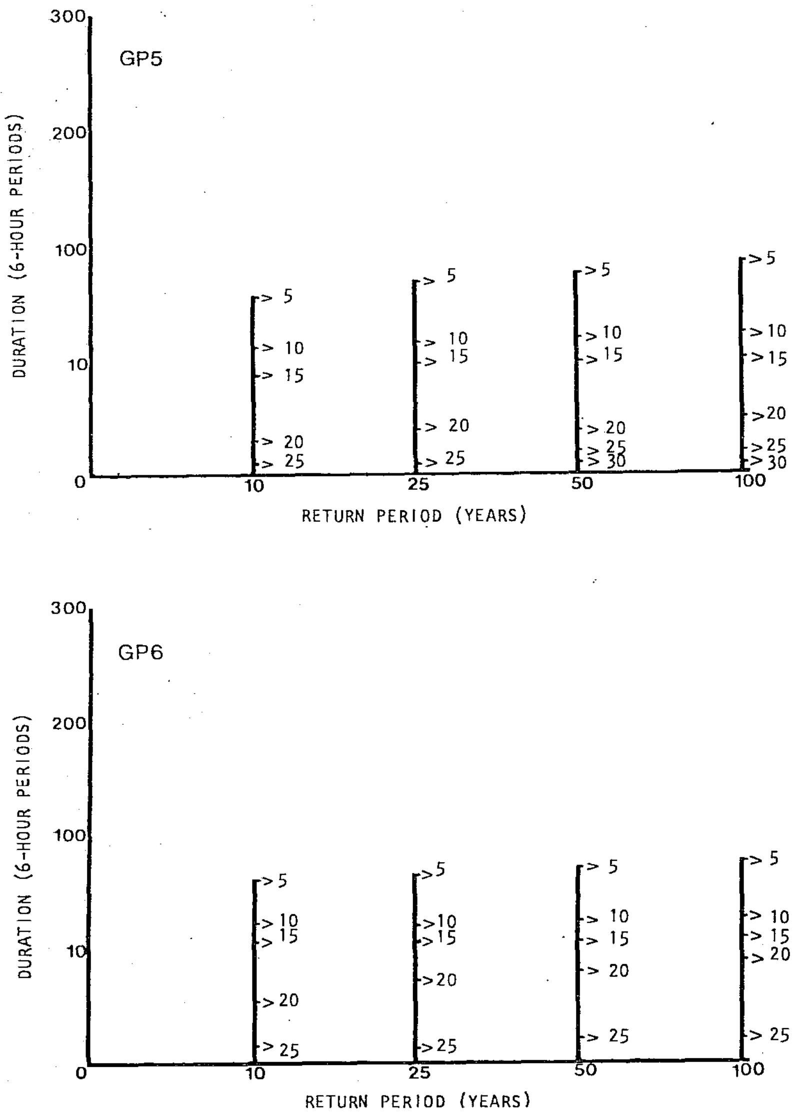


Figure 8.10a Return period for wind speed events of specific duration for Gridpoints 5-6.

The wind speed return periods are presented in Figures 8.9 to 8.10a. Points GP3 through GP6 exhibit similar returns while GP1 and GP2 have generally significantly greater wind speed returns.

(ii) Marine Observations: The marine areas in the eastern Arctic are shown in Figure 8.1. Wind roses for these regions are shown in Figures 8.11 to 8.14.

Of note in these wind roses is a preference for west and east directions at M 9 during July and August with a shift toward winds from the north quadrant in September and October. This shift is likely the result of more frequent excursions of storms into Baffin Bay in the fall. In marine areas M 10, 12 and 14, northwest or southeast directions predominate. This is a result of storms tracking through Baffin Bay giving southeast winds over central and eastern sections of the bay and of lee troughing along the west coast of Greenland giving northwesterly winds. At marine areas M 13, 15, 16 and 17, a high frequency of winds from the north or south is evident.

The percentage frequencies of wind speed ranges by month are shown in Tables 8.7 to 8.15. Notable here is the general increase in percentages for higher wind speed classes in the September to October period as a result of the increased frequency of storm activity during the fall months. It is also interesting to see that the largest percentages in the high wind speed categories occur at M016 and M017, a result likely caused by the passage of strong storms across these marine areas with a subsequent weakening of these systems as they move northward.

In a study of extreme storms of northwestern Baffin Bay completed by Thomson and Vickers (Maxwell, J.B. et al 1980), the meteorological events associated with several storms were examined for the five-year period (1974-1978) using the SSMO data base used in this study. During two of the storms, ship winds of 28 m/s (Sept. 25-27, 1974) and 26 m/s (Sept. 17-19, 1974) were reported.

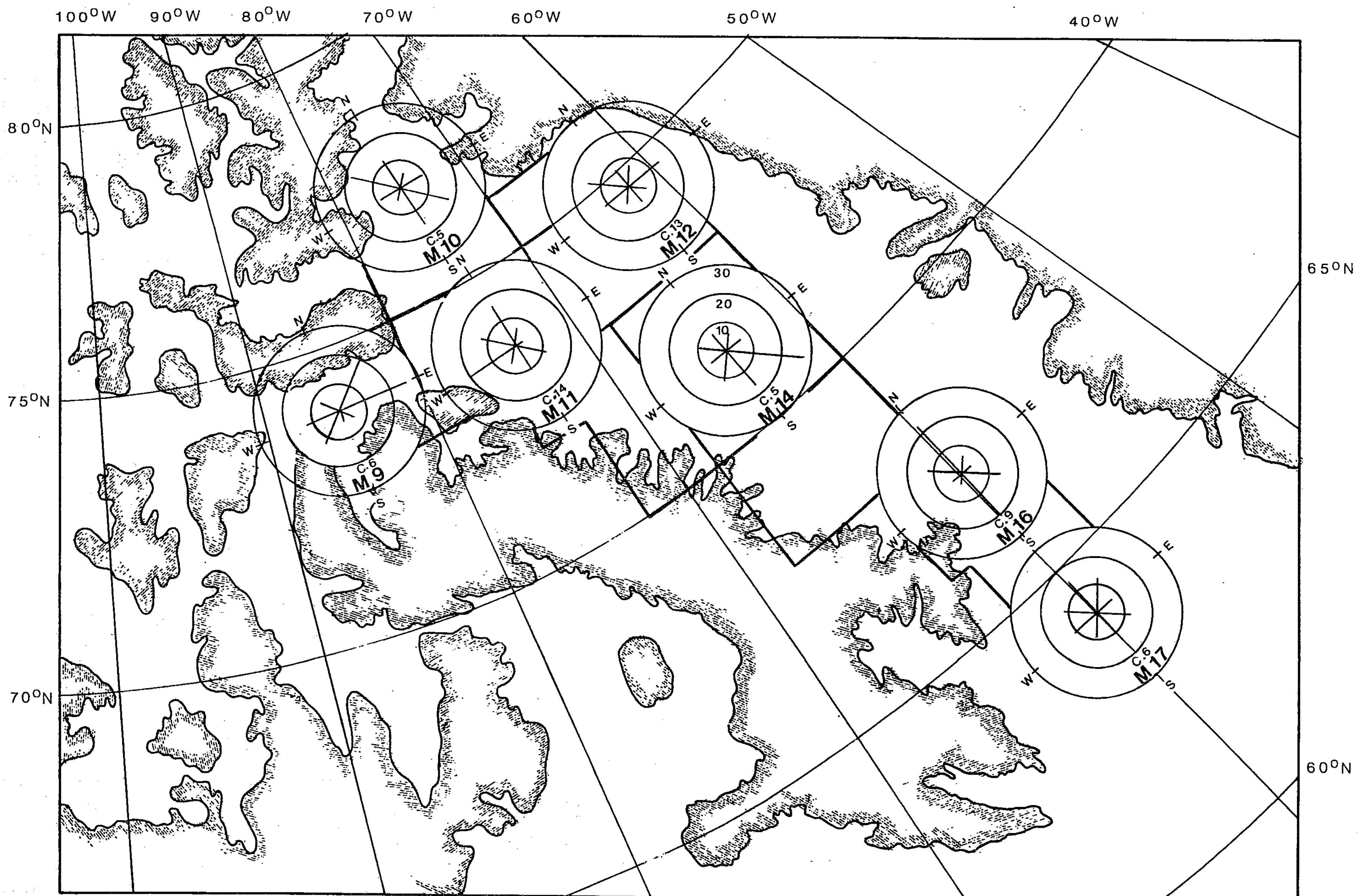


Figure 8.11 Marine Area wind roses - July.

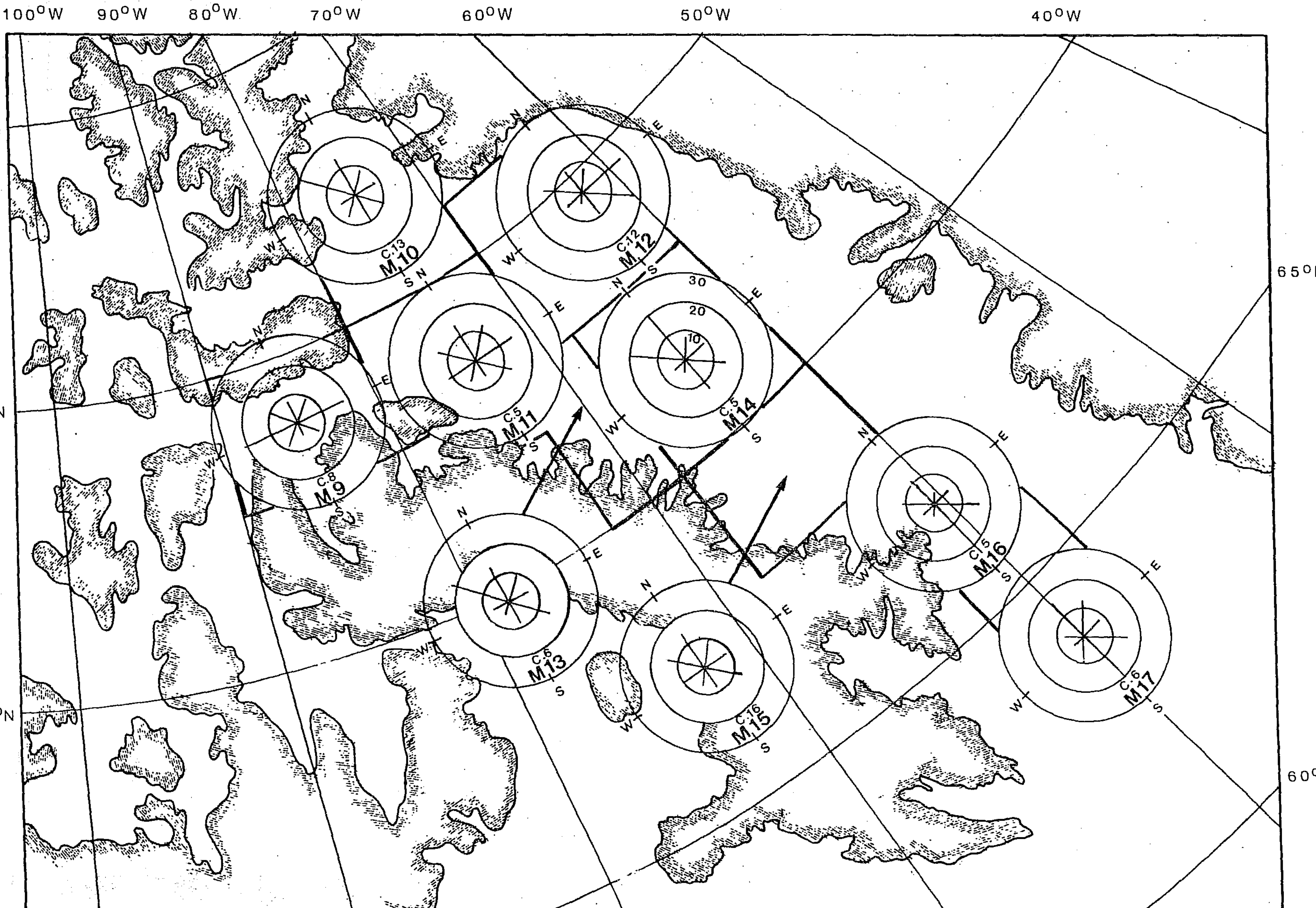


Figure 8.12 Marine Area wind roses - August.

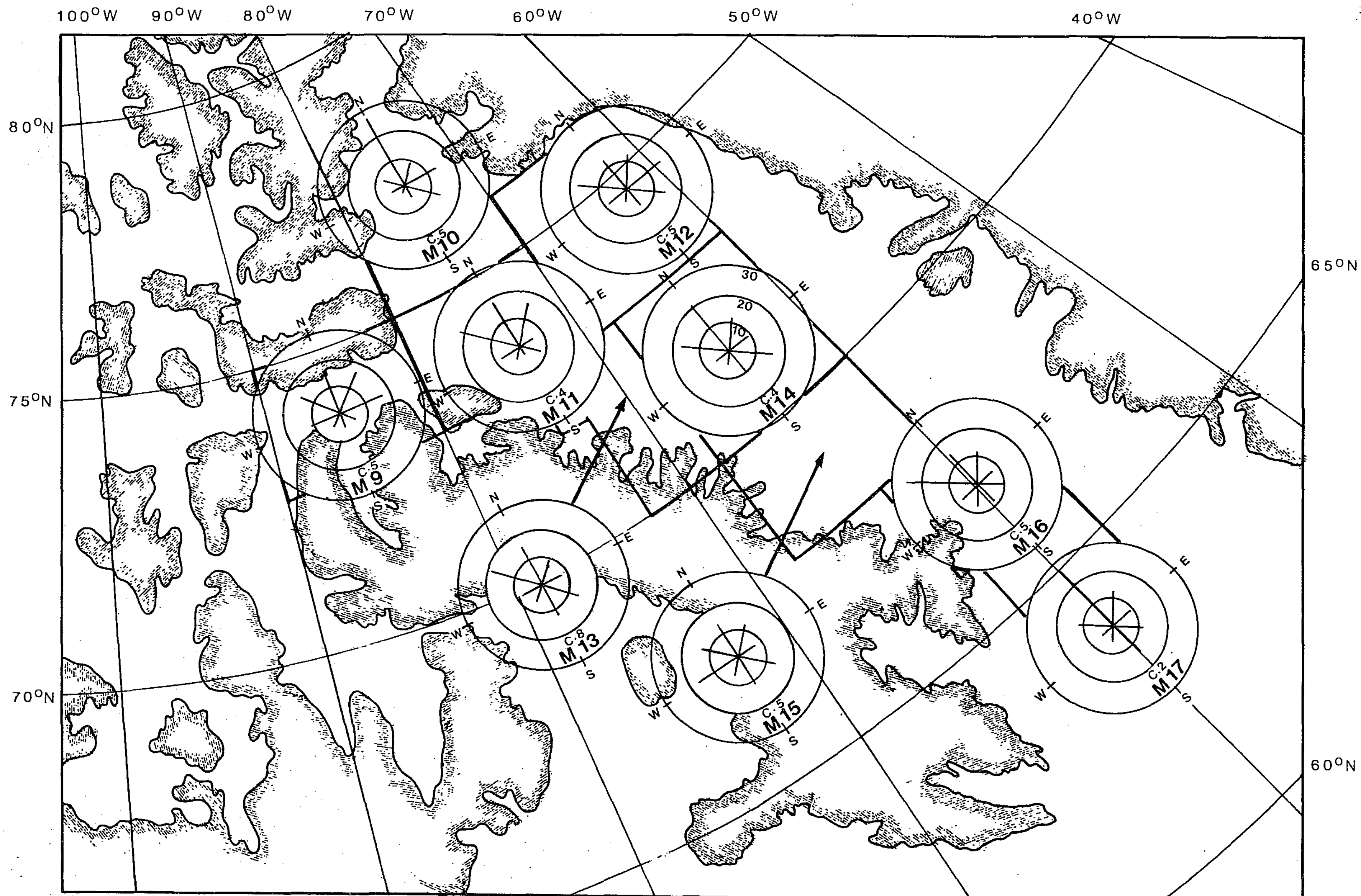


Figure 8.13 Marine Area wind roses - September.

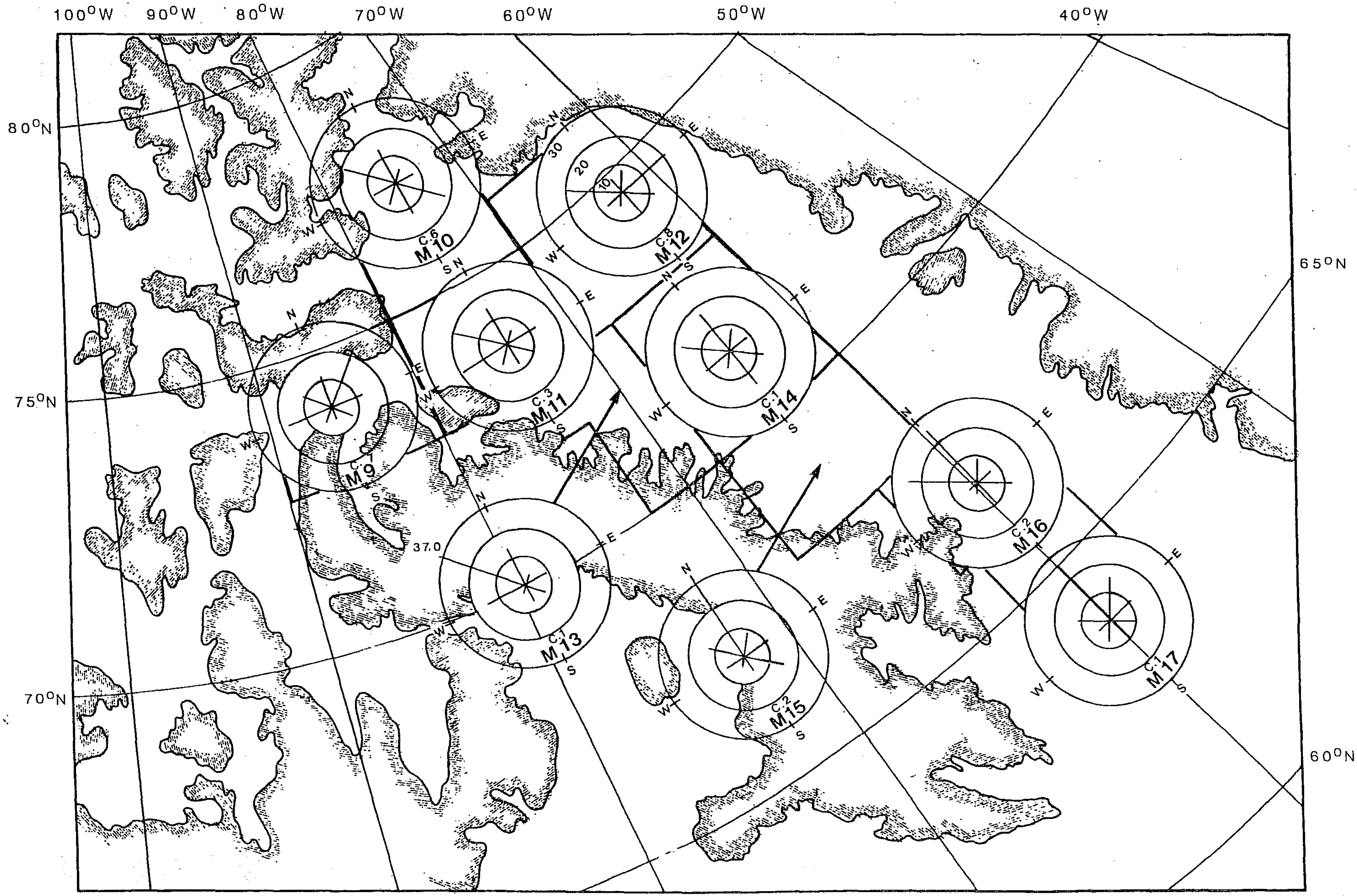


Figure 8.14 Marine Area wind roses - October.

Table 8.7. Percent frequency of wind speed by class for marine areas.

Marine Area M 9

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul.	(60)	30.0	23.3	18.3	28.3	0.0
Aug.	(1114)	48.9	36.1	13.0	1.7	0.0
Sep.	(478)	48.3	38.1	11.9	1.7	0.0
Oct.	(152)	49.4	30.9	15.8	3.9	0.0

Table 8.8. Percent frequency of wind speed by class for marine areas.

Marine Area M 10

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul.	(189)	48.7	37.6	12.7	1.1	0.0
Aug.	(708)	65.0	26.3	7.8	0.8	0.1
Sep.	(537)	43.0	37.6	16.4	2.8	0.2
Oct.	(123)	50.4	35.8	9.8	4.1	0.0

Table 8.9. Percent frequency of wind speed by class for marine areas.

Marine Area M 11

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul.	(62)	71.0	29.0	0.0	0.0	0.0
Aug.	(337)	54.0	35.6	8.9	1.5	0.0
Sep.	(238)	49.6	41.6	8.4	0.4	0.0
Oct.	(155)	40.6	30.3	20.6	7.1	1.3

Table 8.10. Percent frequency of wind speed by class for marine areas.

Marine Area M 12

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul. (1172)	71.6	25.4	3.0	0.0	0.0
Aug. (1197)	71.4	26.1	2.6	0.0	0.0
Sep. (546)	58.8	37.7	3.1	0.4	0.0
Oct. (189)	38.1	46.6	13.2	1.6	0.6

Table 8.11. Percent frequency of wind speed by class for marine areas.

Marine Area M 13

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug. (473)	55.4	38.5	5.7	0.2	0.2
Sep. (382)	42.7	46.6	8.9	1.8	0.0
Oct. (177)	35.1	46.3	18.6	0.0	0.0

Table 8.12. Percent frequency of wind speed by class for marine areas.

Marine Area M14

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul. (93)	62.4	21.5	15.1	1.1	0.0
Aug. (343)	54.5	39.4	6.1	0.0	0.0
Sep. (377)	43.5	47.7	7.4	1.3	0.0
Oct. (152)	37.2	43.7	14.8	4.4	0.0

Table 8.13. Percent frequency of wind speed by class for marine areas.

Marine Area M 15

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug. (501)	65.8	27.9	5.2	1.0	0.0
Sep. (397)	44.8	41.6	12.1	1.5	0.0
Oct. (106)	33.9	44.3	18.9	2.8	0.0

Table 8.14. Percent frequency of wind speed by class for marine areas.

Marine Area M 16

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul. (135)	54.8	35.6	9.6	0.0	0.0
Aug. (1374)	68.9	23.2	6.6	1.1	0.1
Sep. (480)	49.2	34.6	14.2	2.1	0.0
Oct. (182)	30.7	36.3	23.6	9.3	0.0

Table 8.15. Percent frequency of wind speed by class for marine areas.

Marine Area M 17

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul. (157)	47.8	42.7	9.6	0.0	0.0
Aug. (535)	52.1	37.2	8.0	2.6	0.0
Sep. (410)	30.0	46.8	19.3	3.9	0.0
Oct. (196)	24.0	38.3	27.5	8.2	2.0

8.2.2 Waves

Percent frequency of wave heights shown in Tables 8.16 to 8.24 for each of the eastern Arctic Marine areas. The original unit has been retained.

Table 8.16. Marine Area M 9

		Wave Heights (Feet)											
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19		20-22
Aug.	(249)	47.4	20.5	20.1	7.2	2.0	0.8	0.8	0.8	0.4	0.0	0.0	
Sep.	(214)	31.8	18.7	24.3	11.7	6.5	3.3	2.3	0.9	0.5	0.0	0.0	
Oct.	(152)	75.0	15.6	9.4									

Table 8.17. Marine Area M 10

		Wave Heights (Feet)											
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19		20-22
Jul.	(47)	70.2	27.7	2.1									
Aug.	(177)	33.9	34.5	20.9	5.6	1.1	0.6	0.0	0.0	0.0	3.4	0.0	
Sep.	(298)	33.9	25.2	22.1	8.7	5.0	1.0	1.0	1.7	0.3	0.7	0.3	
Oct.	(69)	53.6	23.2	13.0	8.7	0.0	1.4						

Table 8.18. Marine Area M 11

		Wave Heights (Feet)											
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19		20-22
Jul.	(31)	71.0	19.4	9.7									
Aug.	(132)	38.6	28.0	17.4	12.1	2.3	0.0	0.8	0.0	0.8			
Sep.	(122)	28.7	34.4	21.3	5.7	6.6	2.5	0.0	0.8				
Oct.	(53)	47.2	24.5	17.0	5.7	5.7							

Table 8.19. Marine Area M 12

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Jul.	(297)	92.3	6.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug.	(333)	50.8	28.8	13.8	3.0	2.4	1.2	0.0	0.0	0.0	0.0	0.0
Sep.	(229)	31.4	32.8	20.1	9.2	3.9	1.3	0.0	0.0	0.4	0.0	0.0
Oct.	(70)	31.4	32.9	17.1	7.1	5.7	2.9	2.9	0.0	1.6		

Table 8.20. Marine Area M 13

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Aug.	(122)	51.6	29.5	11.5	4.9	0.0	2.5					
Sep.	(178)	32.6	33.1	23.0	6.7	1.7	2.2	0.6				
Oct.	(62)	38.7	21.0	24.2	8.1	8.1						

Table 8.21. Marine Area M 14

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Aug.	(102)	50.0	21.6	20.6	4.9	2.9						
Sep.	(142)	31.0	30.3	24.6	4.9	7.0	0.7	0.7	0.7			
Oct.	(86)	16.3	31.4	20.9	15.1	4.7	7.0	2.3	2.3			

Table 8.22. Marine Area M 15

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Aug.	(115)	57.4	25.2	11.3	2.6	0.9	1.7	0.0	0.0	0.9		
Sep.	(133)	51.1	23.3	12.8	7.5	3.0	0.0	0.8	1.5			
Oct.	(61)	26.2	27.9	18.0	13.1	4.9	4.9	3.3	0.0	1.6		

Table 8.23. Marine Area M 16

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Jul.	(43)	25.6	23.3	46.5	4.7							
Aug.	(334)	54.5	17.4	12.0	7.5	3.0	1.8	0.6	0.9	1.2	0.9	0.3
Sep.	(179)	48.6	15.1	19.6	6.1	5.6	2.2	2.2	0.0	0.6		
Oct.	(103)	22.3	18.4	23.3	19.4	10.7	2.9	1.0	1.0	0.0	0.0	1.0

Table 8.24. Marine Area M 17

		Wave Heights (Feet)										
MONTH	(OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22
Jul.	(51)	23.5	19.6	23.5	5.9	15.7	5.9	3.9	2.0			
Aug.	(262)	31.3	26.7	20.2	8.4	4.6	2.7	2.7	1.1	0.8	0.8	0.8
Sep.	(207)	17.9	26.6	23.7	12.1	7.7	5.3	2.9	2.4	1.0	0.5	
Oct.	(83)	12.0	15.7	24.1	21.7	10.8	7.2	4.8	1.2	2.4		

For each of the marine areas, the tendency toward higher waves later in the season is evident. The small data samples in some cases, especially for October, resulted in wave frequencies decreasing for the higher ranges. Also, areas M 16 and M 17 had the highest waves with some cases of 20 to 22 feet shown. This is reasonable in light of the long north to south fetches and the smaller climatological ice amounts in these areas.

Lachapelle (1980) states that the highest observed wave in areas M 9 and M 11 is 22 feet and 19 feet respectively. These waves are higher than those shown in Tables 8.16 and 8.18 since the time period used in Lachapelle's study is 1953-1972 while this study includes 1963-1973 data.

8.2.3 Visibilities

For each month the percentages for each visibility range for the marine observations are shown in Tables 8.25 to 8.33.

Table 8.25. Percent frequency of visibilities (km)

		Marine Area M 9					
MONTH	(#OBS)	<0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Jul.	(63)	6.3	0.0	0.0	3.2	41.3	49.2
Aug.	(1142)	7.5	2.2	2.4	6.9	28.0	53.0
Sep.	(507)	2.4	1.0	3.7	7.9	33.9	51.1
Oct.	(153)	3.9	5.2	3.9	5.0	39.9	32.0

Table 8.26. Percent frequency of visibilities (km)

Marine Area M 10							
MONTH	(#OBS)	< 0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Jul.	(194)	20.6	3.1	4.1	4.6	20.1	47.4
Aug.	(593)	8.8	2.7	3.0	4.4	23.6	57.5
Sep.	(582)	1.0	1.7	4.6	8.1	38.1	46.4
Oct.	(132)	2.3	0.8	3.8	13.6	48.5	31.1

Table 8.27. Percent frequency of visibilities (km).

Marine Area M 11							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Jul.	(62)	17.7	4.8	1.6	6.5	21.0	48.4
Aug.	(327)	10.7	1.8	3.7	9.8	36.1	37.9
Sep.	(255)	3.9	2.0	2.7	7.8	26.3	57.3
Oct.	(161)	4.3	4.3	8.1	18.0	37.9	27.3

Table 8.28. Percent frequency of visibilities (km).

Marine Area M 12							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Jul.	(1175)	17.5	8.1	4.5	8.1	24.5	38.0
Aug.	(1054)	12.0	4.3	3.4	7.1	26.5	46.7
Sep.	(554)	1.6	2.2	3.1	6.7	33.6	52.9
Oct.	(192)	3.6	3.6	2.1	11.5	36.5	42.7

Table 8.29. Percent frequency of visibilities (km).

Marine Area M 13							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Aug.	(497)	8.7	3.4	4.0	9.7	45.3	29.0
Sep.	(412)	4.9	3.2	2.9	11.2	36.7	41.3
Oct.	(193)	4.7	7.8	5.7	19.7	37.8	24.4

Table 8.30. Percent frequency of visibilities (km).

Marine Area M 14							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Jul.	(83)	6.0	4.8	2.4	7.2	34.9	44.6
Aug.	(345)	21.7	5.8	7.8	7.2	24.6	32.8
Sep.	(387)	5.4	2.3	2.1	5.7	35.7	48.8
Oct.	(194)	4.6	0.5	3.6	13.4	39.7	38.1

Table 8.31. Percent frequency of visibilities (km).

Marine Area M 15							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Aug.	(517)	13.9	3.3	5.6	10.1	27.9	39.3
Sep.	(430)	9.1	1.6	3.3	5.3	27.4	53.3
Oct.	(107)	7.5	0.9	3.7	10.3	34.6	43.0

Table 8.32. Percent frequency of visibilities (km).

Marine Area M 16							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Jul.	(133)	15.0	6.8	3.0	6.8	39.1	29.3
Aug.	(1386)	17.6	4.0	3.6	7.1	27.8	39.9
Sep.	(513)	7.0	2.7	3.5	6.6	30.4	49.7
Oct.	(192)	3.1	4.7	3.6	12.5	33.9	42.2

Table 8.33. Percent frequency of visibilities (km).

Marine Area M 17							
MONTH	(#OBS)	< 0.9	0.9 < 1.9	1.9 < 3.7	3.7 < 9.3	9.3 < 18.5	18.5+
Jul.	(158)	20.9	6.3	4.4	7.6	23.4	37.3
Aug.	(551)	17.2	2.7	4.0	7.4	24.0	44.5
Sep.	(420)	6.0	2.1	1.9	8.3	28.3	53.3
Oct.	(192)	5.7	4.2	1.0	13.0	31.8	44.3

From this table, a general decrease in occurrences of low visibilities is evident through the July to October period over most of the marine areas. Another notable aspect is the increase in occurrences of the " 3.7 < 9.3" and "9.3 < 18.5" percentages in the September to October period over most of the areas. This could be a result of an increase in snowflurry activity at this time of year as cold unstable airmasses begin to move southward across warmer open waters once again.

8.2.4 Freezing Spray

The eastern marine region, especially Baffin Bay and Davis Strait, offers the greatest potential for superstructure icing. The main reason is that the area is ice free throughout the fall when there is a high frequency of disturbances moving northward through Davis Strait into Baffin Bay. Winds of 28 m/s can occur with some of these systems and if water temperatures are around 2°C and air temperature near -5°C, then accumulation rates of about 13 cm/24 hrs can be expected. If winds remain the same but the water temperature lowers to 1°C, the rate increases to about 15 cm/24 hrs.

Rates rapidly increase as air temperature lowers. The average daily temperature at Cape Dyer during October is -14.8°C and lowers to -20°C in November. Using the same wind of 28 m/s, a water temperature of 0°C to 1°C and an air temperature of -10°C the rate goes to over 25 cm/24 hrs. This extreme rating is maintained or increased until the air temperature falls below about -18°C. For temperatures colder than -18°C the spray will normally freeze prior to striking the vessel.

This example used an unusually high wind but even a wind of 20 m/s and a water temperature of 0 to +1°C results in an accumulation rate of about 15 cm/24 hrs. Should heavy icing be encountered on the northward portion of a voyage the ice buildup will likely remain with the ship until a return to warmer waters.

8.2.5 Ice

(i) Median Old Ice Concentrations: In Figures 8.15 and 8.16a, the median concentrations of old ice are shown. The Lancaster Sound-northern Baffin Bay areas remain in the "zero" median amount of old ice through the period. The southern sections of Baffin Bay show an increase in median amounts from the mid- June to mid-August period. This appears to be an anomaly since this is during the melting period. However, the younger thinner ice melts, first allowing the old ice to accumulate in one area rather than remaining scattered throughout the pack where such small amounts would not show in the medians. Another possible reason is the better identification of old ice as the snow cover overlying it melts away during June and July. The increase in median amounts is real but may be exaggerated since the earlier June and May reports could have been underestimated due to a problem of identification of old ice covered with snow. Later, during September and October, these median areas disappear as the melt proceeds.

(ii) Worst Ice Conditions: In the Lancaster Sound area, complete consolidation can persist from late May through early July with a gradual improvement through August and September. (See Figures 8.17 and 8.18). Northern and northwestern Baffin Bay is only partly consolidated early in the period and opens to a large "0" area during late August and September. The eastern sections of Baffin Bay-Davis Strait show "3" and "0" areas in late May and eventually open up entirely by mid-August through late October. The central and western parts of Baffin Bay and Davis Strait begin the period in the completely consolidated area and remain in the "7" area later in the season.

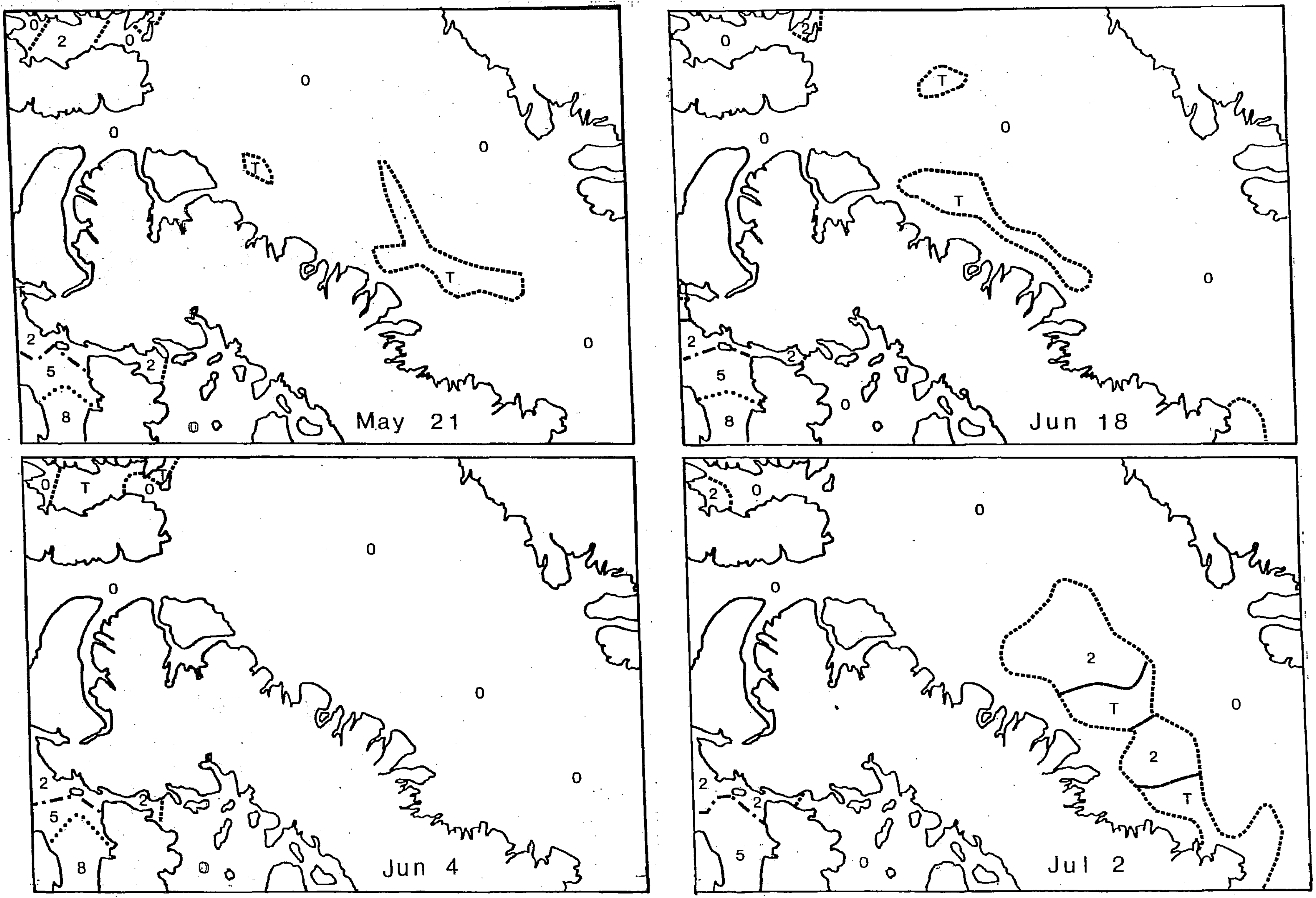


Figure 8.15 Median concentration of old ice (after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

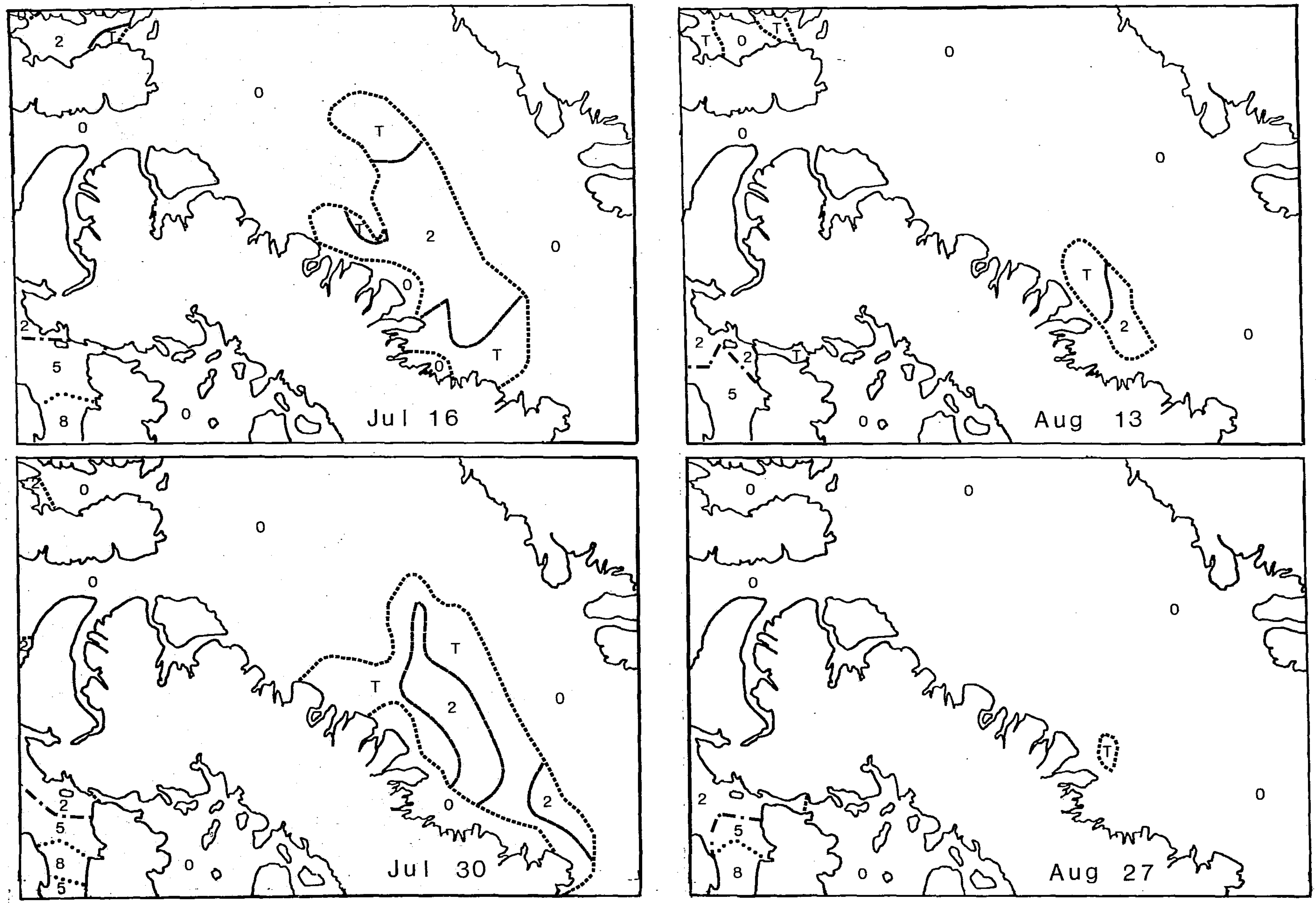


Figure 8.16 Median concentration of old ice (after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

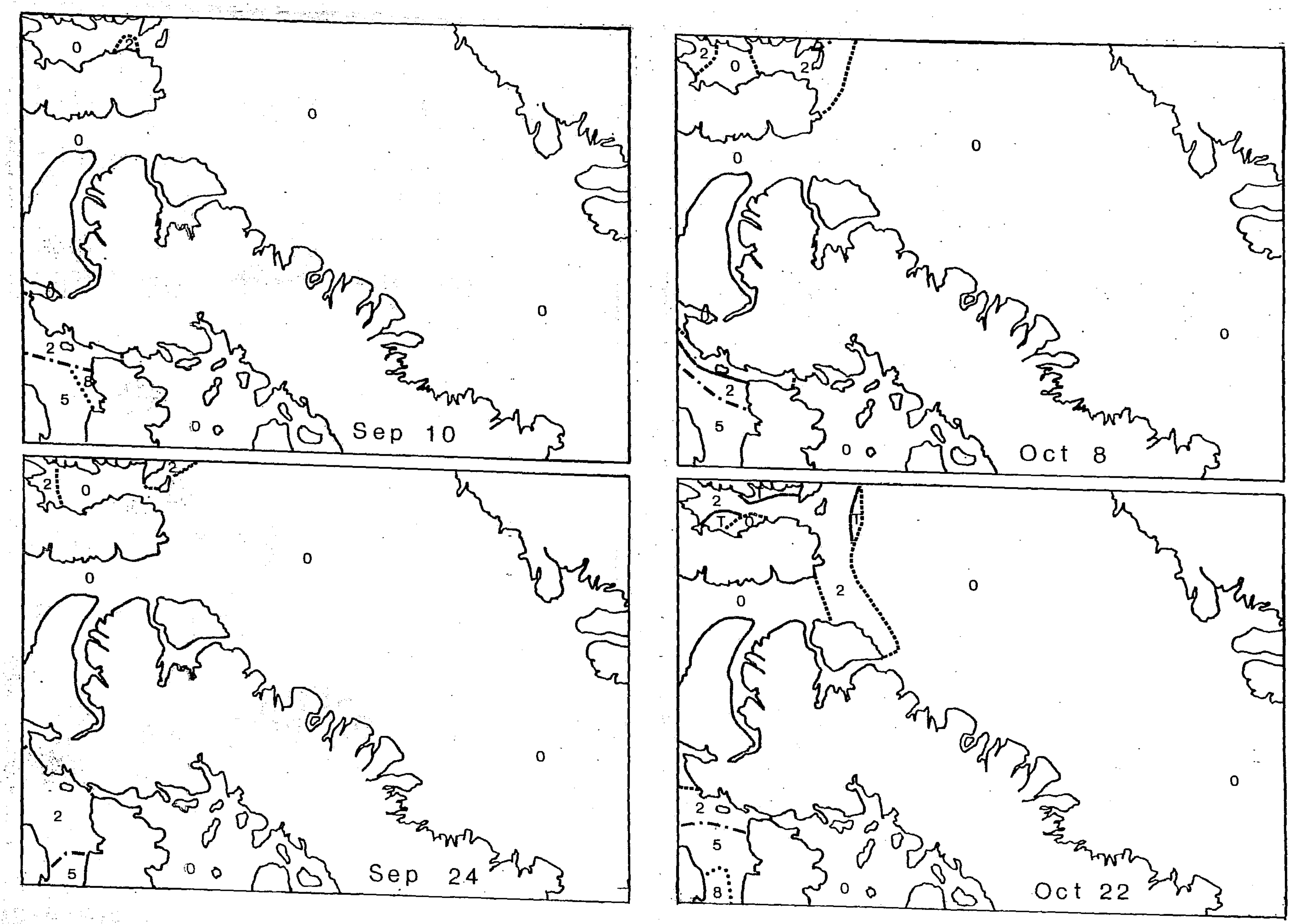


Figure 8.16a Median concentration of old ice
(after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

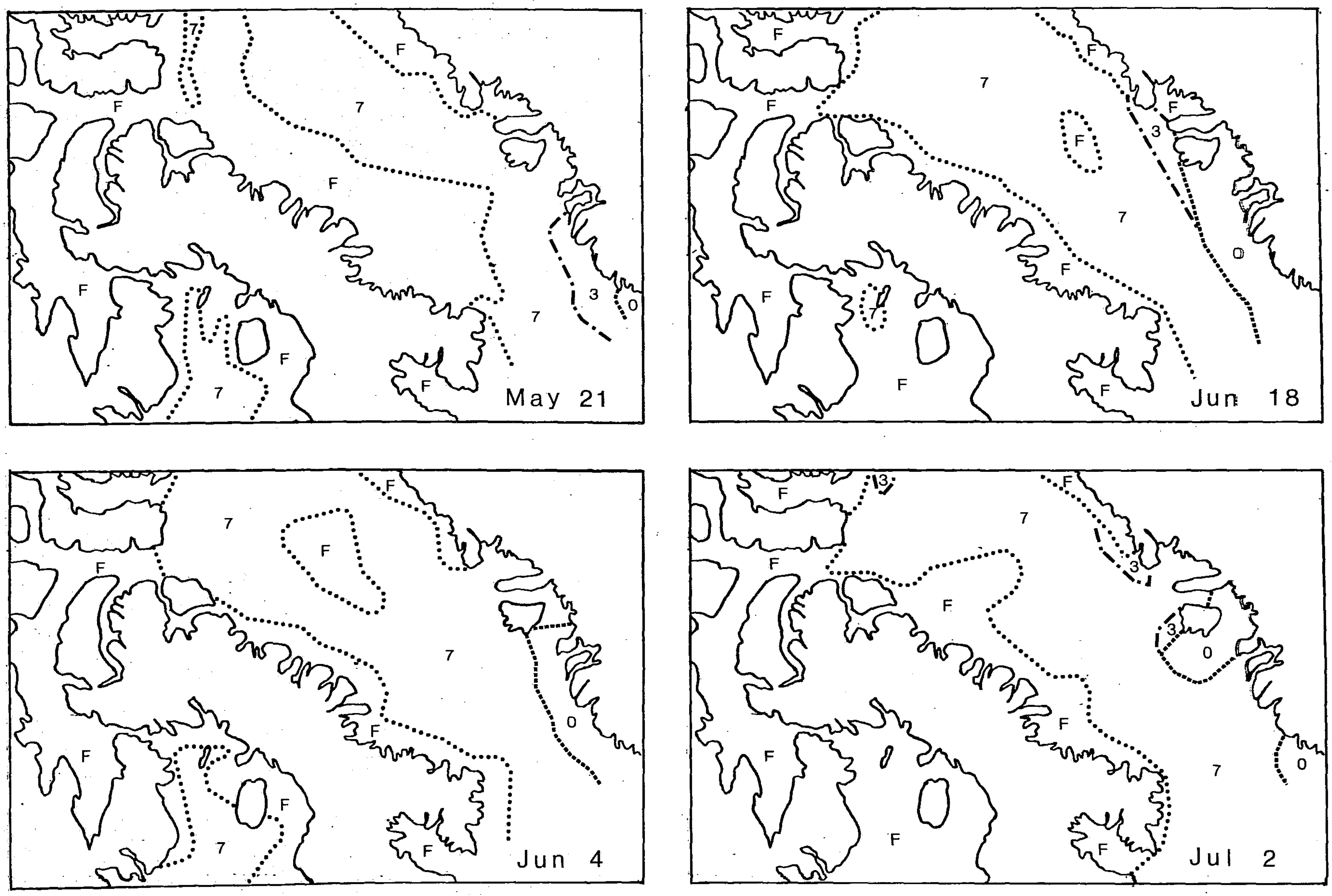


Figure 8.17 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

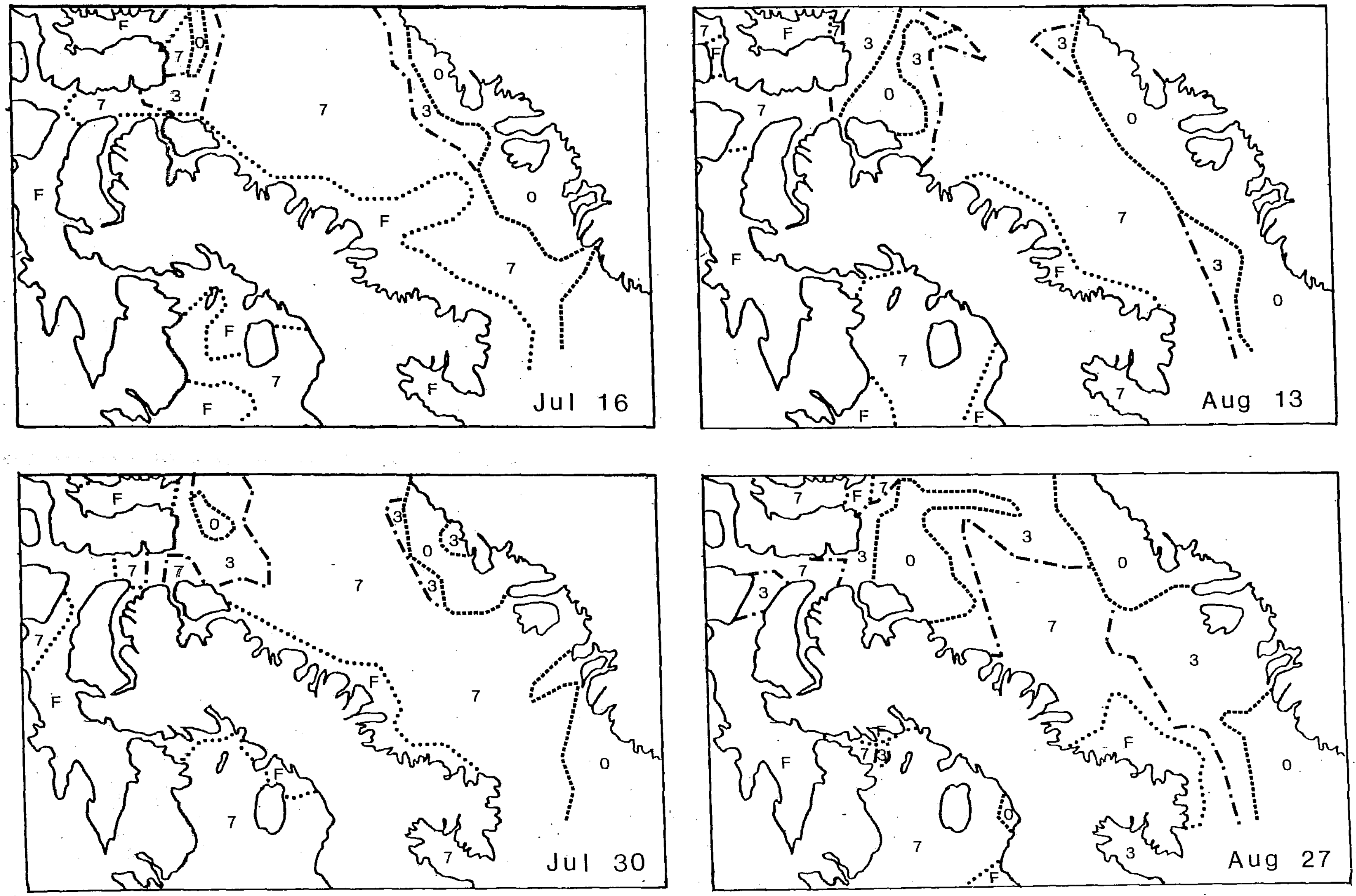


Figure 8.18 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

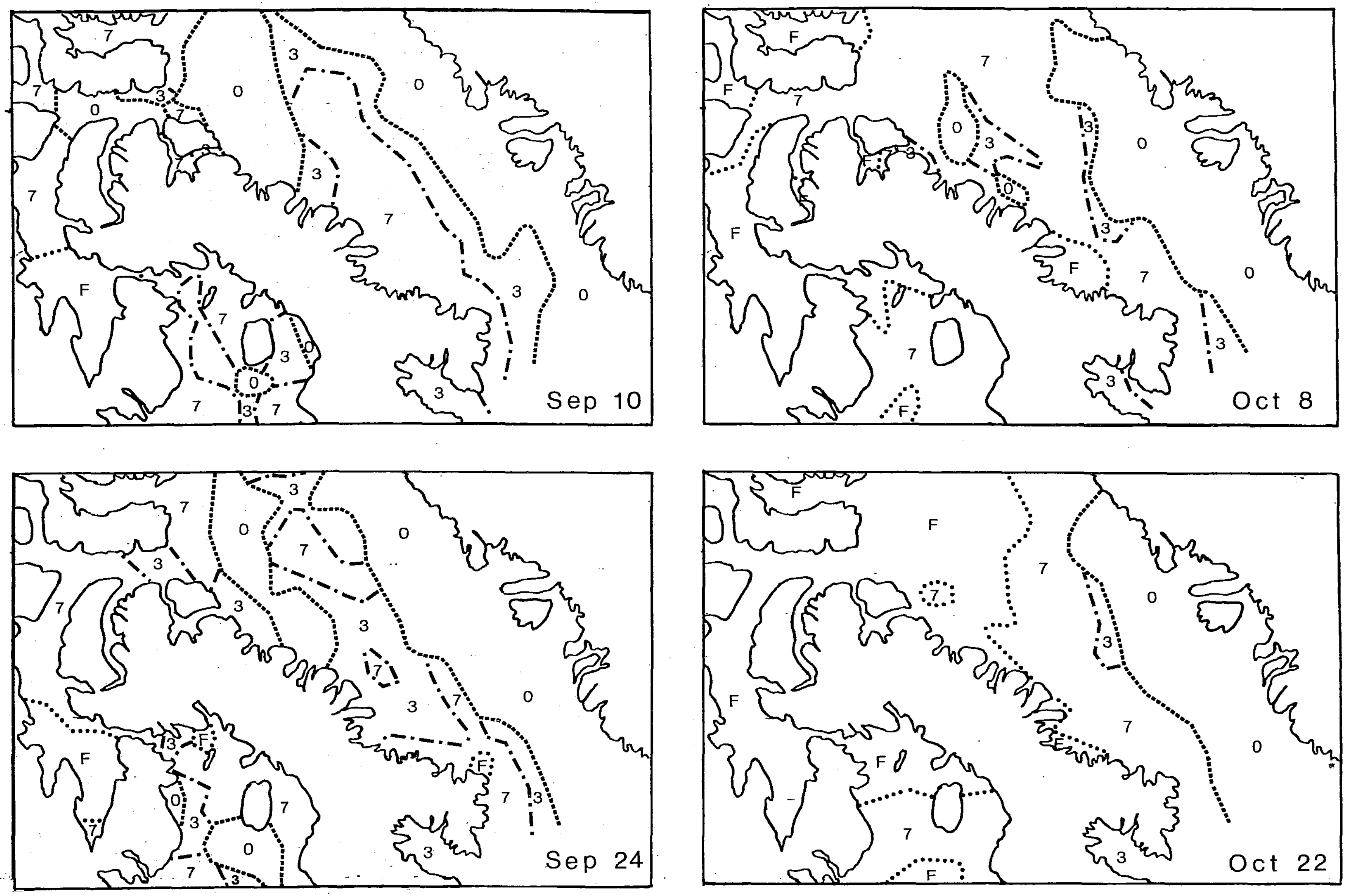


Figure 8.18a Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

8.3 CENTRAL ARCTIC MARINE AREA

Figure 8.19 shows the central Arctic marine area with the gridpoints and marine regions.

8.3.1 Winds

(i) FNOC Gridpoint Wind Results: For gridpoints GP7 to GP10, the wind roses are shown in Figures 8.20 to 8.24. (Figure 8.25 presents extreme wind statistics for the same gridpoints). For point GP10, the dominant wind directions are generally northwest and southeast with the exception of the May period when a shift to northerly appears along with a reduced occurrence percentage. In the annual peak geostrophic wind figure, the extreme winds occur from the northwest or southeast in agreement with the prevailing wind directions. The winter-time wind extremes are from the northwest with the remaining months' extremes generally from the southeast.

In the gridpoint GP9 diagrams, the north to northwesterly directions prevail throughout the year with a lesser secondary peak from the east to south. For the peak geostrophic winds, the winter winds are again from the north to northwest. For the remaining months, however, no predominant directions are evident in the peak winds.

Finally, at points GP7 and GP8 the predominant wind direction shifts slightly to northerly with little preference indicated in the remaining directions. Despite the high northerly percentage frequency, the peak winds can occur from other directions throughout the year.

In Tables 8.34 to 8.37, the percentages are shown for each month and for each wind speed range for the four gridpoints under consideration. The dominant trend in these tables is toward stronger wind speeds during the winter months for all points. Otherwise, there appears to be little differences among the percentages for the four points for a given month.

The wind speed durations for the gridpoints are shown in Figure 8.26. Points GP9 and GP10 show a tendency toward higher durations than either GP7 or GP8.

The return periods for both the wind speeds and duration are shown in Figures 8.27 and 8.28 for the four points. For both sets of return periods, the values do not appear significantly different for all four gridpoints.

(ii) Marine Observations: The wind roses for marine areas M 4 through M 8 are shown in Figures 8.29 to 8.32. For M 4 the roses are consistent for the three-month period in showing a preference toward east and northwest winds. In the M 5 area, the August wind rose shows the expected channeling from the northeast and east while the September data indicates southeast to northwesterly dominant directions. The small samples could be the cause of this discrepancy; otherwise, no reason for this can be seen. The M 6 marine area roses show no directional biases. In area M 7 the September and October wind

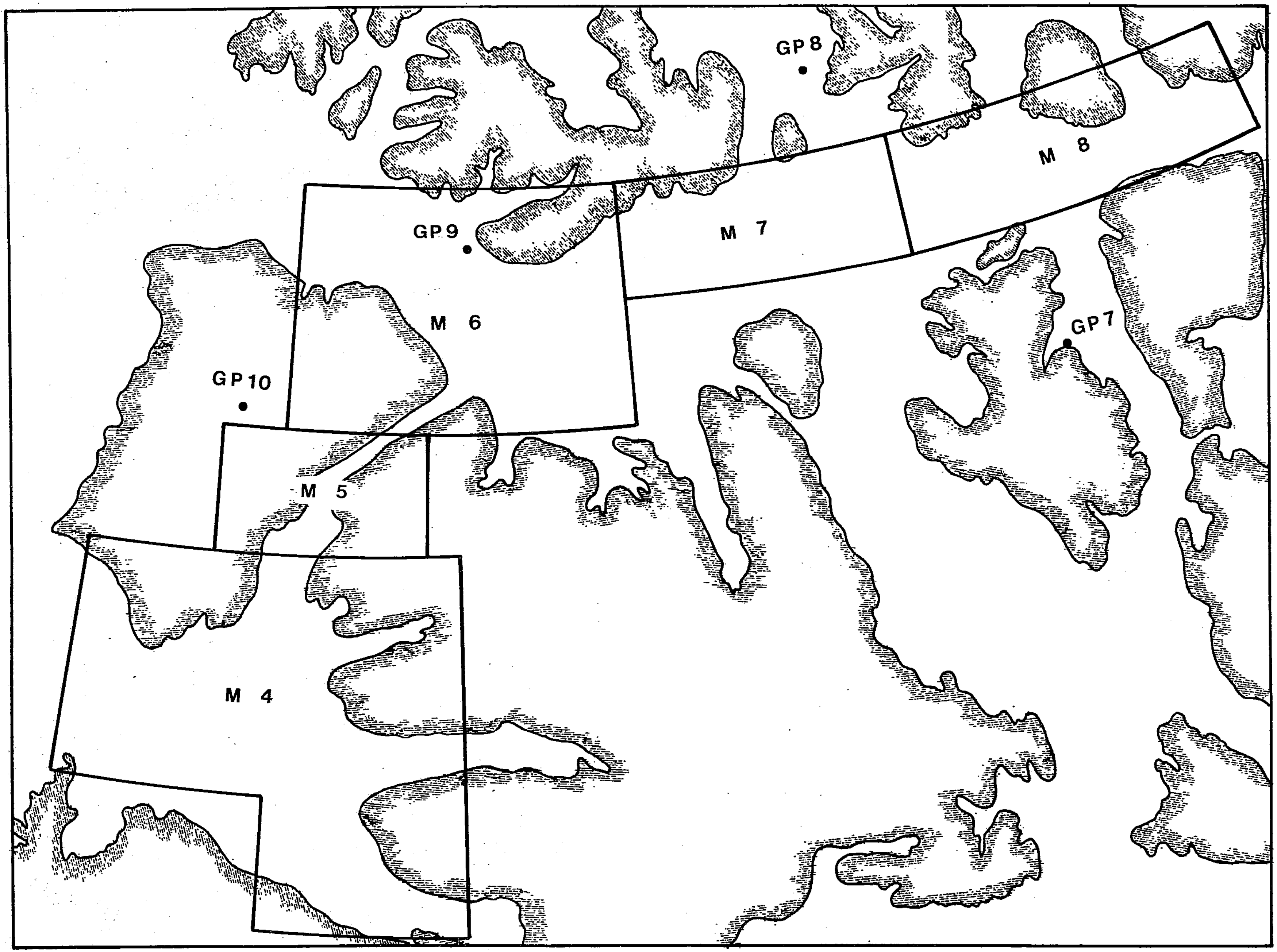


Figure 8.19   Central Arctic Marine Area.

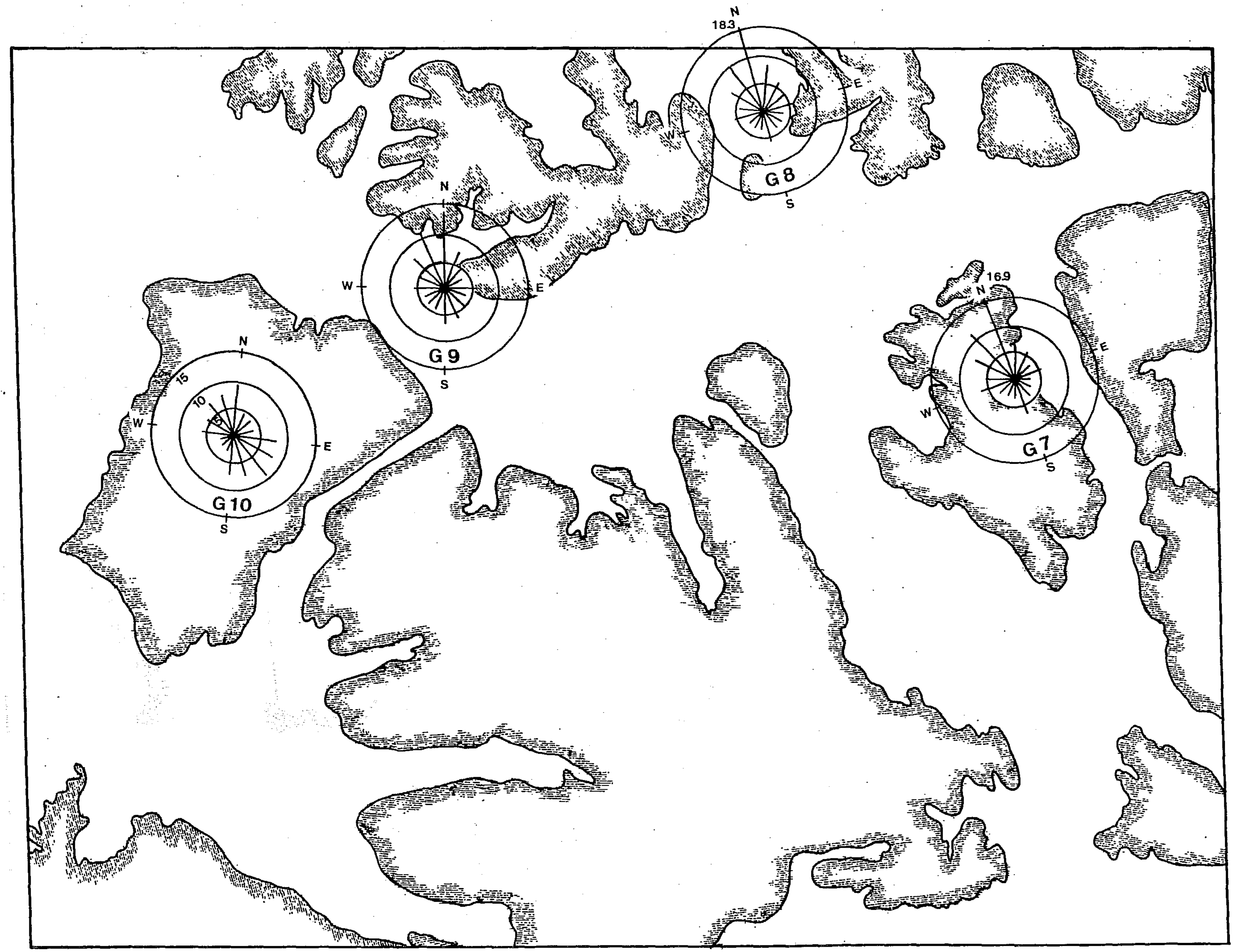


Figure 8.20 Gridpoint wind roses - annual.

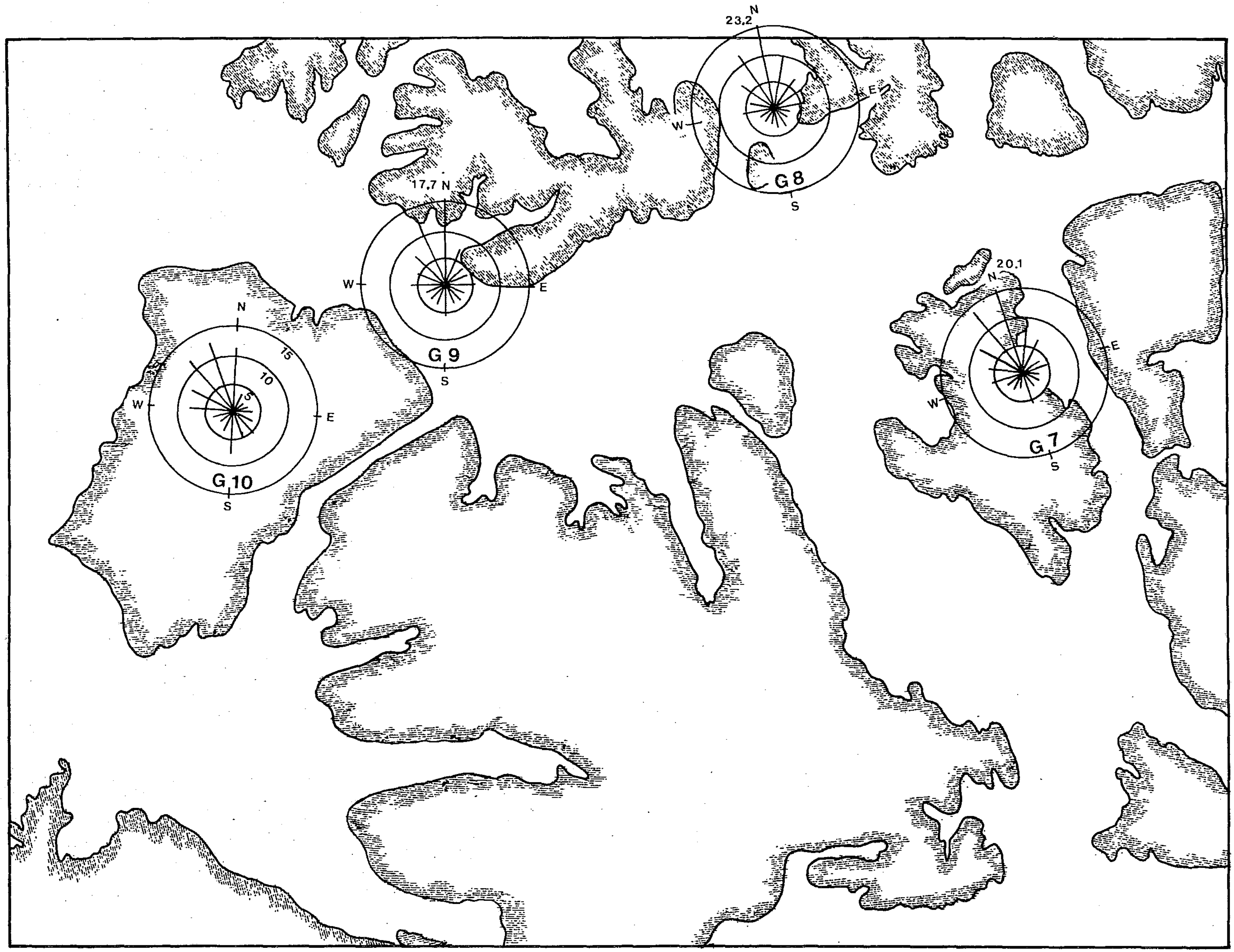


Figure 8.21 Gridpoint wind roses - January.

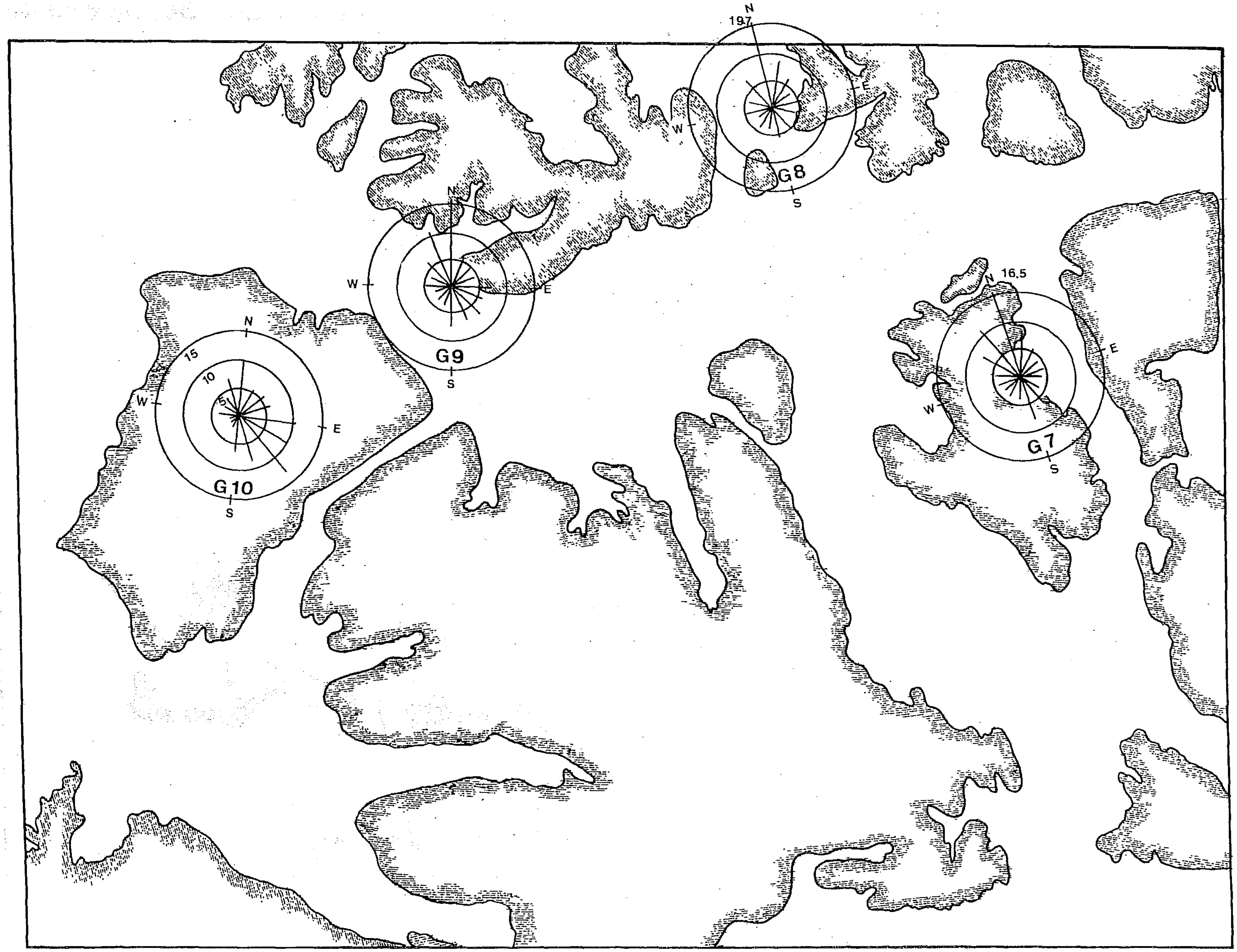


Figure 8.22 Gridpoint wind roses - May.

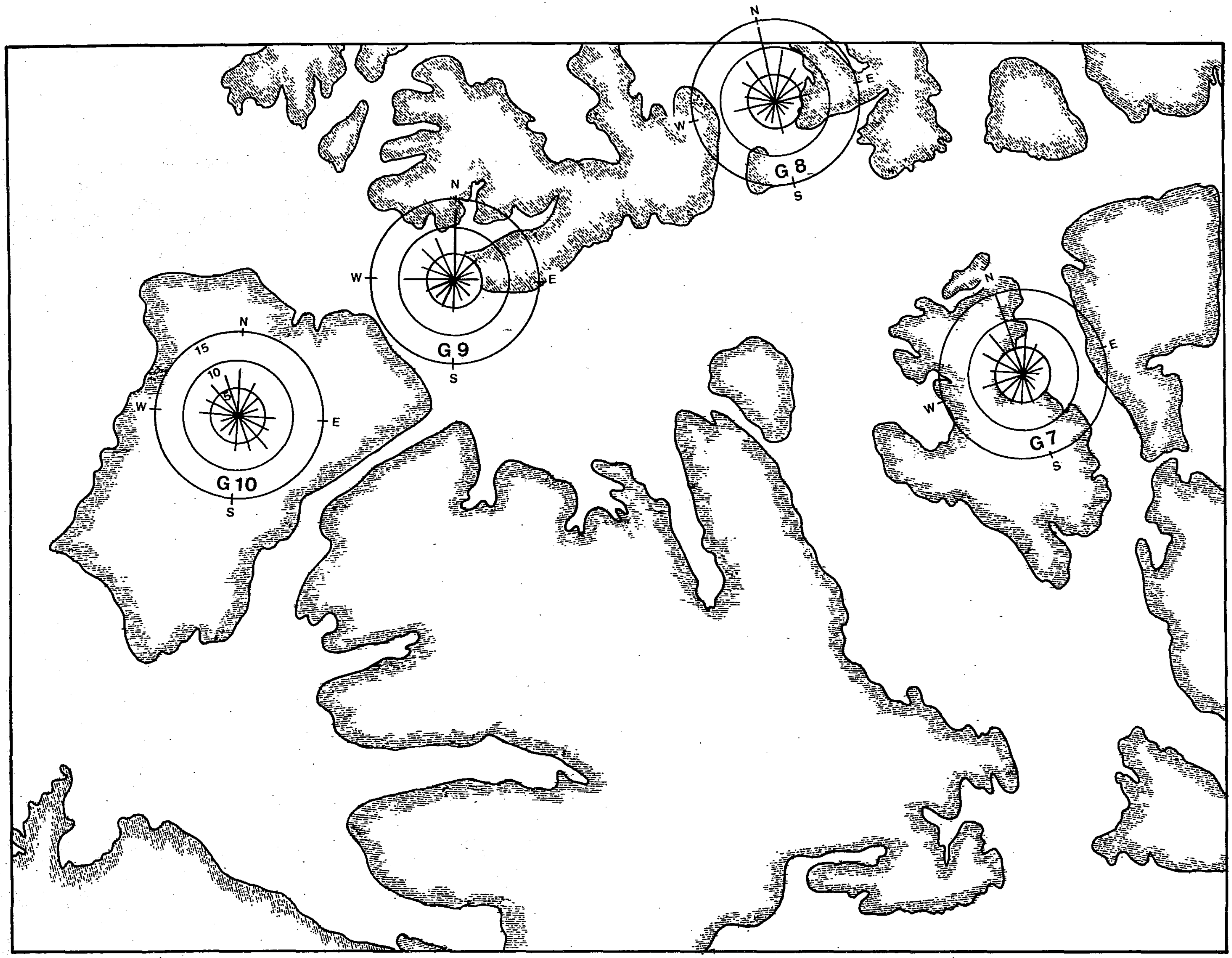


Figure 8.23 Gridpoint wind roses - July.

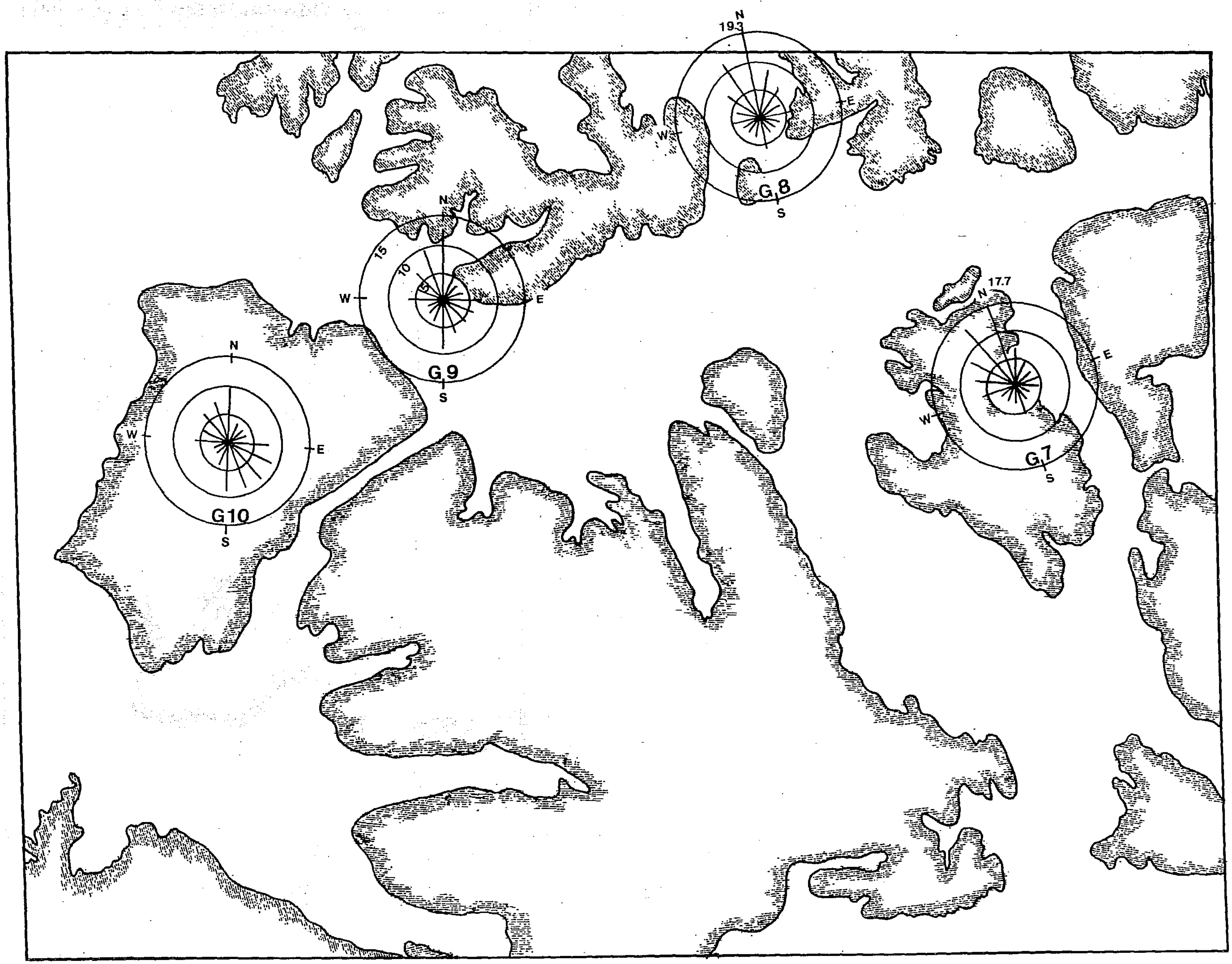


Figure 8.24   Gridpoint wind roses - September.

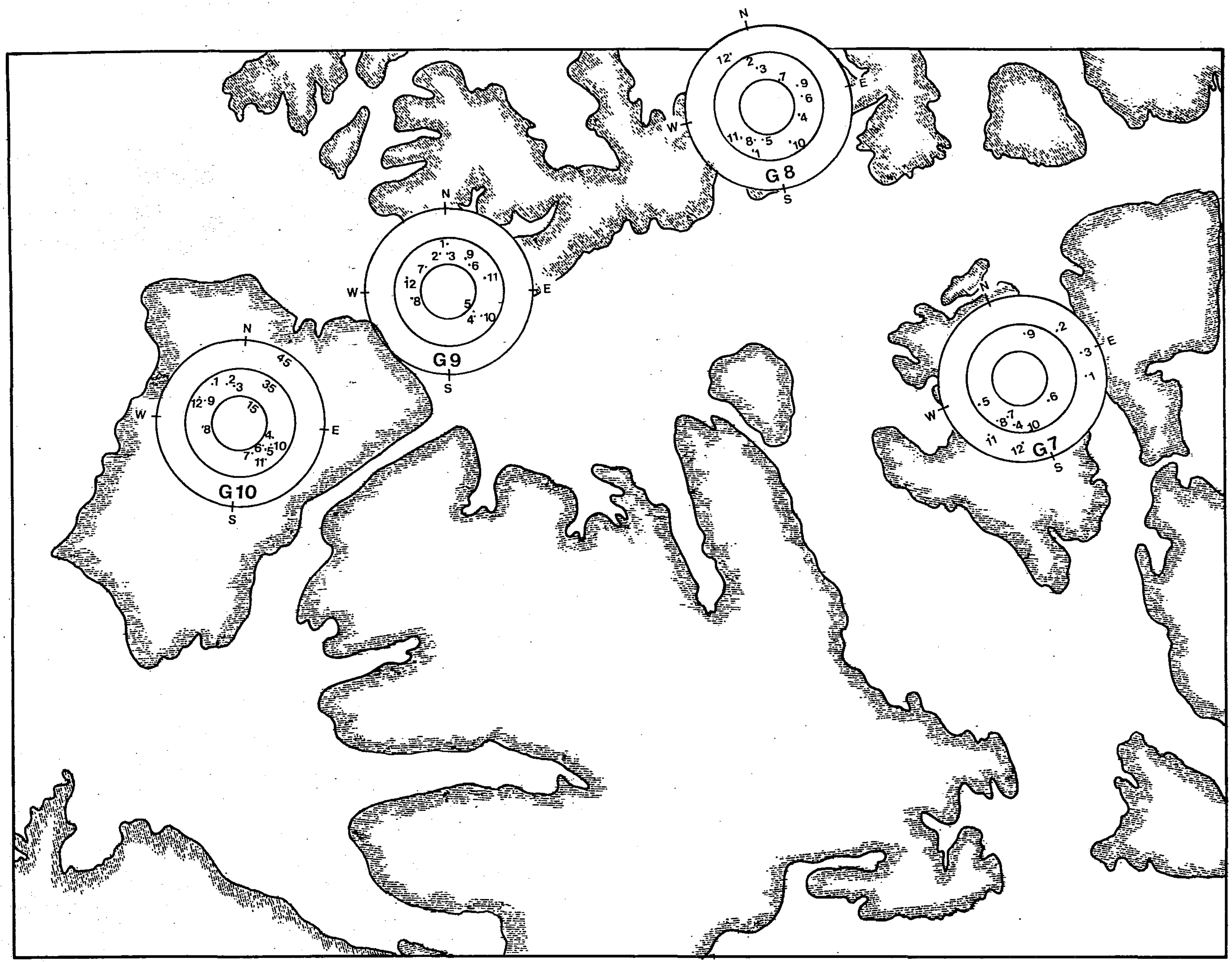


Figure 8.25 Direction and speed of maximum wind by month for Gridpoints 7-10. (Months shown by number; i.e., Jan =1)

Table 8.34. Gridpoint wind speed percent frequency by month.

Gridpoint GP10 (Metres/Second)								
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	27.6	43.9	21.1	6.1	1.3	0.1	-	-
Feb.	33.6	43.0	18.7	4.4	0.4	-	-	-
Mar.	31.9	46.7	17.9	3.2	0.3	-	-	-
Apr.	36.6	45.1	15.4	2.8	0.1	-	-	-
May	40.1	46.9	11.7	1.4	-	-	-	-
Jun.	47.0	45.4	7.3	0.2	-	-	-	-
Jul.	49.5	44.3	6.0	0.2	-	-	-	-
Aug.	41.9	47.0	10.2	0.9	-	-	-	-
Sep.	38.6	45.8	13.5	2.0	0.1	-	-	-
Oct.	34.5	44.3	16.8	4.1	0.3	-	-	-
Nov.	32.4	43.1	19.2	4.8	0.4	-	-	-
Dec.	30.7	44.3	20.3	4.3	0.5	-	-	-
Annual	37.0	45.0	14.8	2.9	0.3	-	-	-

Table 8.35. Gridpoint wind speed percent frequency by month.

Gridpoint GP9 (Metres/Second)								
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	27.7	44.0	22.2	5.1	0.9	0.2	-	-
Feb.	30.2	46.6	18.5	4.5	0.2	-	-	-
Mar.	33.4	45.5	18.6	2.5	0.1	-	-	-
Apr.	38.2	46.3	13.7	1.8	-	-	-	-
May	44.1	42.8	11.5	1.5	-	-	-	-
Jun.	47.2	44.4	7.5	0.9	-	-	-	-
Jul.	45.5	46.7	7.3	0.5	-	-	-	-
Aug.	46.4	43.4	8.8	1.3	-	-	-	-
Sep.	40.6	44.3	13.8	1.1	0.1	-	-	-
Oct.	37.2	43.9	16.2	2.7	-	-	-	-
Nov.	34.7	44.9	16.7	3.3	0.4	-	-	-
Dec.	32.1	43.6	19.3	4.1	0.8	-	-	-
Annual	38.2	44.7	14.5	2.4	0.2	-	-	-

Table 8.36. Gridpoint wind speed percent frequency by month.

	Gridpoint GP8 (Metres/Second)							
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	26.2	43.6	24.6	5.0	0.6	-	-	-
Feb.	28.9	48.3	17.6	4.5	0.5	0.2	-	-
Mar.	33.1	45.8	17.7	3.3	0.2	-	-	-
Apr.	37.8	49.2	12.0	1.1	-	-	-	-
May	43.4	44.6	11.0	1.0	-	-	-	-
Jun.	43.0	47.3	8.9	0.8	0.1	-	-	-
Jul.	47.0	46.0	6.9	0.1	-	-	-	-
Aug.	47.8	43.9	7.7	0.6	-	-	-	-
Sep.	37.5	46.9	14.0	1.6	0.1	-	-	-
Oct.	34.2	47.7	15.5	2.4	0.2	-	-	-
Nov.	36.3	44.1	16.4	3.1	0.2	-	-	-
Dec.	30.4	46.5	18.8	3.7	0.6	-	-	-
Annual	37.2	46.2	14.2	2.3	0.2	-	-	-

Table 8.37. Gridpoint wind speed percent frequency by month.

	Gridpoint GP7 (Metres/Second)							
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	25.4	43.4	24.7	5.6	1.0	-	-	-
Feb.	25.9	48.5	20.8	4.0	0.8	0.1	-	-
Mar.	31.8	44.4	19.7	3.8	0.3	-	-	-
Apr.	34.6	49.5	14.0	1.8	0.1	-	-	-
May	40.9	44.6	13.0	1.5	-	-	-	-
Jun.	42.3	46.2	10.0	1.5	-	-	-	-
Jul.	47.3	44.3	8.0	0.3	-	-	-	-
Aug.	45.6	44.3	9.4	0.7	-	-	-	-
Sep.	35.4	45.0	16.7	2.6	0.2	0.1	-	-
Oct.	29.6	46.6	19.7	3.9	0.2	-	-	-
Nov.	33.6	46.9	16.1	2.9	0.4	0.1	-	-
Dec.	30.0	45.1	19.4	4.6	0.6	0.2	-	-
Annual	35.3	45.7	15.9	2.8	0.3	-	-	-

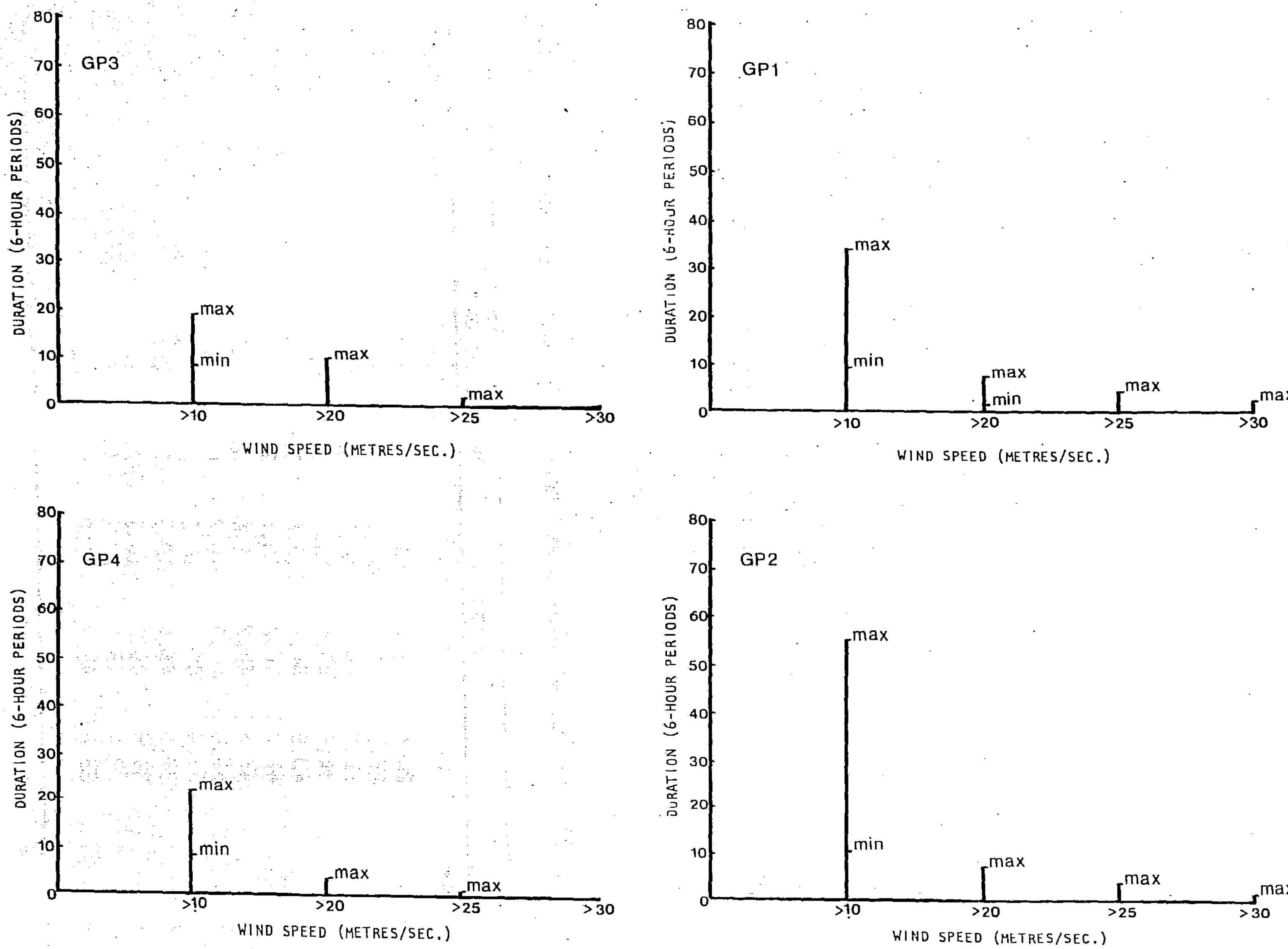


Figure 8.26 Duration (No. of 6-hr periods) for yearly maximum wind speed at Gridpoints 7-10. (The extreme event for any given year lies at or between the Max and Min points).

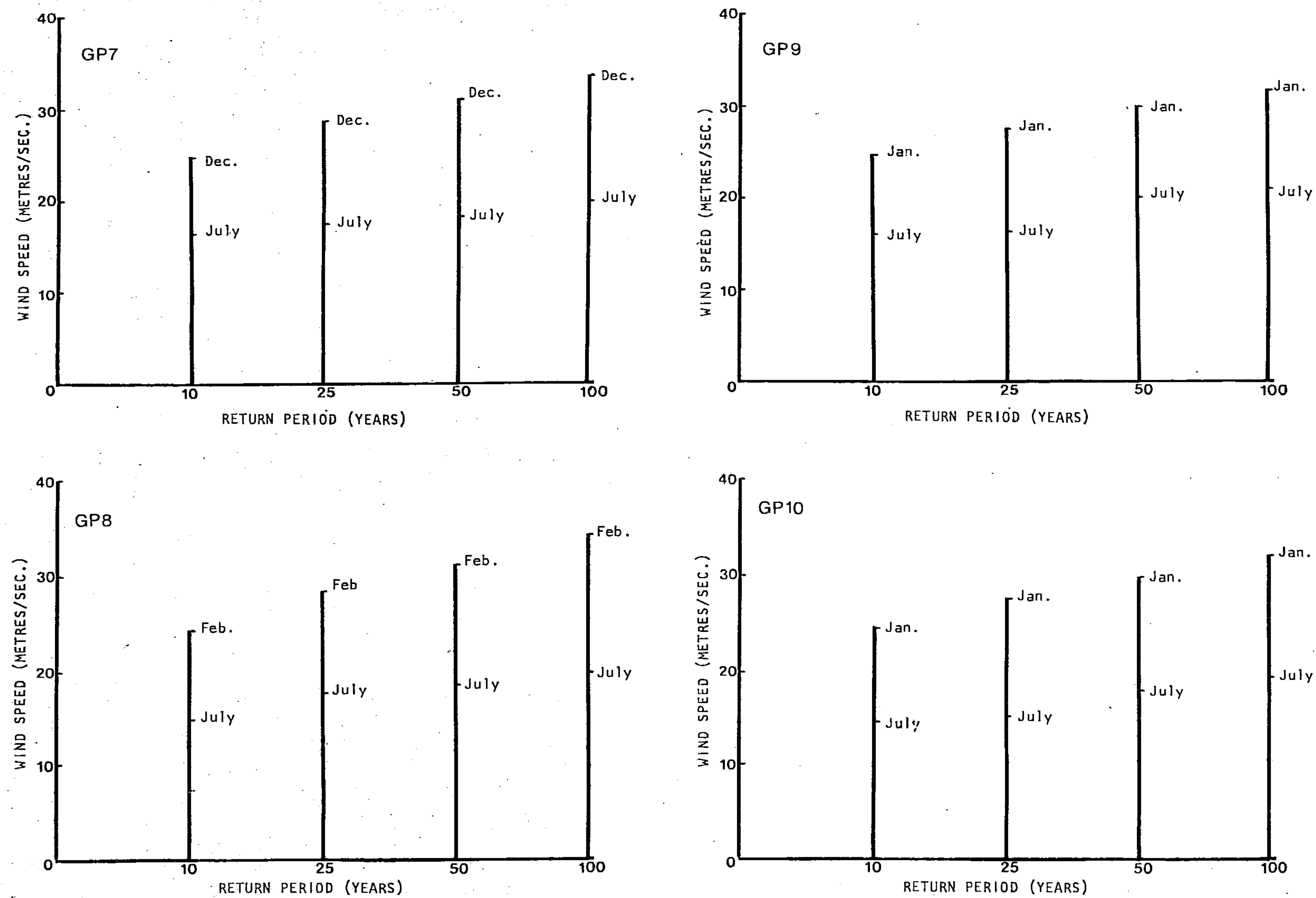


Figure 8.27 Return period for maximum wind speed by month, Gridpoints 7-10. (All values lie at or between the two points).

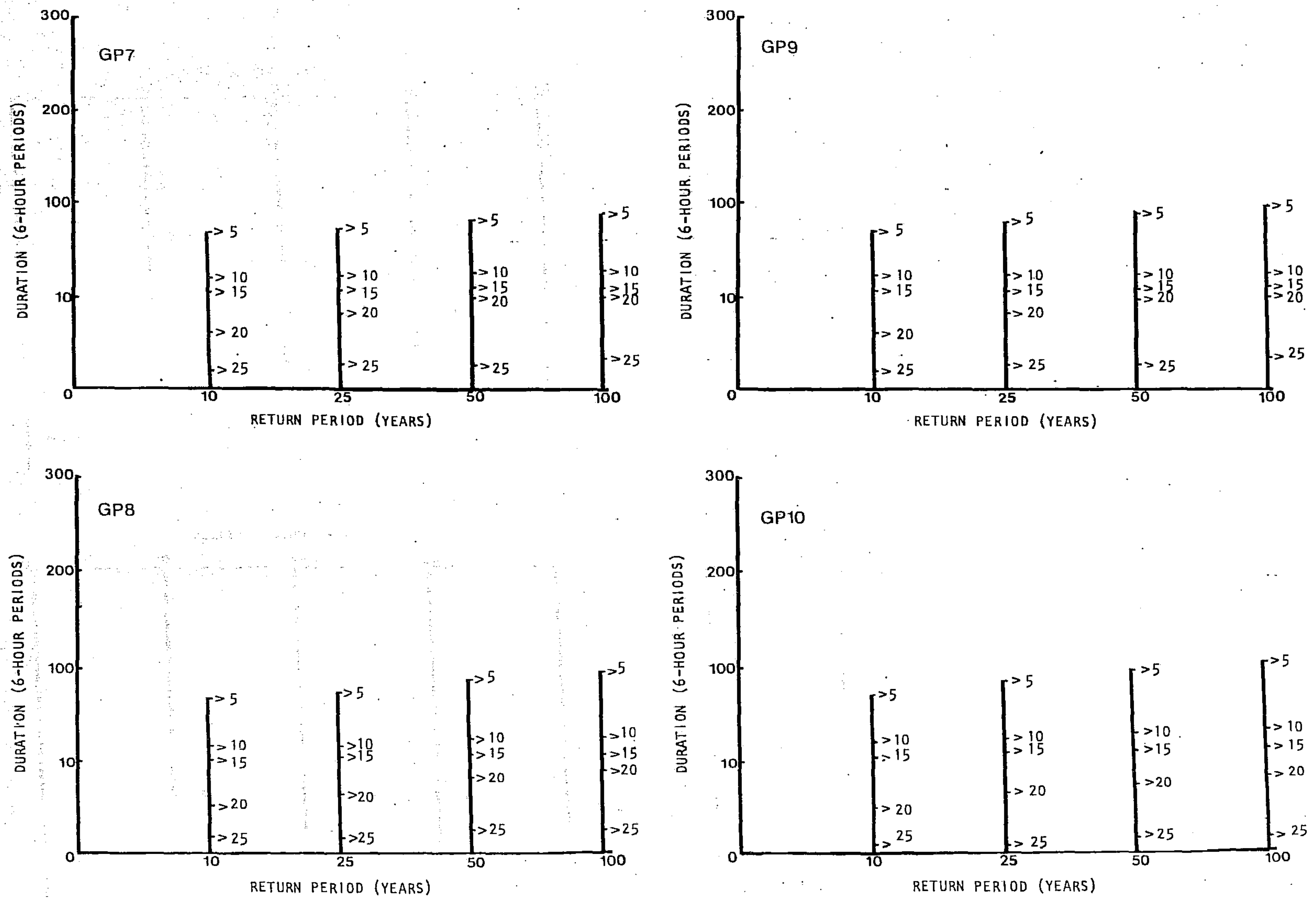


Figure 8.28 Return period for wind speed events of specific duration, Gridpoints 7-10.

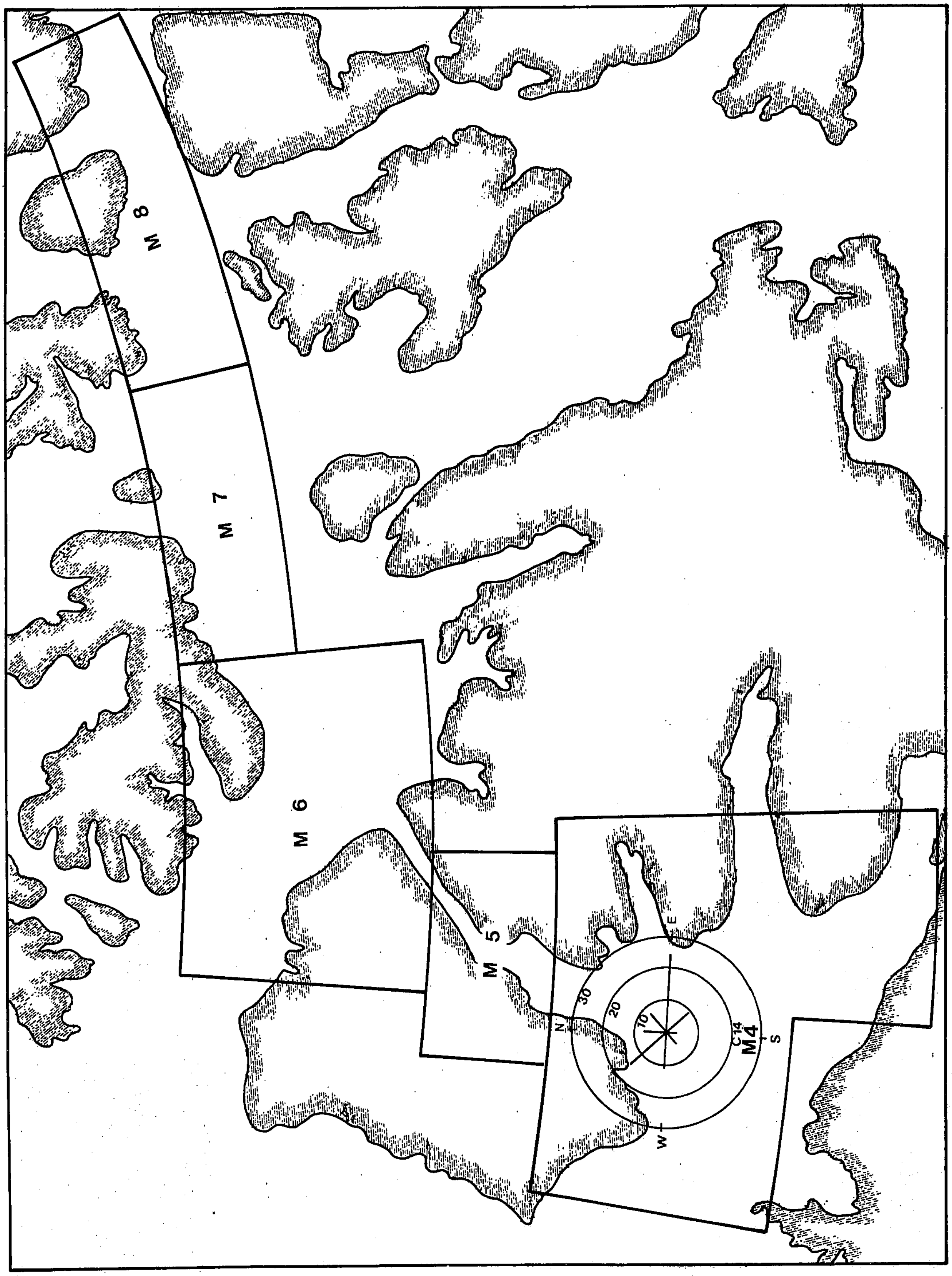


Figure 8.29 Marine Area wind rose - July.

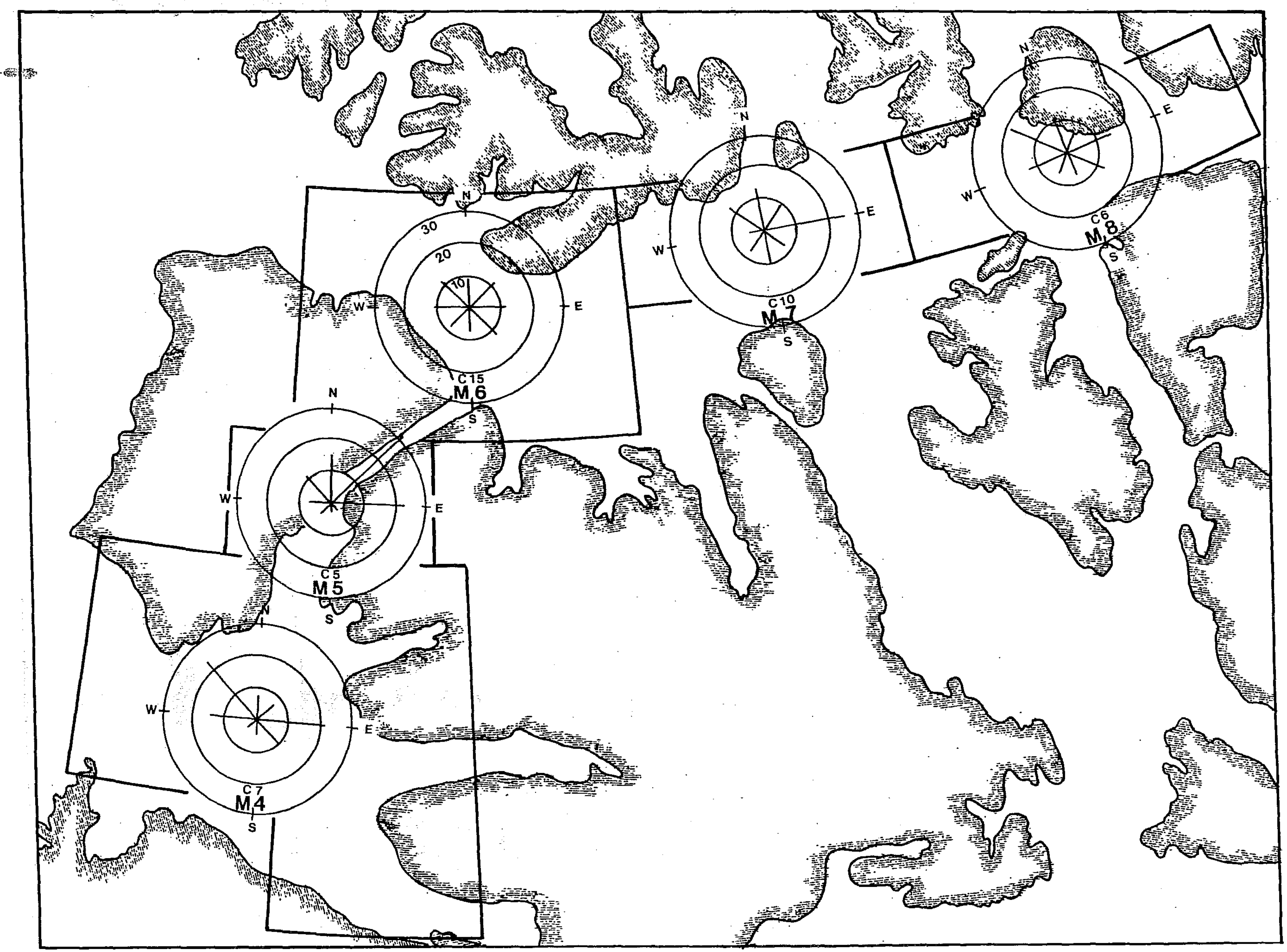


Figure 8.30   Marine Area wind roses - August.

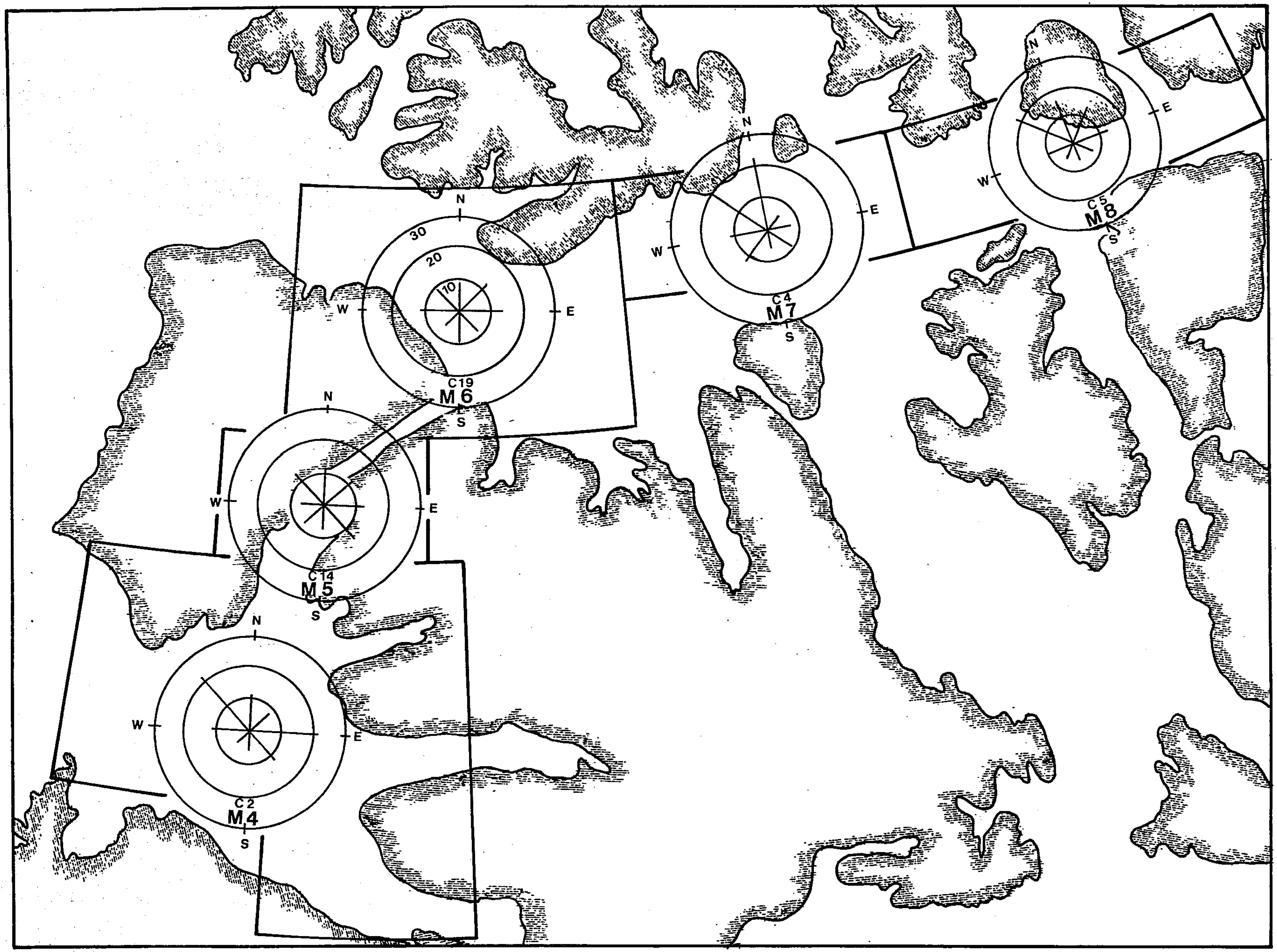


Figure 8.31 Marine Area wind roses - September.

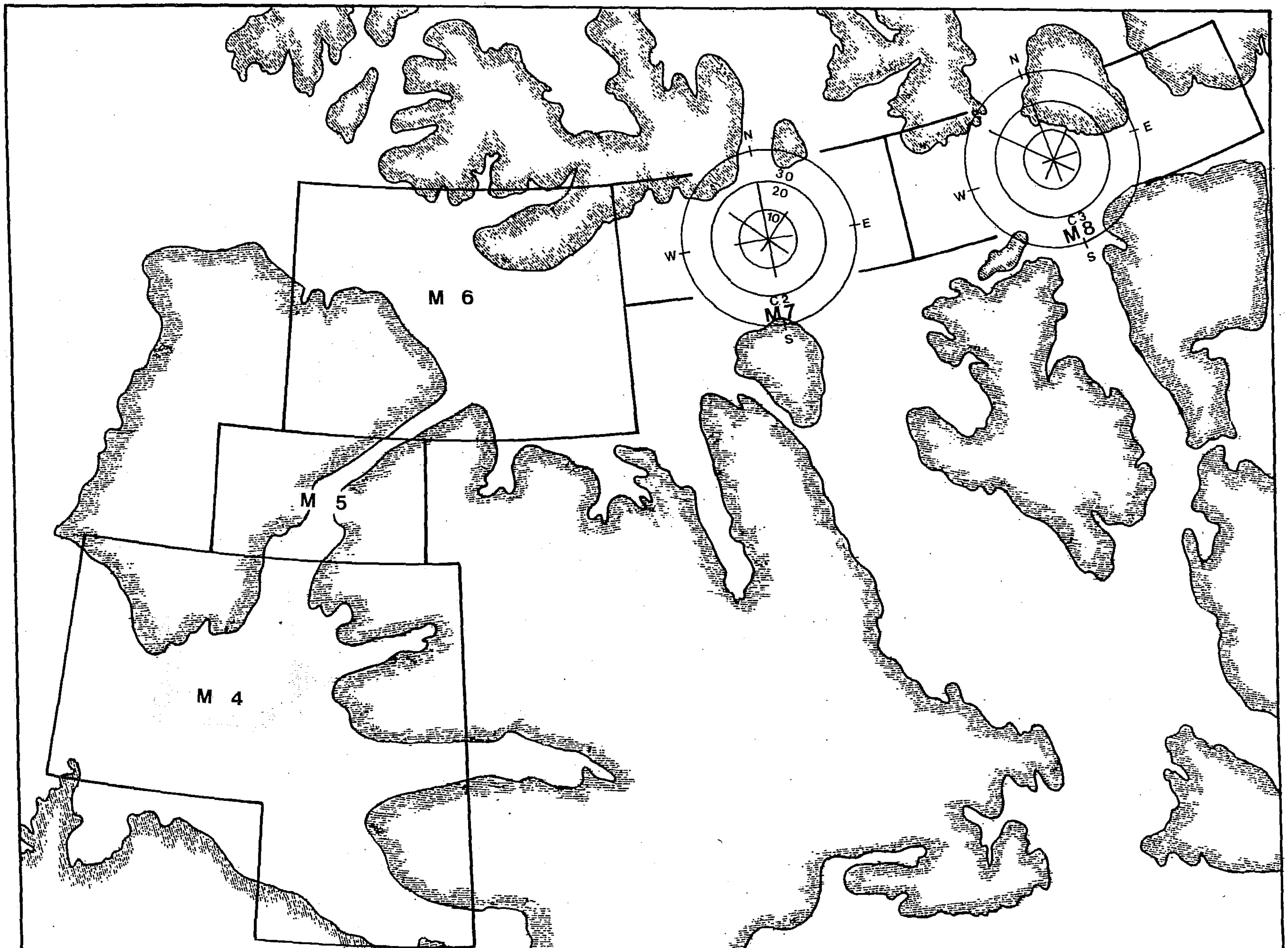


Figure 8.32 Marine Area wind roses - October.

roses show a preference toward north to northwesterlies, while the main August maximum is toward the easterlies. Finally, for the M 8 region, the north to northwesterlies appear to predominate.

For each month for the marine areas, the percentage frequency of wind speeds are shown in Tables 8.38 to 8.42. The small number of cases for many of the months makes interpretation of these wind statistics difficult. The high occurrence of the lowest speeds and lower incidence of higher speeds for M 6 are evident. Also, area M 8 appears to experience the strongest winds.

Table 8.38. Percent frequency of wind speed for marine areas.

Marine Area M 4

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul.	(142)	43.0	43.0	13.4	0.7	0.0
Aug.	(941)	48.1	43.0	10.2	0.7	0.0
Sep.	(342)	36.3	43.0	18.1	2.6	0.0

Table 8.39. Percent frequency of wind speed for marine areas.

Marine Area M 5

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug.	(110)	40.9	44.5	14.5	0.0	0.0
Sep.	(167)	52.7	37.7	9.6	0.0	0.0

Table 8.40. Percent frequency of wind speed for marine areas.

Marine Area M 6

		Wind Speed (Metres/Second)				
MONTH	(#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug.	(254)	64.2	29.4	6.3	0.0	0.0
Sep.	(280)	1.7	27.9	10.0	0.4	0.0

Table 8.41. Percent frequency of wind speed for marine areas.

Marine Area M 7

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug. (138)	57.8	36.2	5.8	0.0	0.0
Sep. (132)	49.2	34.8	12.9	3.0	0.0
Oct. (213)	34.7	45.1	19.2	0.9	0.0

Table 8.42. Percent frequency of wind speed for marine areas.

Marine Area M 8

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Aug. (982)	43.8	42.9	12.4	0.9	0.0
Sep. (569)	34.3	46.2	17.6	1.8	0.2
Oct. (190)	52.6	34.2	11.6	1.1	0.5

8.3.2 Waves

The wave height percentage frequencies for the five marine areas are shown in Table 8.43. Unfortunately, the number of observations is very limited with many of the areas showing reports from only a single month. The low wave heights in the often ice-infested waters of M 6 and M 7 are apparent. Low heights in area M 5 could be caused by the narrow channel and the consequent limit on the fetch of the winds.

Table 8.43. Percent frequency of wave heights for marine areas (original units retained).

Marine Area M 4

		Wave Heights (Feet)							
MONTH	(#OBS)	< 1	1-2	3-4	5-6	7	8-9	10-11	12
Aug.	(213)	54.9	20.7	16.4	6.1	1.9	0.1	-	-
Sep.	(132)	20.5	31.1	28.8	8.3	9.8	1.5	-	-

Marine Area M 5

		Wave Heights (Feet)							
MONTH	(#OBS)	1	1-2	3-4	5-6	7	8-9	10-11	12
Sep.	(83)	19.3	49.4	26.5	4.8	-	-	-	-

Marine Area M 6

		Wave Heights (Feet)							
MONTH	(#OBS)	1	1-2	3-4	5-6	7	8-9	10-11	12
Sep.	(25)	92.0	8.0	-	-	-	-	-	-

Marine Area M 7

		Wave Heights (Feet)							
MONTH	(#OBS)	1	1-2	3-4	5-6	7	8-9	10-11	12
Aug.	(16)	75.0	12.5	0.0	0.0	12.5	-	-	-
Sep.	(21)	57.1	23.8	19.0	-	-	-	-	-

Marine Area M 8

		Wave Heights (Feet)							
MONTH	(#OBS)	1	1-2	3-4	5-6	7	8-9	10-11	12
Aug.	(109)	63.3	25.7	7.3	2.8	-	-	-	-
Sep.	(115)	35.7	27.8	19.1	7.0	2.6	1.7	5.2	0.9

8.3.3 Visibilities

Fog is the main reason for restricted visibilities during the summer months. While some fog is present during the winter season, blowing snow is frequently the main reason for reduced visibilities. This section uses available ship reports to assess summer visibilities while statistics on blowing snow are derived using land stations.

For the summer and early fall months, the percentage frequency for the visibility ranges are shown in Table 8.44 for marine regions M 4 through M 8.

Table 8.44. Percent frequency of visibilities for marine areas.

Marine Area M 4

MONTH	(#OBS)	Visibilities (km) <0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Jul.	(109)	6.2	2.7	2.7	6.8	28.8	52.7
Aug.	(992)	7.3	1.8	2.2	7.7	32.4	48.7
Sep.	(354)	4.0	1.4	2.8	12.4	42.9	36.4

Marine Area M 5

MONTH	(#OBS)	Visibilities (km) <0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Aug.	(110)	2.7	0.9	0.0	9.1	64.5	22.7
Sep.	(180)	4.4	2.2	5.0	11.7	36.7	40.0

Marine Area M 6

MONTH	(#OBS)	Visibilities (km) <0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Aug.	(254)	14.2	3.9	3.5	5.1	41.7	31.5
Sep.	(316)	9.2	6.3	5.4	12.0	35.1	32.0
Oct.	(22)	13.6	13.6	0.0	13.6	40.9	18.2

Marine Area M 7

MONTH	(#OBS)	Visibilities (km) <0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Aug.	(146)	25.3	3.4	4.1	2.7	28.8	35.6
Sep.	(146)	7.5	6.2	5.5	17.8	33.6	29.5
Oct.	(211)	5.7	4.7	5.7	22.3	31.3	30.3

Marine Area M8

MONTH	(#OBS)	Visibilities (km) <0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Jul.	(13)	23.1	0.0	0.0	0.0	15.4	61.5
Aug.	(1003)	9.8	2.7	5.1	11.1	28.7	42.7
Sep.	(585)	5.1	3.4	3.4	10.1	34.4	43.6
Oct.	(188)	3.7	2.1	9.5	26.6	37.8	20.2

One notable feature is the reduction in the percentages in the less than 0.9 km range during September and October. This fact was not shown in areas M 5 and M 6 in October but the small data sample could be causing this. Also, area M06 has higher percentages in the ranges less than 3.6 km for a given month. The more frequent ice congestion even into the late summer and early fall periods could be resulting in more fog production and, thus, the higher percentages. Ice concentrations will be further examined in a later section. Another aspect of these percentages is the reduction in the greater than 18 km visibilities with an increase in the 4.5 to 18.0 km occurrences for all except area M 5 during September and October. This may be caused by an increase in snowshower activity as the cold unstable airmasses flow over the open waters producing visibilities below 18 km. This effect is not seen in area M 5, possibly due to short open water trajectories for snowshower production in this narrow channel.

Table 8.45 shows the mean and extreme duration of blizzard conditions for a number of land stations while Table 8.46 shows the absolute percentage frequency of occurrence of blizzard conditions.

Even though values for the Rea Point are based only on four years of data, the high frequency of blizzard conditions during January does not appear to be an anomaly as it corresponds with the peak observed at Isachsen. The 1.5 percent frequency of occurrence at Rea Point for December does however look low in relation to other stations, and may be the result of the small data sample. The main point obtained from these tables is the fact that blizzards are not only a common occurrence but that they can, at times, last in excess of two days.

Table 8.47 shows expected maximum duration of blizzard conditions for various return periods. Rea Point has not been included because of insufficient data. It is of interest to note that both Isachsen and Mould Bay have observed durations longer than the 40-year return value.

8.3.4 Freezing Spray

Areas of open water can begin to appear in Amundsen Gulf in May. They are relatively small though, and a ship moving through such a polynya during a period of strong winds should not encounter significant accumulations of freezing spray. During a good ice year, areas of open water develop in Viscount Melville Sound in early August and large areas can become open by late August. However, the median condition is for nine-tenths coverage as far east as Barrow Strait and, thus, for most years, little in the way of freezing spray would be expected. A worst case might occur during a year in which Viscount Melville Sound became open and then just prior to freeze-up the synoptic pattern changed and cold arctic air moved into the region. The mean September minimum for Mould Bay is -9.1°C and for Rea Point -7.6°C. Extreme values are, of course, much lower but the air would be modified to some extent by the open water and extreme lows are normally established during periods of light winds. Temperature of -10°C to

Table 8.45. Mean and extreme duration of observed blizzard conditions (hrs) (after Maxwell, 1980).

STATION	SEP.		OCT.		NOV.		DEC.		JAN.		FEB.		MAR.		APR.		MAY	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Isachsen	7	27	8	51	8	39	11	108	12	60	11	90	9	45	8	66	7	21
Resolute Bay		3	5	26	8	27	8	58	8	45	7	47	7	49	8	63	6	24
Rea Point			6	16	4	13	3	12	8	39	11	27	3	9	4	15	4	12
Mould Bay	3	3	9	36	7	33	7	24	8	87	7	27	7	24	8	27	3	3
Sachs Harbour			7	21	6	42	10	39	7	27	8	24	7	39	10	30		15

Blizzard conditions are defined as snow or blowing snow occurring with winds of 40 km/h or greater visibility of 0.8 km or less and a temperature below -12.2°C. These conditions must continue for 6 hours or more.

Table 8.46. Absolute percentage frequency of *blizzard conditions (after Maxwell, 1980).

STATION	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Isachsen	0.4	3.6	4.3	6.8	12.4	8.1	5.7	3.0	1.2
Resolute Bay		1.7	2.6	5.1	6.4	5.5	4.7	3.0	0.6
Rea Point		2.3	4.2	1.5	14.9	4.7	2.7	1.3	1.3
Mould Bay	0.1	1.4	2.0	3.0	5.1	3.6	2.7	1.5	0.1
Sachs Harbour		0.9	2.6	3.2	3.0	2.0	2.0	1.4	0.2

See Table 5.4 for table of record.

Table 8.47. Expected maximum duration of *blizzard conditions (hrs) for various return periods (after Maxwell, 1980).

	Return Periods (yrs)					
	2	5	10	20	30	40
Isachsen	48	64	75	86	93	97
Resolute Bay	32	46	55	64	70	74
Mould Bay	21	34	42	50	56	59
Sachs Harbour	25	35	42	48	52	55

*Blizzard conditions are defined as snow or blowing snow occurring with winds of 40 km/h or greater, visibilities of 0.8 km or less, and a temperature below -12.2°C. These conditions must continue for 6 hours or more.

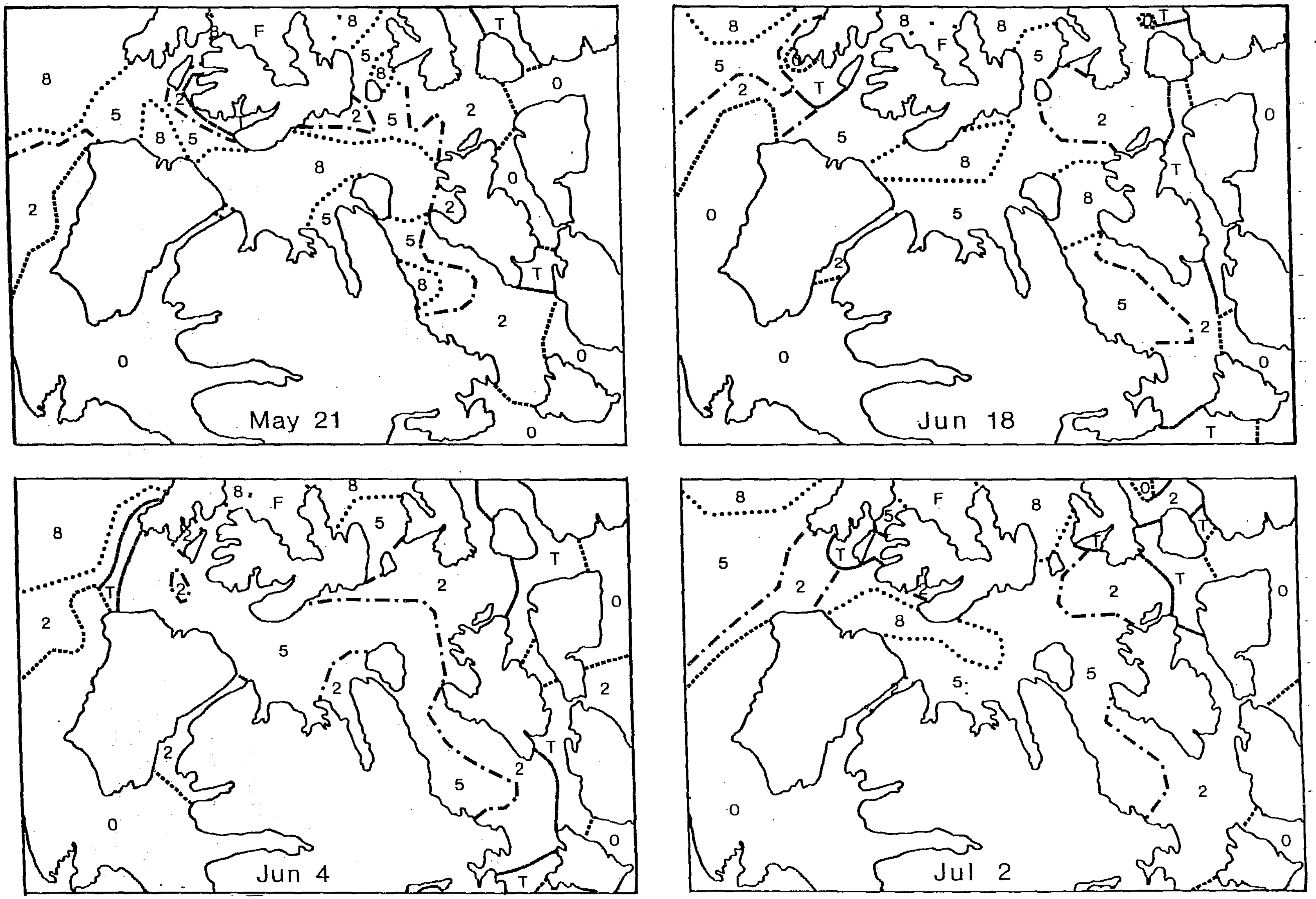


Figure 8.33 Median concentration of old ice (after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10–3/10 old ice.
5: 4/10–6/10 old ice.
8: 7/10–9/10 old ice.
F: 10/10 old ice.

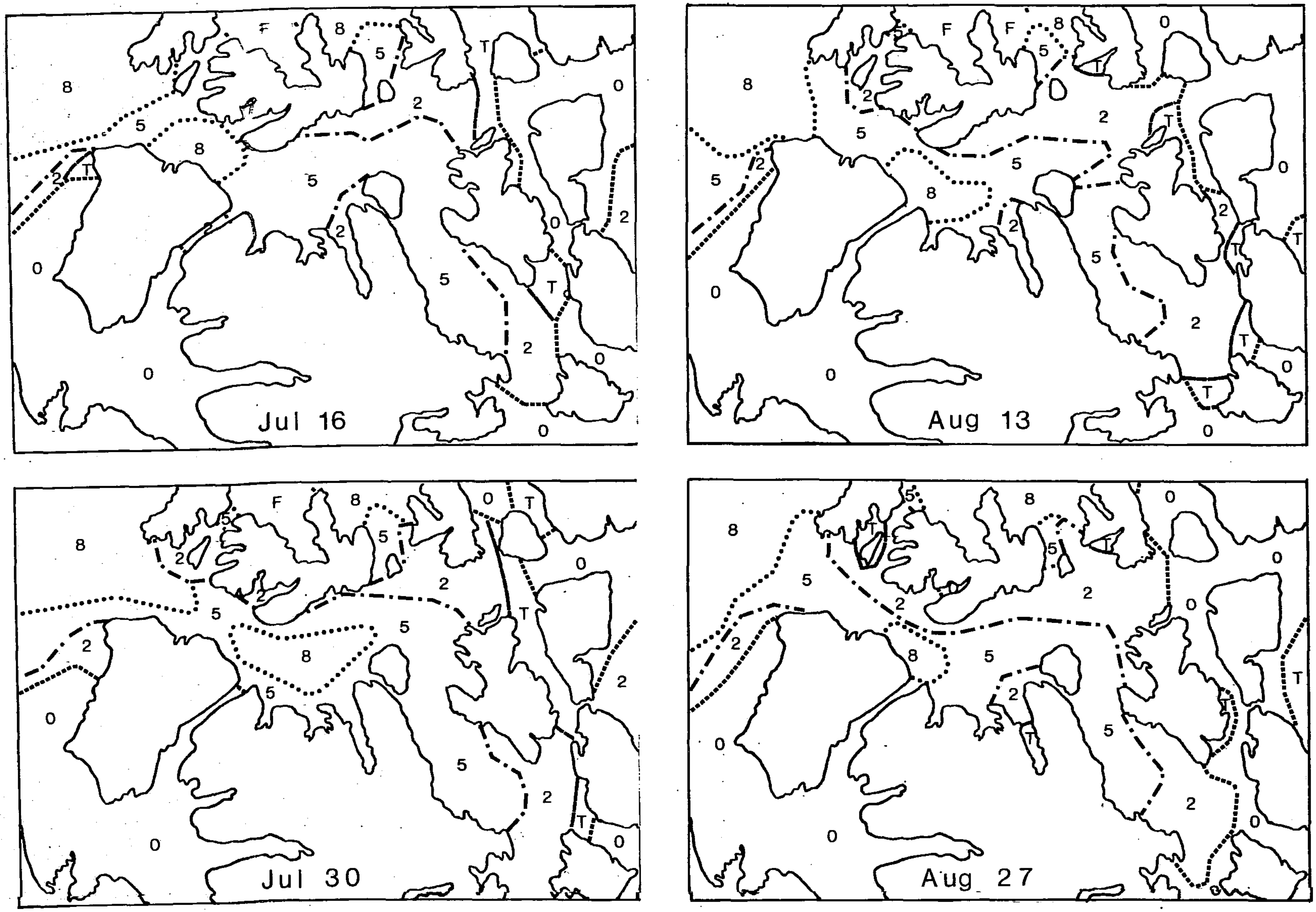


Figure 8.34 Median concentration of old ice (after Markham, 1981).

O: No old ice.
T: A few old floes.
2: 1/10–3/10 old ice.
5: 4/10–6/10 old ice.
8: 7/10–9/10 old ice.
F: 10/10 old ice.

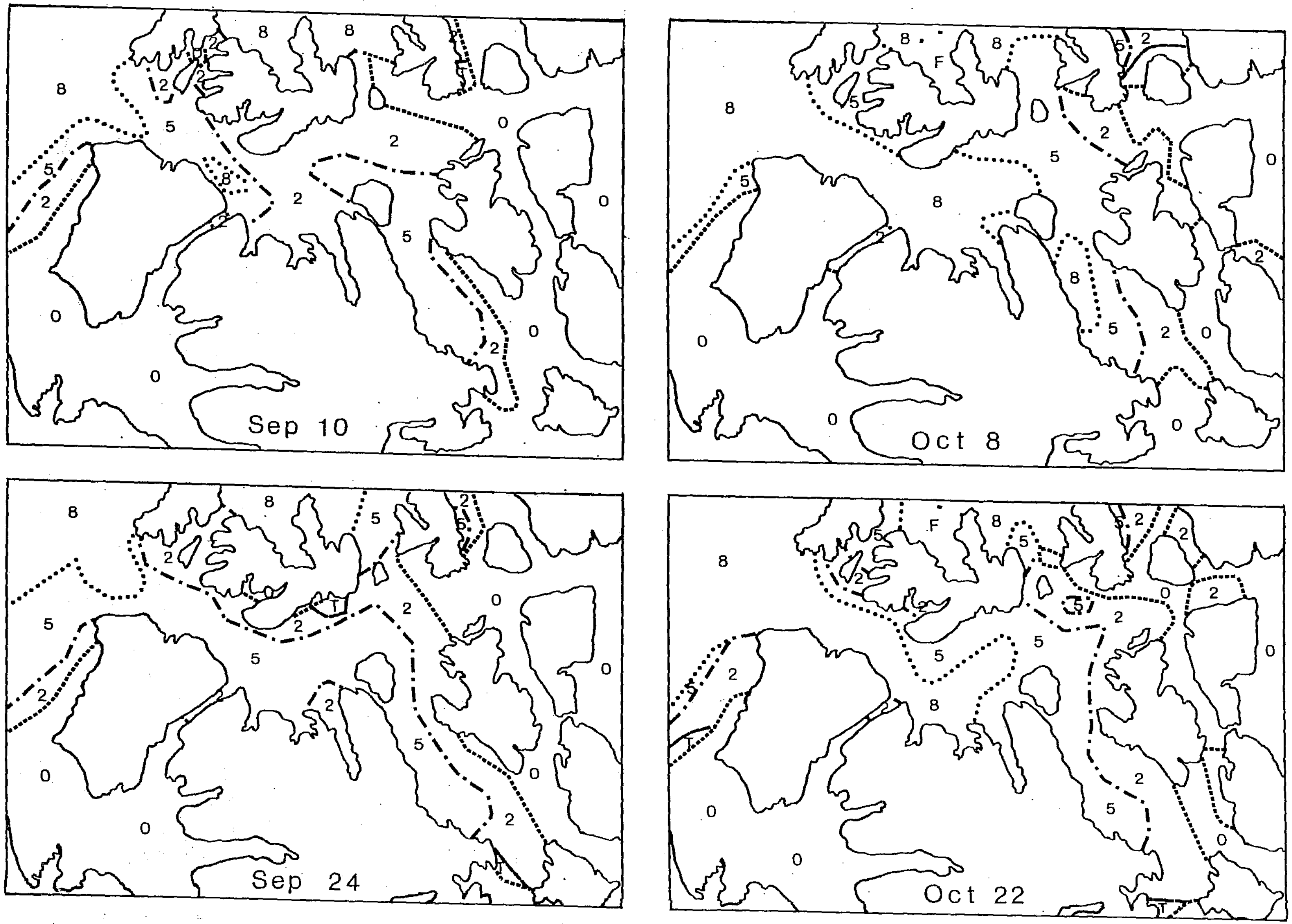


Figure 8.34a Median concentration of old ice (after Markham, 1981).

O: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

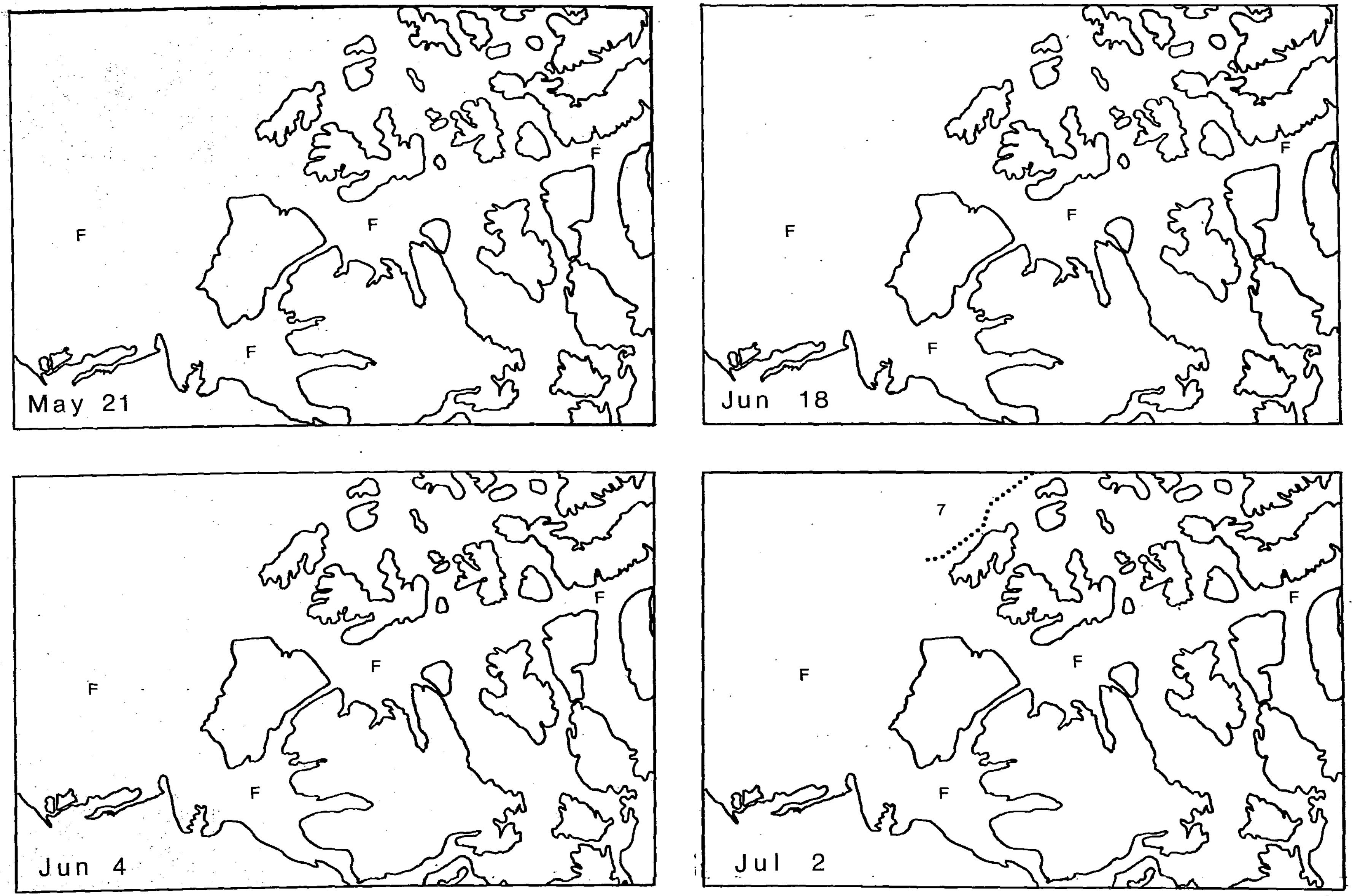


Figure 8.35 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

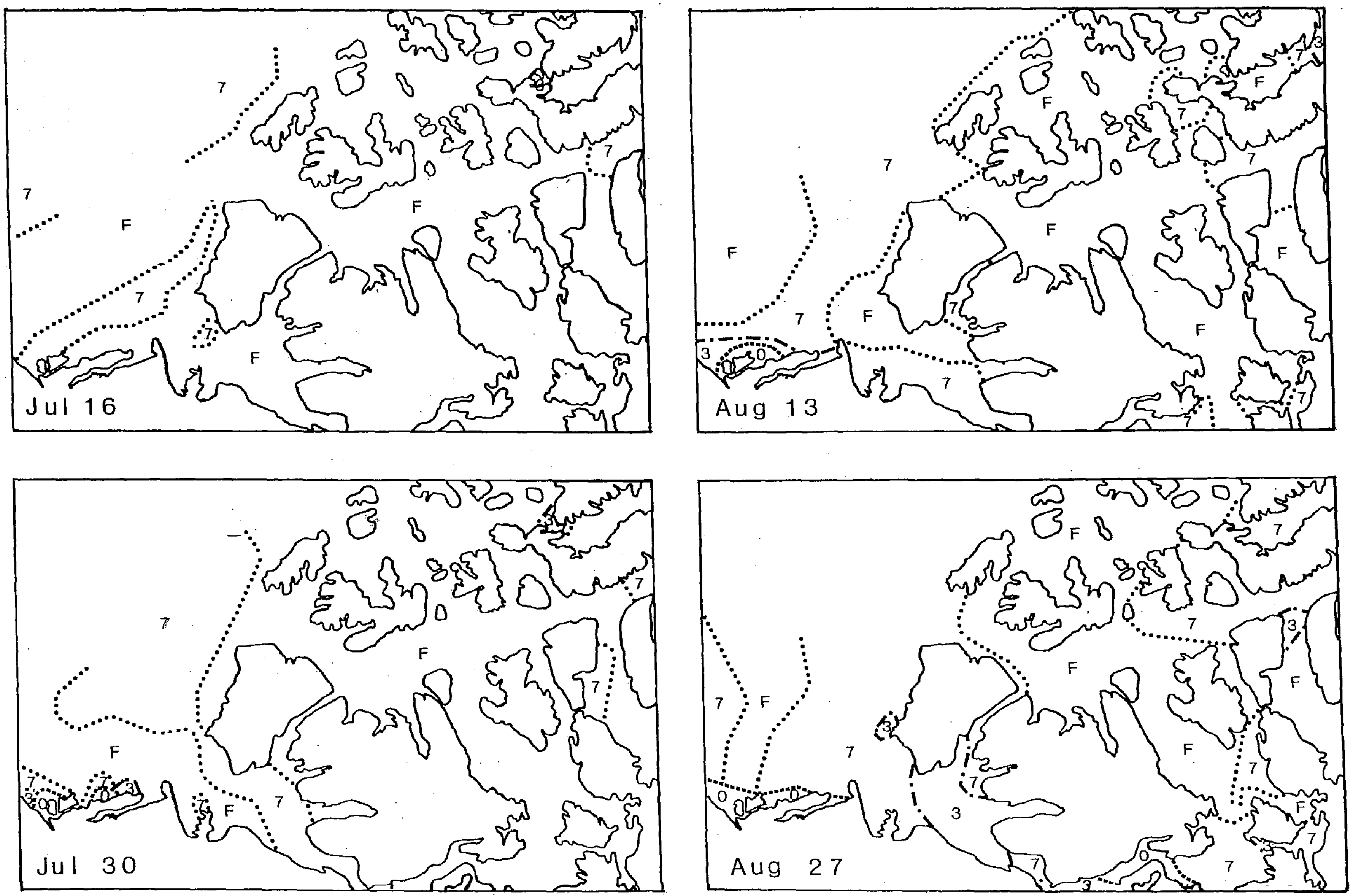


Figure 8.36 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

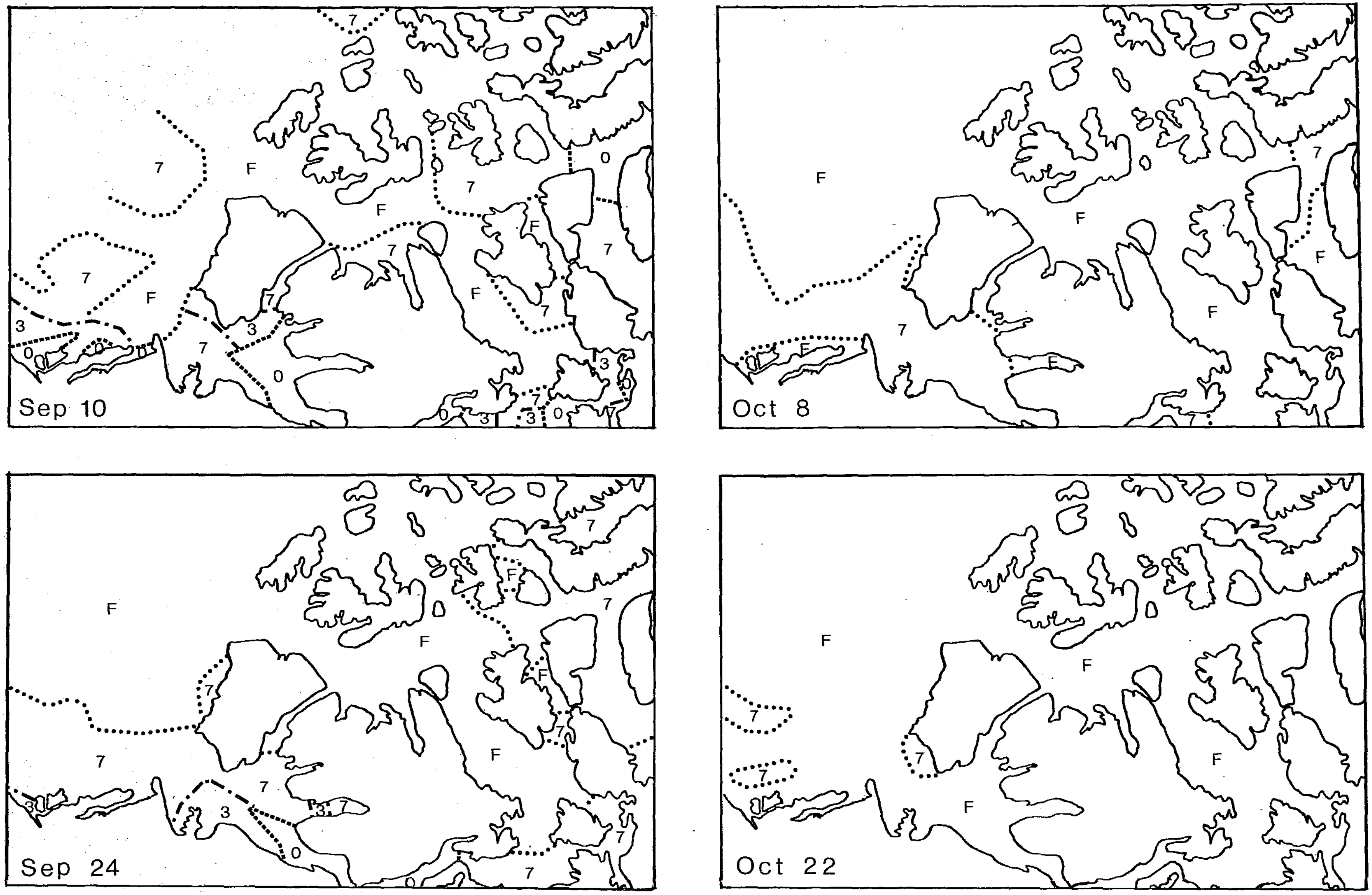


Figure 8.36a Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

-15°C would seem to be realistic values, and if these are combined with a wind of 20 m/s and a water temperature of 0 to plus 1°C, a rate in excess of 15 cm/24 hrs could be expected. An extreme case of -15°C would result in an ice buildup in excess of 25 cm/24 hours. This is assuming an ice concentration of less than three-tenths which is likely to exist only over a small portion of Viscount Melville Sound at any one time.

In section 8.4.4 a similar exercise yielded accumulation rates of 13 cm/24 hrs for the Beaufort Sea. The situation in Amundsen Gulf is quite similar to the southern Beaufort Sea, and under conditions of low temperatures and strong winds accumulation rates of 13 to 15 cm/24 hrs do not appear unreasonable. Once new ice begins to form, cases of freezing spray would be expected to rapidly diminish.

8.3.5 Ice

(i) Median Old Ice Concentrations: Median amounts of old ice concentrations are shown in Figures 8.33 and 8.34a for the May 21 to October 22 period. In the Amundsen Gulf area, median amounts of old ice remain at zero through the period. However, occasionally old ice floes could drift into the area from the northwest.

In the Prince of Wales Strait region, a considerable amount of variability in the amounts is seen and is likely due to the short length data base used. For the most part, multi-year ice amounts are at a maximum in the one to three-tenths range.

Moving further north to the extreme southeastern M'Clure Strait and western Viscount Melville Sound areas a significant increase in the medians to the "5" or "8" categories is evident. Prior to July 16, the relatively low median amounts of old ice could be explained by a general east to west ice drift through the winter and spring. The reason for the abrupt end to this pattern on the July 30 map is not known and could be a result of the short data base. Certainly more study of the M'Clure Strait and western Viscount Melville Sound area is required, for it is a region of high old ice concentrations and, historically, a difficult ice navigation section.

In the remainder of the Viscount Melville Sound area the median amounts are generally in the "5" to "8" ranges in the west and in the "2" range in the east through the May to early July period. As July progresses and later into August and early September, the "2" range area expands to cover most of the Sound. By late September and through October as freeze-up begins and with the arbitrary change on October 1st from first year to second year ice occurring, increases in the median values are seen once again.

Finally, in the Barrow Strait area, favourable "0" to "2" old ice concentrations are evident through the entire period of concern with the "0" area predominating in late August and September.

(ii) Worst Ice Conditions: Through the May to early July period the entire central portions of the Passage are, at worst, entirely consolidated. (See Figures 8.35 and 8.36). During July the "7" area appears in Amundsen Gulf and expands northeastward through Prince of Wales Strait during August. The "7" area begins to appear over eastern Barrow Strait in early August and expands westward later in August. In September the "7" area expands to cover most of the central part of the marine area with "0" and "3" areas appearing in Amundsen Gulf. Later in September and into October, the worst ice conditions progressively return to the predominantly "F" area once again.

Of interest is the fact that the M'Clure Strait and western Viscount Melville Sound areas remain in the "F" consolidated ice area throughout the entire period and would thus be representative of the worst ice areas.

8.3.6 Ice Ridges

Little information is available on ice ridges throughout this portion of the Arctic. Through personal communication, E. Stasyshyn of Ice Reconnaissance Division of Atmospheric Environment Service, revealed that in 1978 an ice ridge of considerable size was detected in eastern M'Clure Strait. Subsequent investigation showed that this ridge most likely developed when a 60-mile wide area of new ice was compressed to 20 miles. This ridge was followed for two seasons and eventually moved across the northern entrance to Prince of Wales Strait.

Table 8.48 Range of pressure ridge heights (m).

	.5-.7	.7-.9	.9-1.1	1.1-1.3	1.3-1.5	1.5-1.7	1.7-1.9	1.9-2.1	2.1-2.3	2.3-2.5	2.5-2.7	2.7-3.0	3.0
Number of Ridges	810	306	266	63	79	15	6	39	3	14	2	2	31

Above data sample was collected during six flights between 1974-1980. This represents 300 km of data containing approximately 1600 ridges of which 520 were greater than .9 metres. The maximum observed ridge was 9.5 metres in September 1974. The sample area was bounded in the west by 75.0W 124.48W and in the east by 74.20N 111.48W. (Information obtained from Ice Climatology... personal communication).

8.4 BEAUFORT SEA MARINE AREA

In Figure 8.37, the Beaufort Sea marine area with the grid-points and marine region outlined are shown.

8.4.1 Winds

(i) FNOC Gridpoint Wind Results: The wind roses for grid-points GP11 to GP13 are presented in Figures 8.38 to 8.42. The main directions for all three points are from the east to southeast, with the exception of the January roses where the west to northwest directions in some cases predominate.

In Figure 8.43, the extreme wind data by month are shown. Here the extreme winds are generally from the southeast to east or the west to northwest direction. Note that despite the fact that the predominant wind rose directions are generally east to southeast, many of the extreme geostrophic winds are from the west to northwest. Also, the maximum geostrophic winds are seen to occur during the late fall and winter months with the minima showing in the summer season.

In Tables 8.49 to 8.51, the percentage frequencies for each of the wind speed ranges are shown for each month. The main feature of these tables is the larger percentages of occurrence for the higher wind speeds in the fall and winter months. There appears to be little notable differences in the percentages among the gridpoints.

In Figure 8.44, the wind speed durations are shown. The durations for gridpoint GP13 are longer than for either gridpoints GP12 and GP11.

Return periods for the wind speeds and durations are shown in Figures 8.45 and 8.46. The winter months' wind speed return periods are shown to be greater than the summer with the gridpoint GP13 wind speeds larger for each return period. For the durations, again GP13 exhibits the longest durations for a given return period.

Table 8.49. Gridpoint wind speed percent frequency by month.

	Gridpoint GP13				(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	25.8	45.9	22.1	5.0	1.0	0.1	0.1	0.0
Feb.	29.5	45.4	20.8	4.0	0.3	0.1	0.0	0.0
Mar.	27.3	48.6	19.9	3.9	0.2	0.1	0.0	0.0
Apr.	32.2	48.5	16.3	2.4	0.2	0.0	0.0	0.0
May	37.9	48.2	12.9	1.0	0.0	0.0	0.0	0.0
Jun.	47.2	44.6	8.0	0.2	0.0	0.0	0.0	0.0
Jul.	52.3	42.9	4.8	0.0	0.0	0.0	0.0	0.0
Aug.	53.9	39.1	6.8	0.2	0.1	0.0	0.0	0.0
Sep.	43.3	45.3	10.1	1.1	0.2	0.1	0.0	0.0
Oct.	31.9	48.0	17.7	2.9	0.3	0.0	0.0	0.0
Nov.	26.4	42.4	23.3	6.6	1.1	0.1	0.0	0.0
Dec.	29.7	44.9	20.8	4.3	0.4	0.0	0.0	0.0
Annual	36.4	44.3	15.3	2.6	0.3	0.0	0.0	0.0

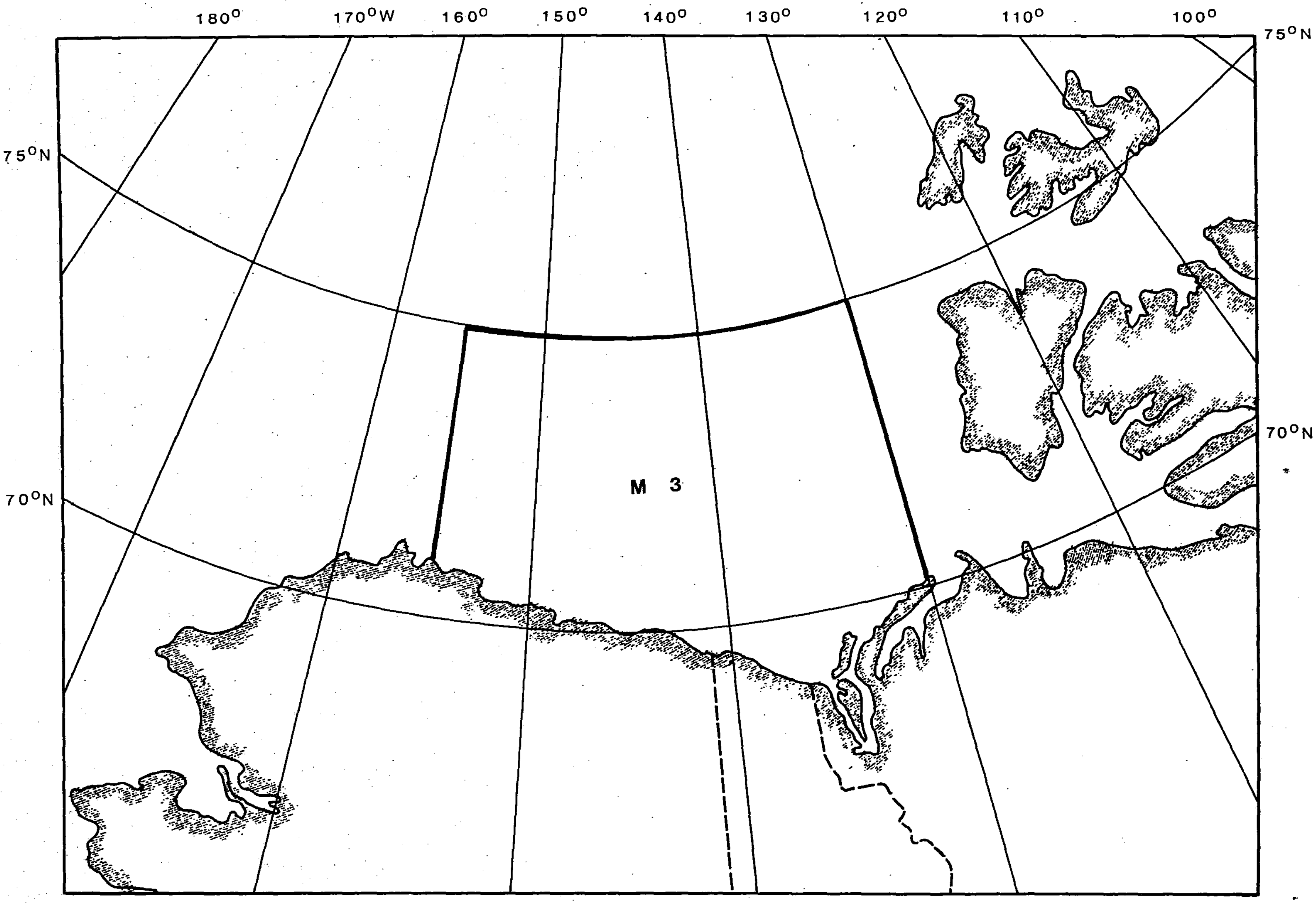


Figure 8.37 Beaufort Sea marine area.

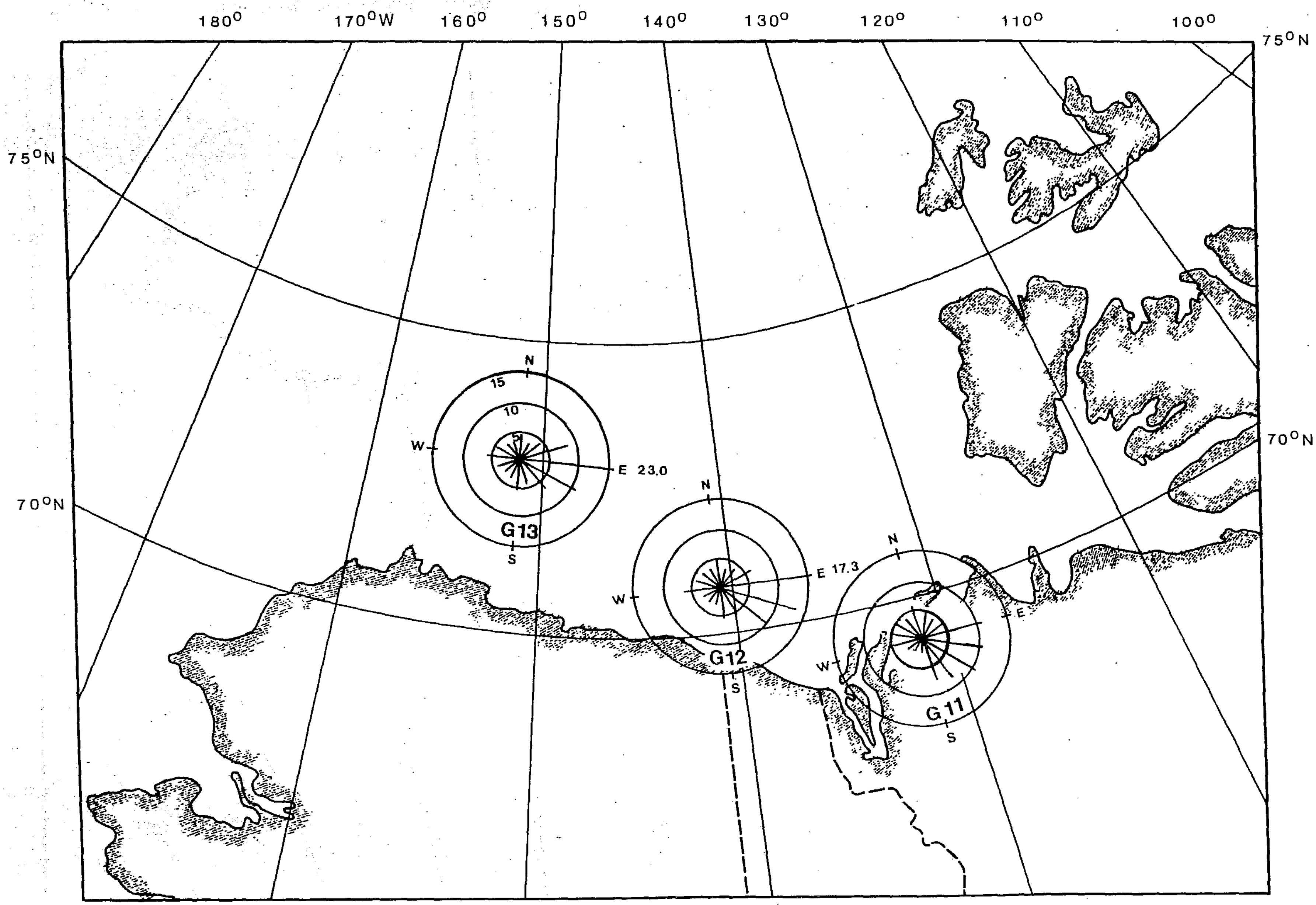


Figure 8.38 Gridpoint wind roses - annual.

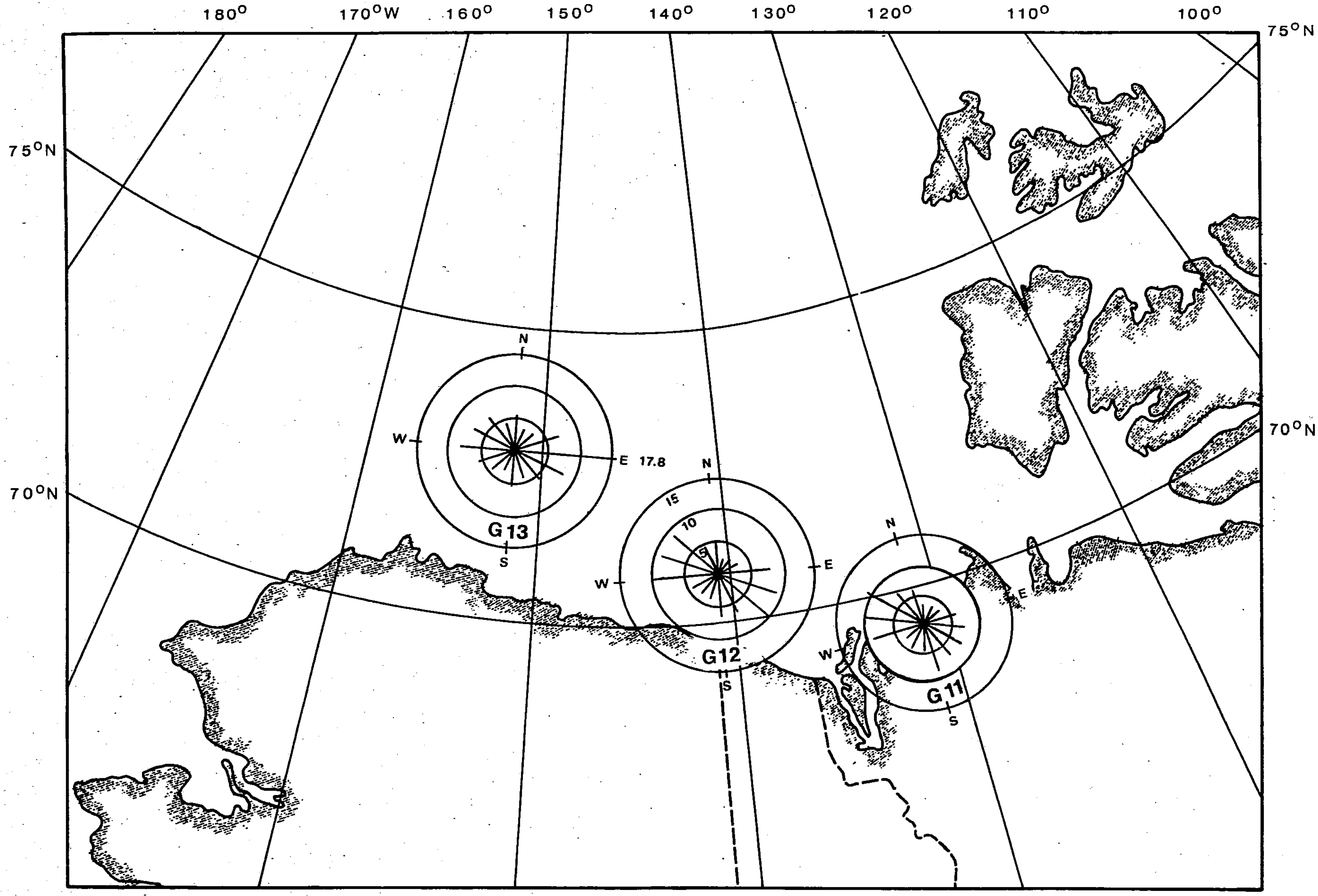


Figure 8.39 Gridpoint wind roses - January.

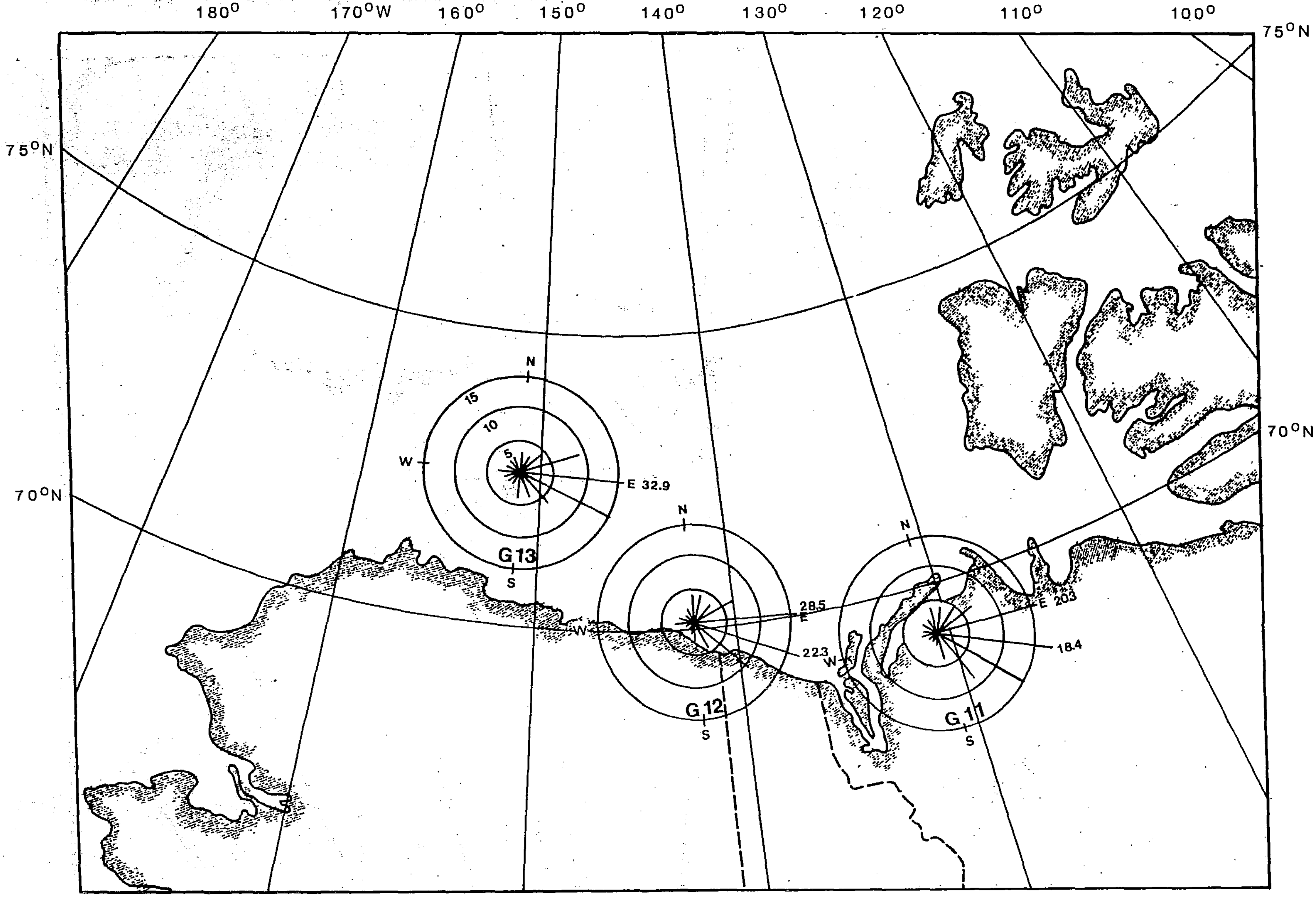


Figure 8.40 Gridpoint wind roses - May.

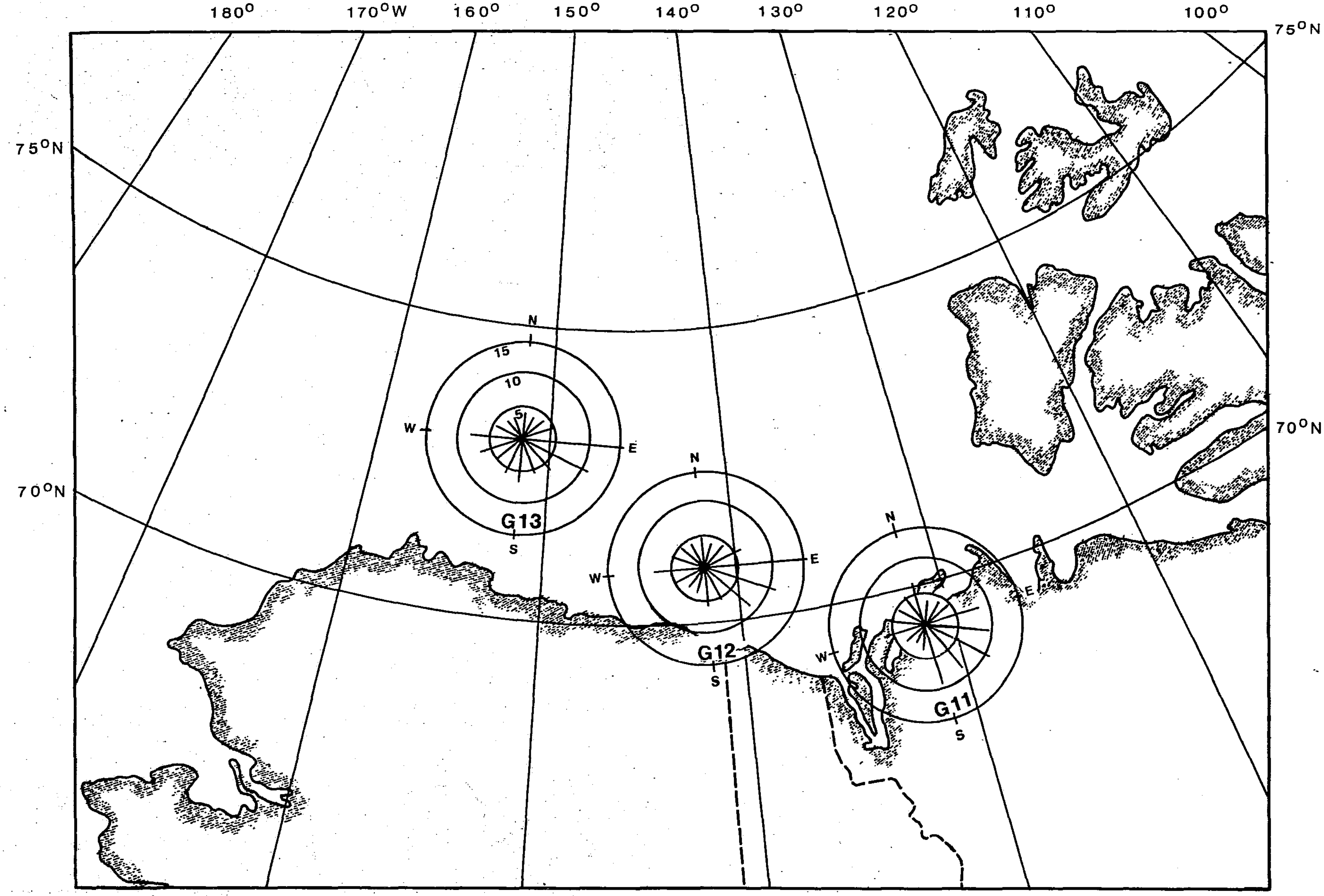


Figure 8.41 Gridpoint wind roses - July.

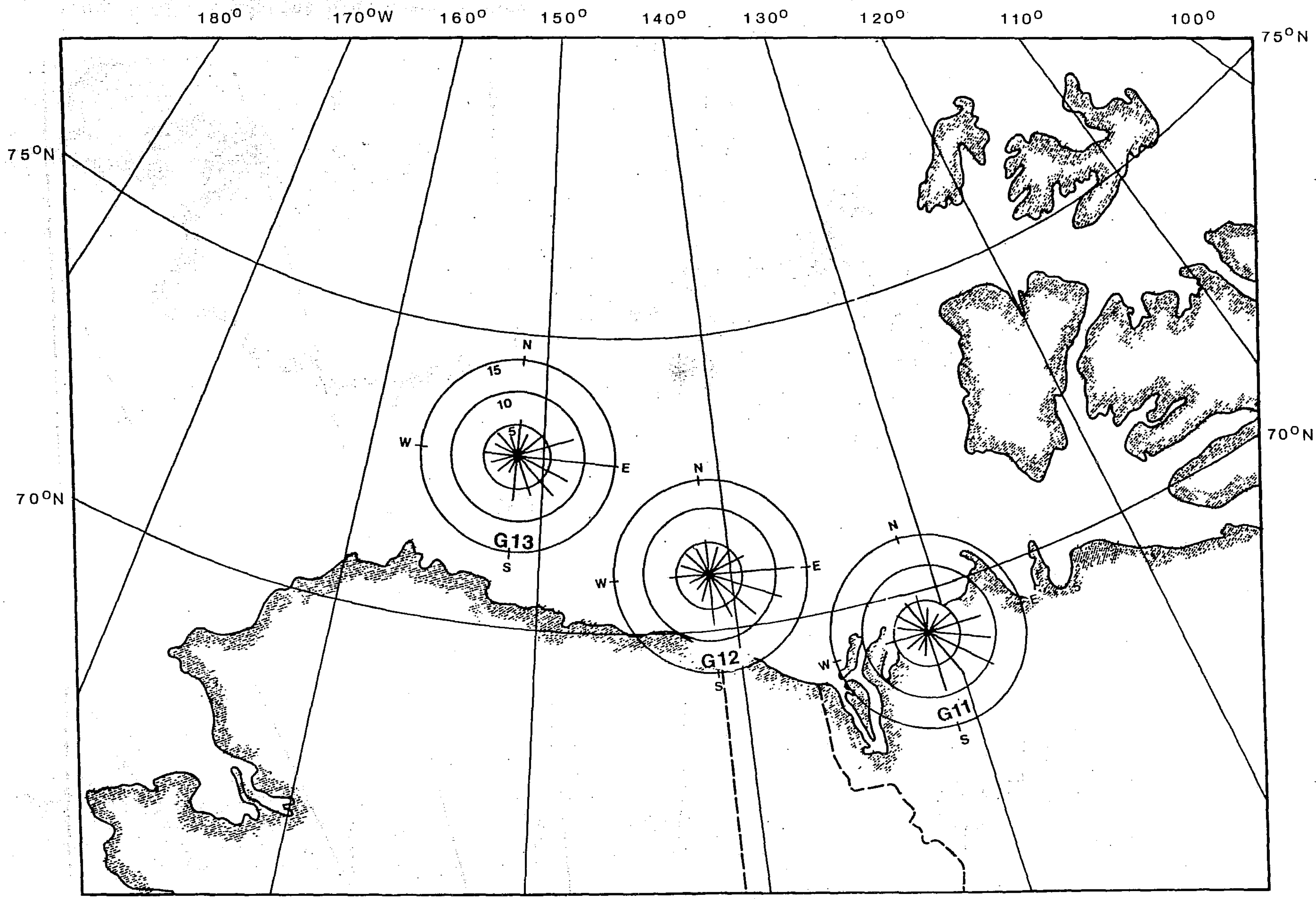


Figure 8.42   Gridpoint wind roses - September.

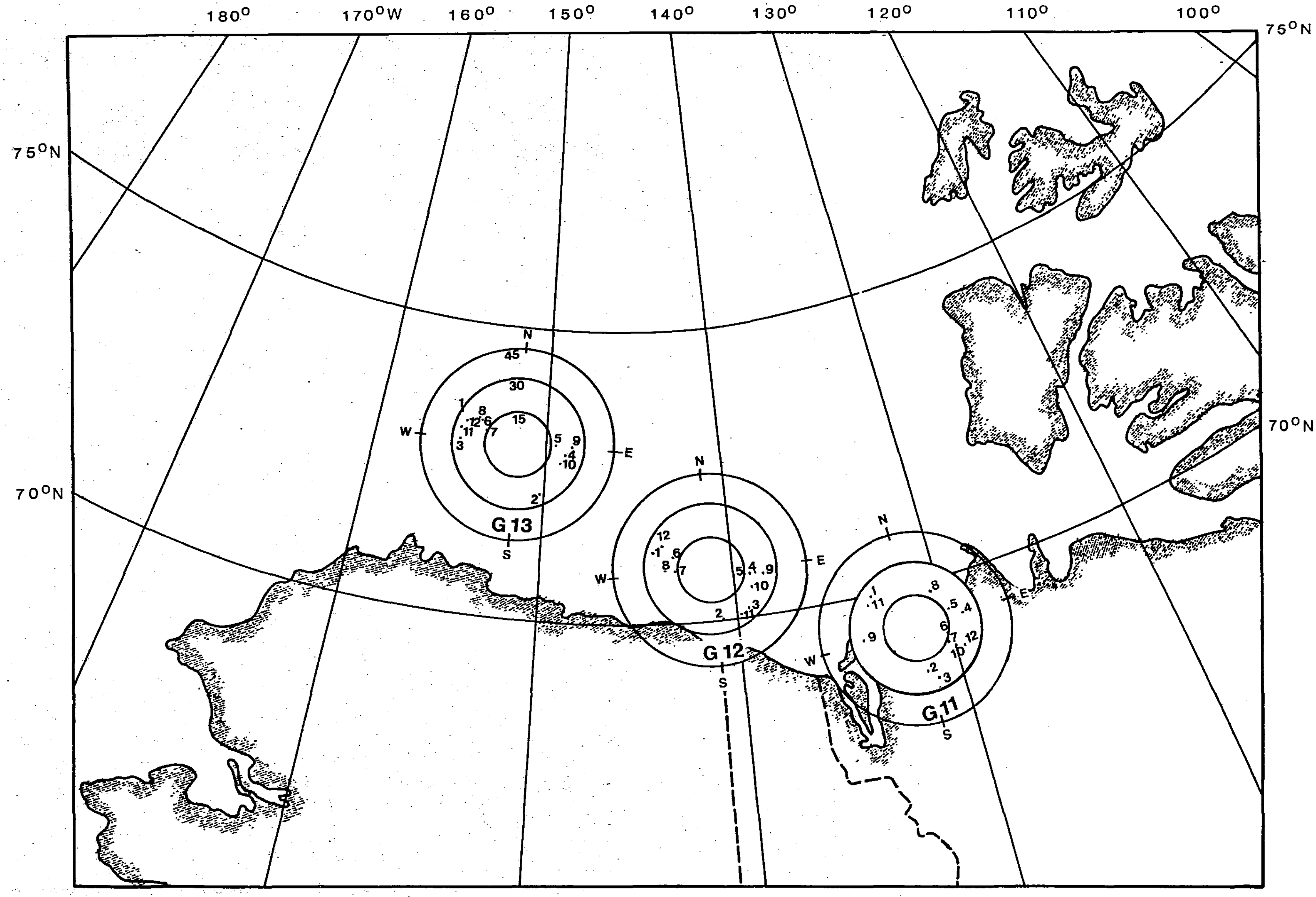


Figure 8.43 Direction and speed of maximum wind by month for Gridpoints 11-13. (Months shown by number; i.e., Jan = 1).

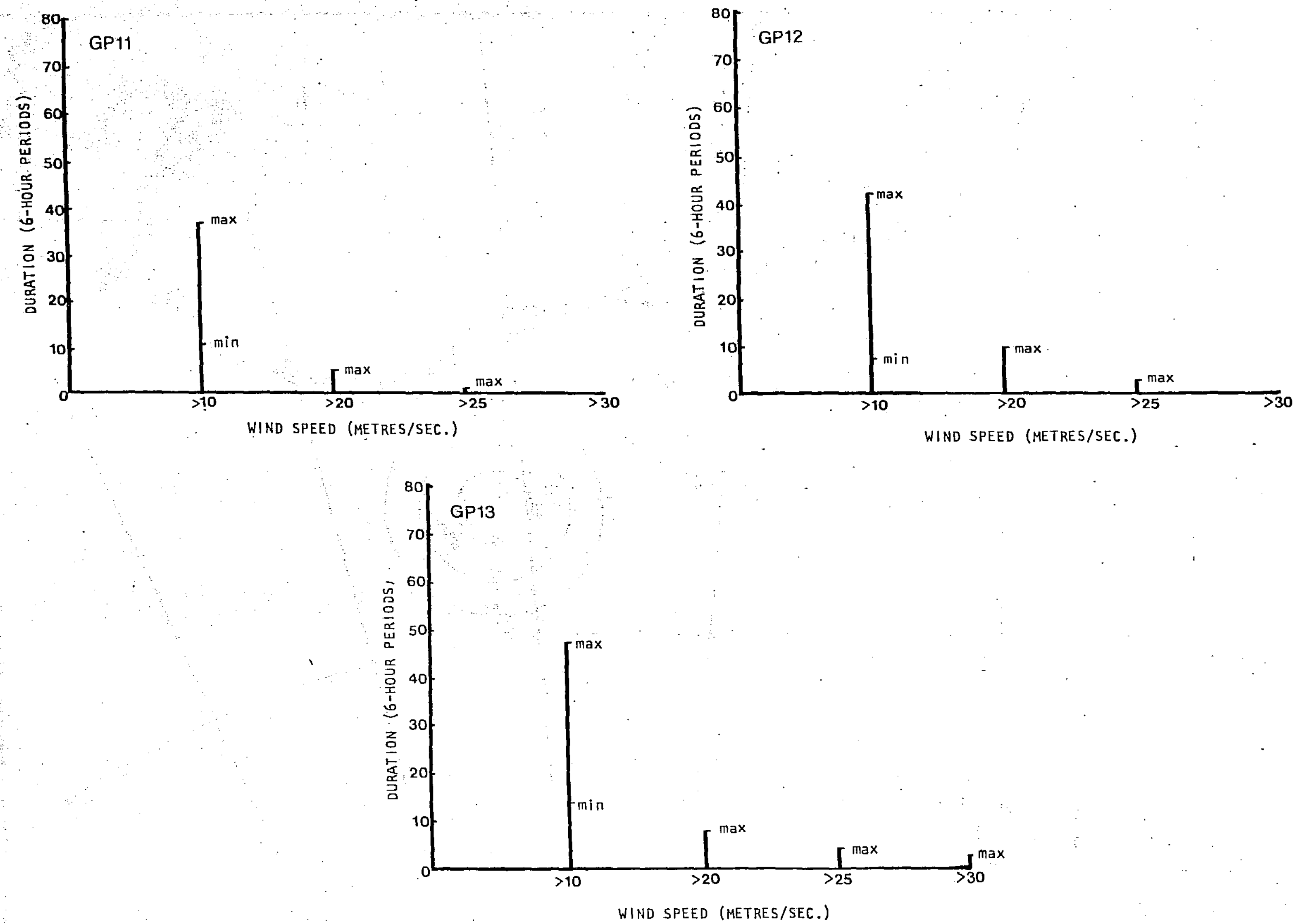


Figure 8.44 Duration (No. of 6-hr periods) for yearly maximum wind speed at Gridpoints 11-13. (The extreme event for any given year lies at or between the Max and Min points).

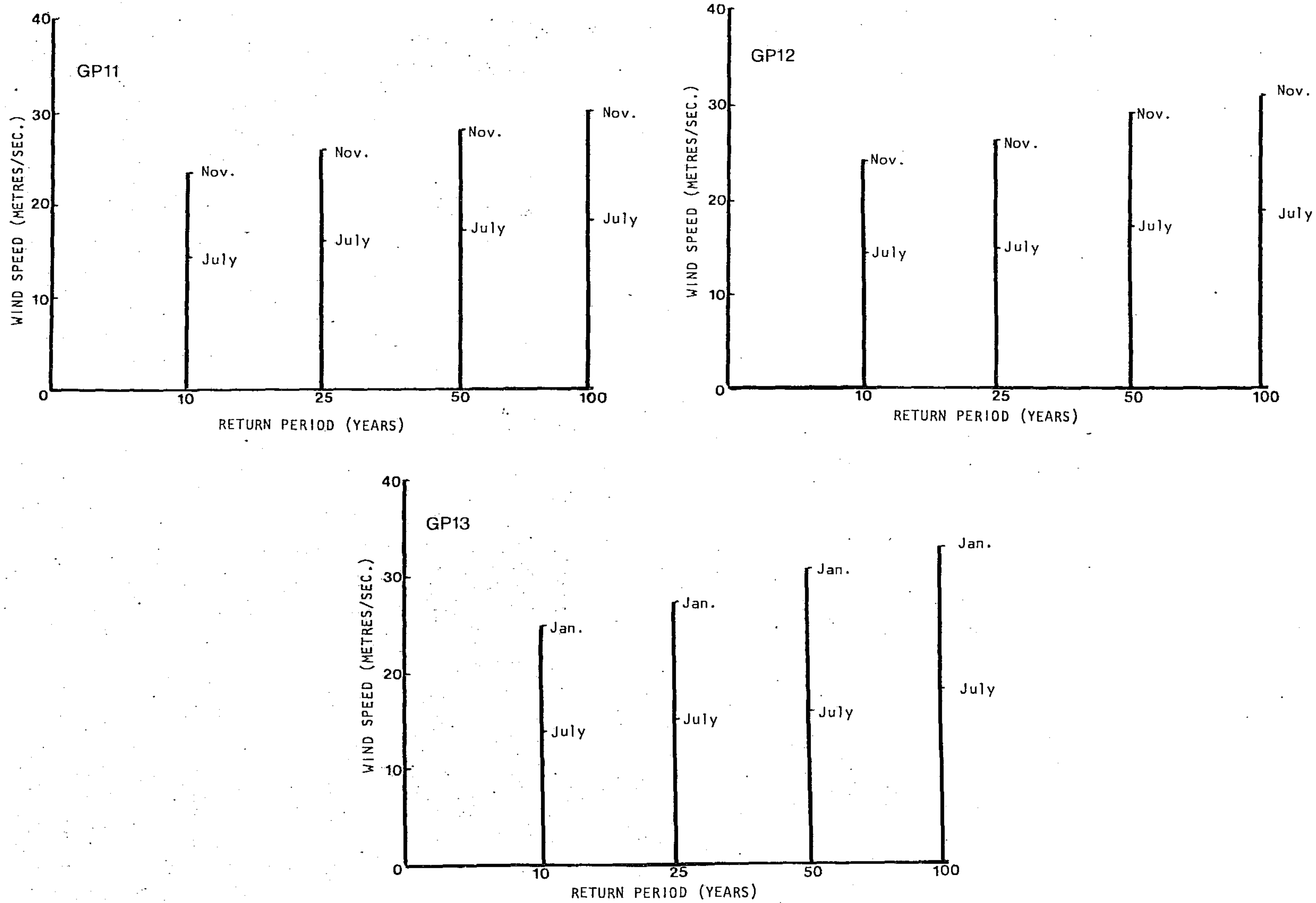


Figure 8.45 Return period for maximum wind speed by month for Gridpoints 11-13. (All values lie at or between the two points).

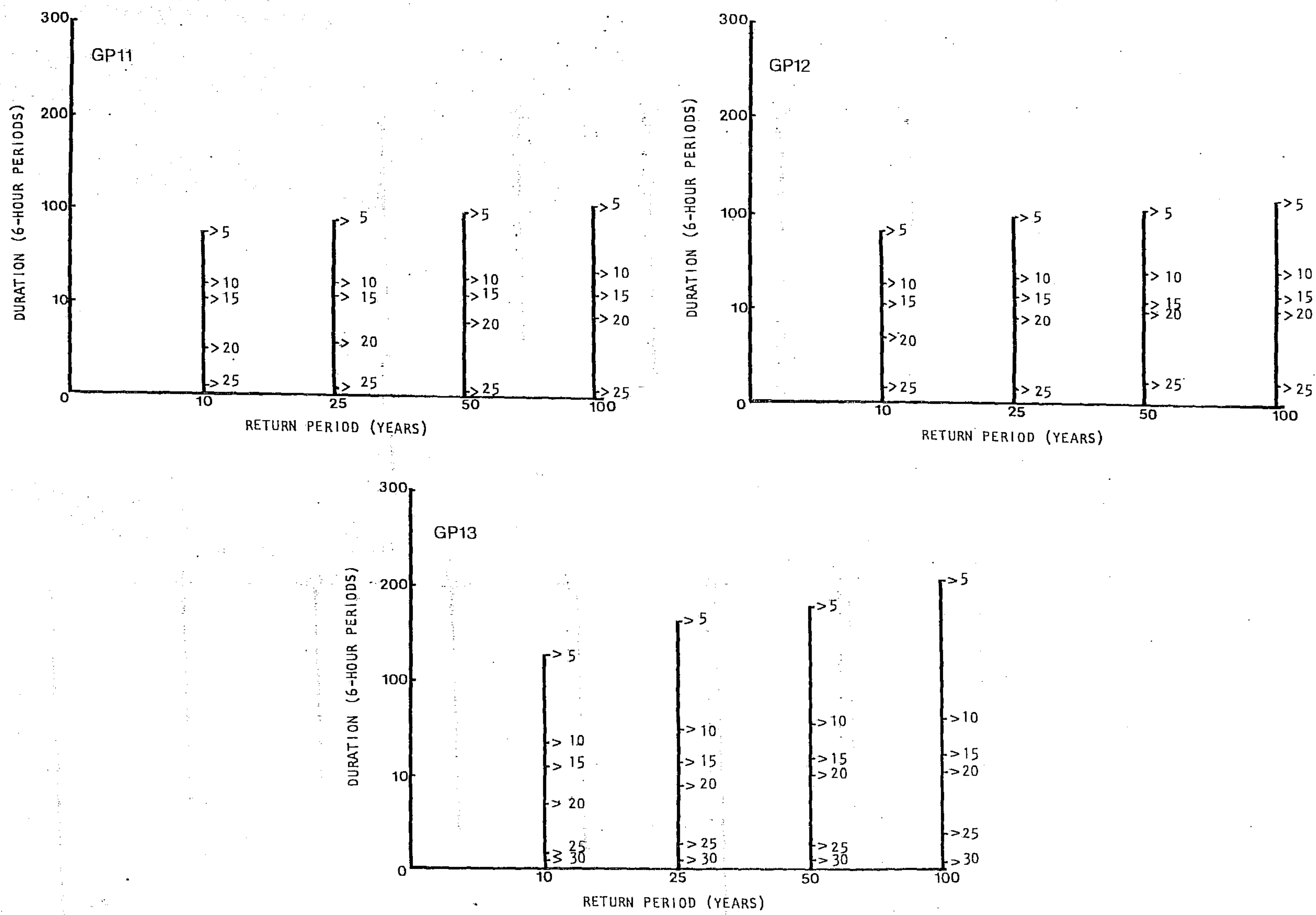


Figure 8.46 Return period for wind speed events of specific duration for Gridpoints 11-13.

Table 8.50. Gridpoint wind speed percent frequency by month.

	Gridpoint GP12				(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	26.4	43.4	22.7	6.5	0.8	0.2	0.0	0.0
Feb.	32.0	43.8	19.8	3.9	0.5	0.0	0.0	0.0
Mar.	29.7	46.7	19.8	3.5	0.3	0.1	0.0	0.0
Apr.	34.0	46.1	17.3	2.4	0.2	0.0	0.0	0.0
May	35.6	49.3	13.9	1.1	0.0	0.0	0.0	0.0
Jun.	45.0	46.1	8.7	0.3	0.0	0.0	0.0	0.0
Jul.	54.8	41.1	4.0	0.1	0.0	0.0	0.0	0.0
Aug.	52.1	39.9	7.7	0.2	0.0	0.0	0.0	0.0
Sep.	42.8	44.8	10.9	1.4	0.1	0.0	0.0	0.0
Oct.	33.9	45.6	17.3	3.0	0.2	0.0	0.0	0.0
Nov.	29.0	42.2	21.4	6.1	1.2	0.2	0.0	0.0
Dec.	30.6	43.0	21.4	4.3	0.0	0.0	0.0	0.0
Annual	37.2	44.3	15.4	2.7	0.3	0.0	0.0	0.0

Table 8.51. Gridpoint wind speed percent frequency by month.

	Gridpoint GP11				(Metres/Second)			
MONTH	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40
Jan.	27.2	42.3	23.1	6.3	1.1	0.0	0.0	0.0
Feb.	35.6	43.2	17.4	3.6	0.2	0.0	0.0	0.0
Mar.	32.4	45.0	19.2	3.1	0.3	0.0	0.0	0.0
Apr.	32.9	47.0	18.0	1.9	0.2	0.0	0.0	0.0
May	34.5	51.4	13.1	1.0	0.0	0.0	0.0	0.0
Jun.	43.4	47.8	8.7	0.2	0.0	0.0	0.0	0.0
Jul.	56.7	39.4	3.8	0.1	0.0	0.0	0.0	0.0
Aug.	48.3	44.2	7.3	0.3	0.0	0.0	0.0	0.0
Sep.	41.7	46.7	10.2	1.3	0.1	0.0	0.0	0.0
Oct.	34.9	46.0	16.1	2.7	0.2	0.0	0.0	0.0
Nov.	33.7	41.9	19.1	4.4	0.8	0.0	0.0	0.0
Dec.	31.8	41.9	21.0	4.6	0.7	0.0	0.0	0.0
Annual	37.8	44.7	14.7	2.5	0.3	0.0	0.0	0.0

(ii) Marine Observations: The wind roses for marine area M 3 for the July to October period are shown in Figures 8.47 to 8.50. From these, the predominance of east to northeast winds is evident for all months. A secondary preference toward the northwest to west directions is also shown. Referring to the gridpoint GP11 to GP13 wind roses in Figures 8.38 to 8.42, it can be seen that the patterns are similar in the predominance of easterly directions with secondary maxima showing in the westerly direction.

Percentage occurrence of wind speeds by month are shown in Table 8.52. The increasing frequencies of the higher wind speeds toward fall months is seen.

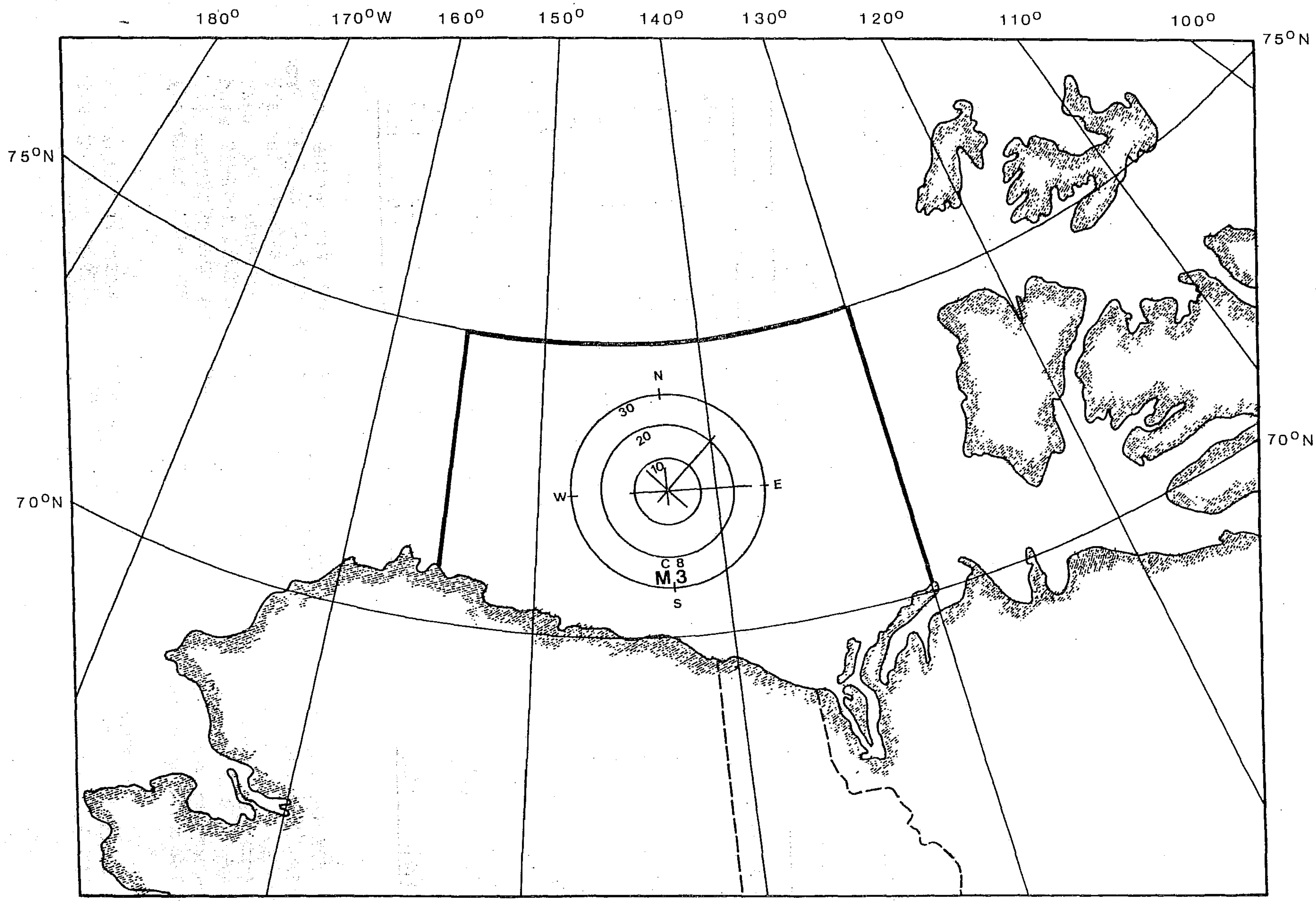


Figure 8.47 July wind rose for Marine Area 3 (percent calm shown in circle).

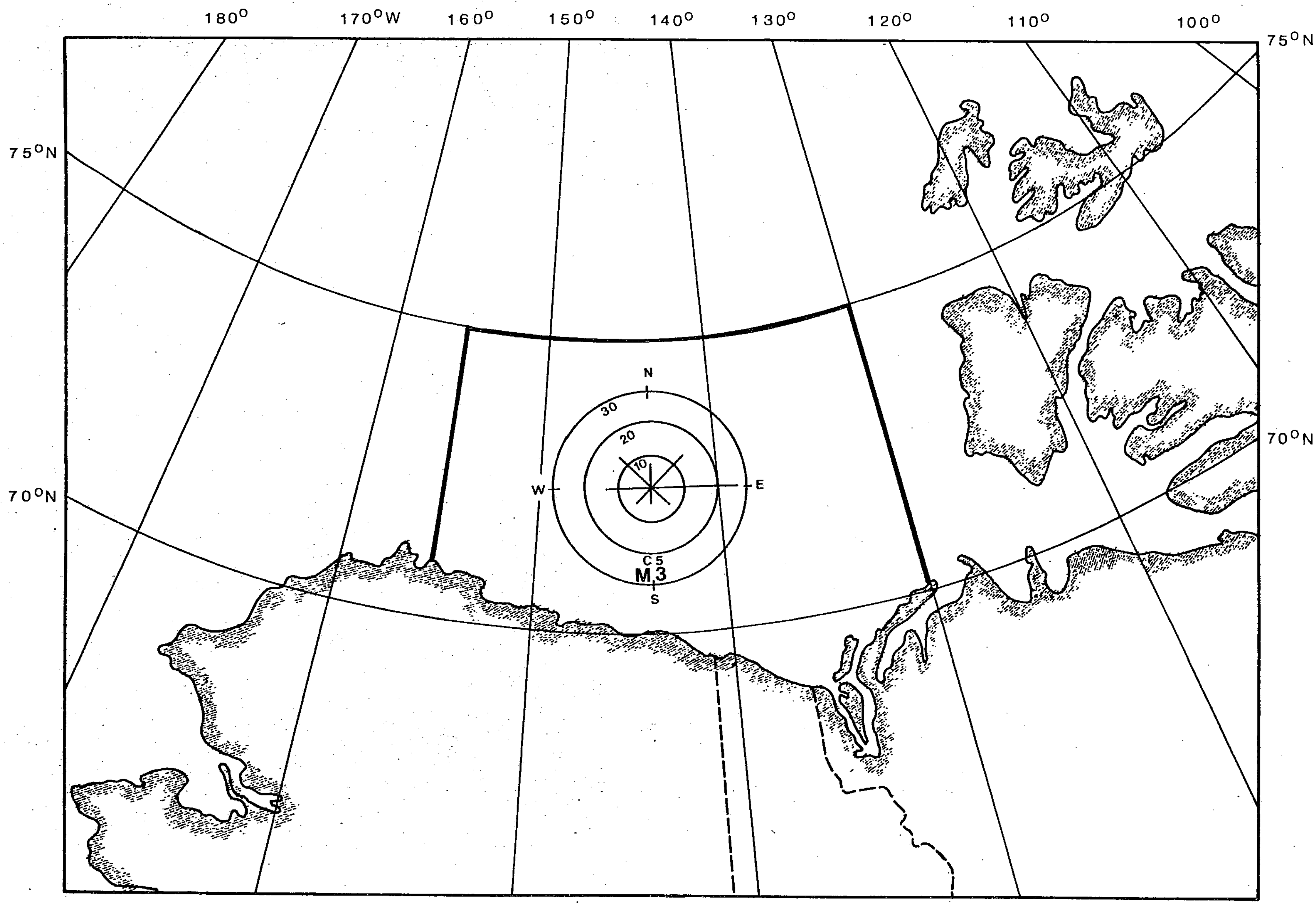


Figure 8.48 August wind rose for Marine Area 3 (percent calm shown in circle).

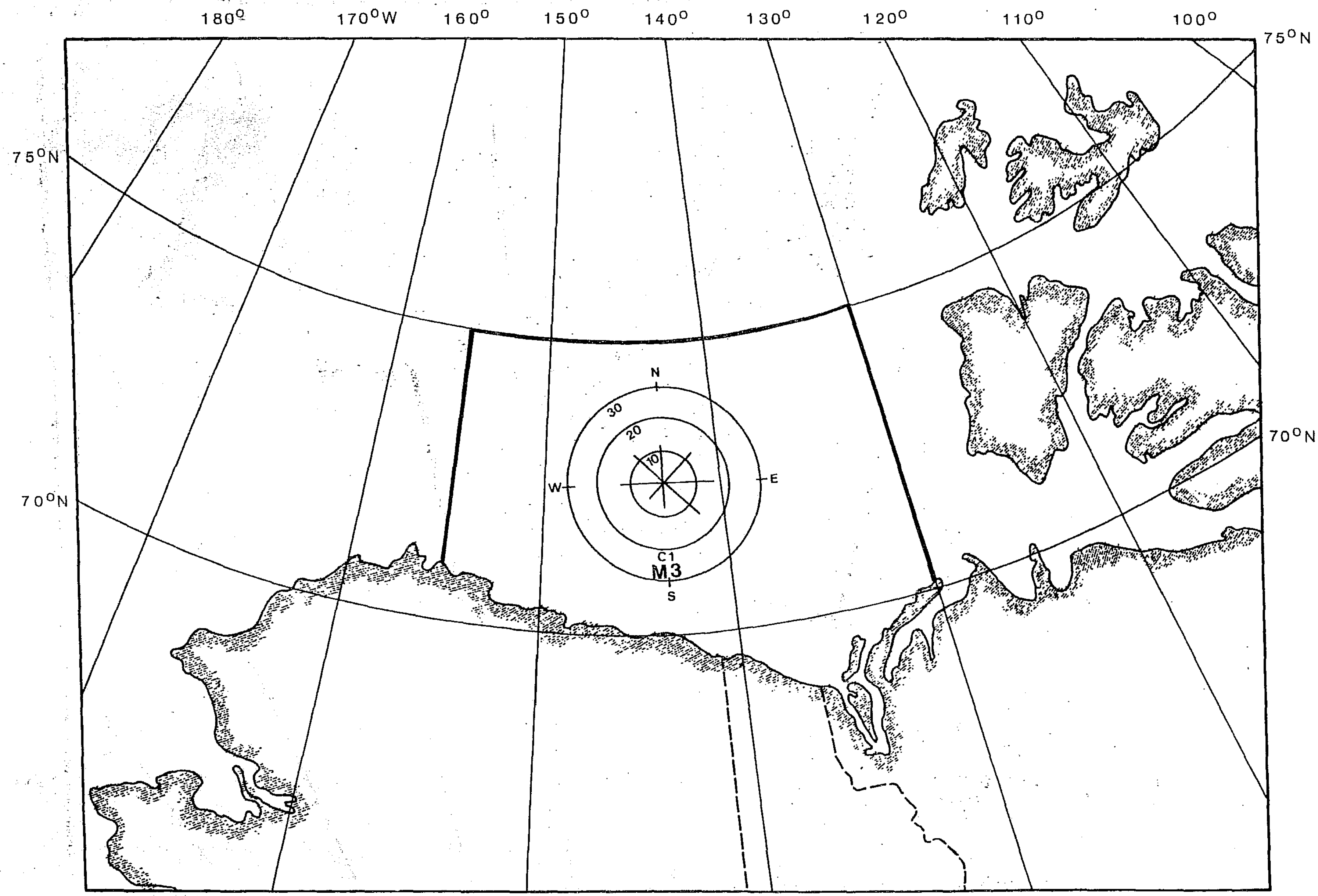


Figure 8.49 October wind rose for Marine Area 3 (percent calm shown in circle).

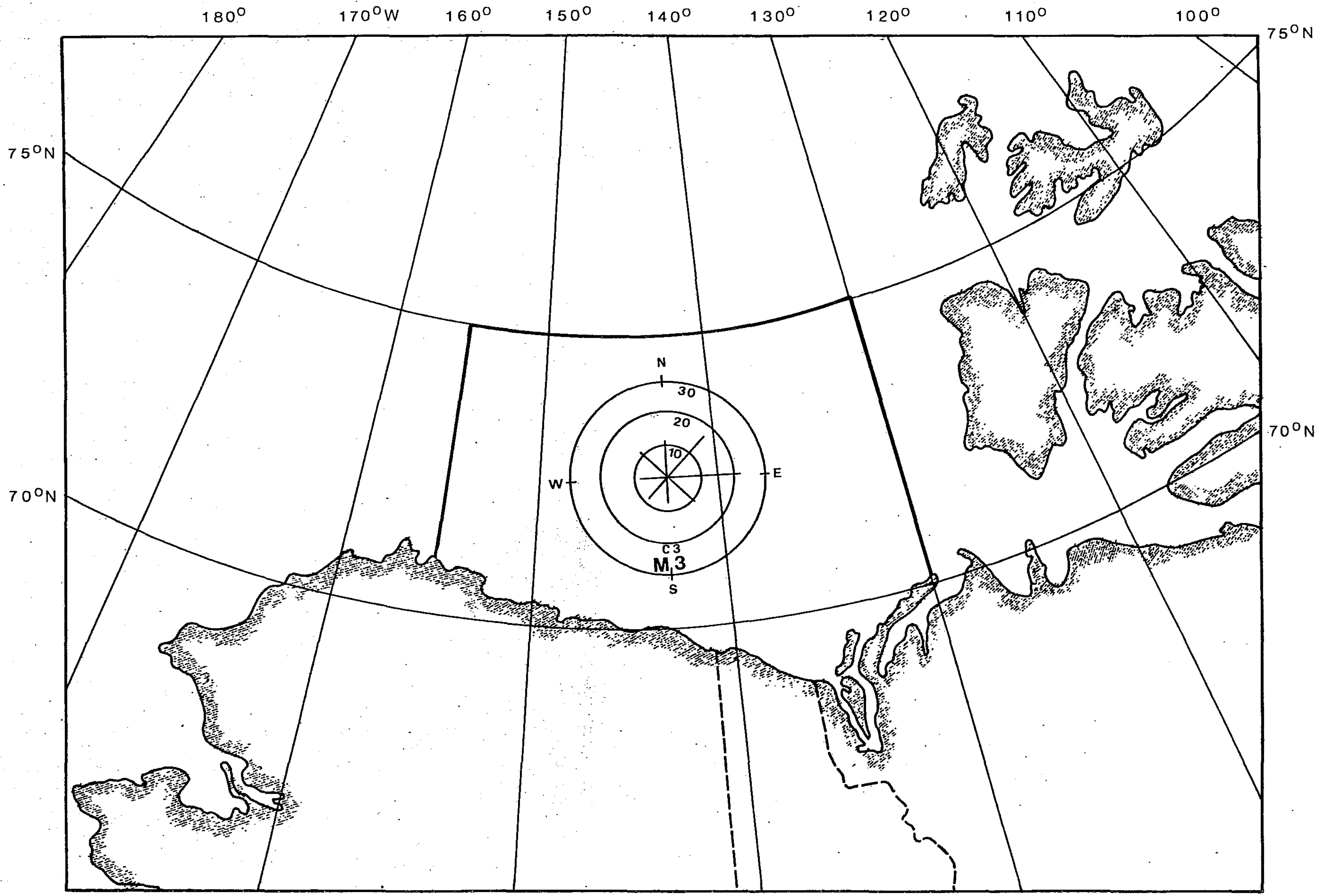


Figure 8.50 September wind rose for Marine Area 3 (percent calm shown in circle).

Table 8.52. Percent frequency of wind speed for Marine Area M 3.

	Wind Speed (Metres/Second)				
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
Jul. (1139)	62	33	5	*	*
Aug. (2764)	54	39	7	*	*
Sep. (1369)	49	41	10	*	0
Oct. (107)	48	40	8	4	*

* =<1%

8.4.2 Waves

In Table 8.53, percentage frequencies of wave height ranges are shown for marine area M 3. The increasing frequency of occurrences of the higher wave heights later in the season is seen here.

Table 8.53. Percent frequency of wave heights for Marine Area M 3 (original units retained).

		Wave Heights (Feet)					
MONTH	(#OBS)	0-2	3-6	7-9	10-12	13-19	20+
Aug.	(213)	54.9	20.7	16.4	6.1	1.9	0.1
Sep.	(132)	20.5	31.1	28.8	8.3	9.8	1.5

From subsequent seasons of offshore drilling in the Beaufort Sea, statistics of wave heights have been assembled (Beaufort Sea Report, 1975). Such maximum heights are in the range reported in the S.S.M.O. marine tables but are still considerably smaller than waves occurring in large open ocean regions.

8.4.3 Visibilities

The variation in percentages of the visibility ranges is shown in Table 8.54 for marine area M 3. The main feature to note is the decrease in percentages for less than 0.9 km visibilities in the late summer and fall. This again reflects the higher incidence of lower visibilities during the early summer ice break-up as compared to the later better visibilities during the open water period.

Table 8.54. Percent frequency of visibilities for Marine Area M 3.

	Visibilities (Kilometres)					
MONTH (#OBS)	< 0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
Jul. (1214)	19	5	2	7	35	32
Aug. (2815)	15	4	4	9	36	32
Sep. (1440)	8	5	5	11	49	22
Oct. (118)	3	1	2	4	19	71

8.4.4 Freezing Spray

Freezing spray in the Beaufort Sea is basically a problem during the late summer and fall. The reason for this is that by the time significant areas of open water have developed early in the season, temperatures have increased to near or above freezing. However, later in the year, but prior to freeze-up, cold arctic air can sweep across the area producing accumulations of freezing spray which could be a hazard for smaller ships, especially those with extensive superstructures. For example, both land stations and ship reports indicate a wind of 20 m/s which, although not common, is by no means a rare occurrence. The average September temperature at Tuktoyaktuk is 2.3°C with a record low of -10.6°C while the October average is -5.9°C with a record low of -31.1°C. Therefore, using an air temperature of -5°C would not be choosing an unusually low value. If these two are combined with a water temperature of +1°C an accumulation rate of about 13 cm/24 hrs is obtained. This is rated as heavy, however; climatic data for Tuktoyaktuk for September and October between the years of 1958 and 1976 shows that all cases of winds of 60 km/hr or 16.6 m/s have lasted for less than 12 hours. Winds over the sea would likely be slightly stronger; however, high rates of accumulation should be of relatively short duration.

8.4.5 Ice

Break-up and Freeze-up: The Beaufort Sea, by late winter, has an area of shore-fast ice extending along its entire shore and westward along the northern Alaskan coast. In the offshore area, the main pack resides, consisting mainly of first year ice near the edge, with older flows further north. The edge of the shore-fast and main polar pack varies from year to year with this zone being characterized frequently by a lead of open water whose width and position vary mainly according to the winds.

During early June ice openings become more prevalent in the Cape Bathurst-Cape Kellet areas and extend east, west and north as the month progresses. In the shore-fast ice zone, as early as May, the melting Mackenzie River waters flow over the winter ice. Eventually, drain holes called "strudels" form in the winter Bay ice to allow these flood waters to drain downward. The flooding by Mackenzie River water and drainage contributes to the shore-fast ice breakup. Thus, the Mackenzie Bay breakup occurs from the north in the zone between the main pack and the shore-fast ice, and from the south due to the Mackenzie River outflow waters.

During July, this shore-fast ice is generally melted and the final "ice-bridge" separating the open water to the north from the open Mackenzie Bay waters finally disintegrates. The exact timing of the breakup patterns is, of course, dependent on the seasonal weather pattern with the concentrations remaining variable during this period.

The general clearing of the southern Beaufort Sea continues through July and August with the least ice concentrations occurring in

Table 8.55. Summary of summer ice conditions - Point Barrow to Prudhoe Bay 1953-1975.

Severity Order	Year	1 n.mi.	2 n.mi.	3 n.mi.	4 n.mi.	5 Date	6 #Days	7 #Days
1	1958	50	150	50	210	19/7	92	99
2	1968	25	165	30	200	19/7	86	91
3	1962	25	150	30	150	19/7	49+	68+
4	1961	15	105	15	135	25/7	49+	62+
5	1973	5	80	5	190	31/7	73	62
6	1963	5	130	5	130	13/8	67	67
7	1959	20	65	20	65	19/7	42	86
8	1972	0	60	30	90	31/7	45	63
9	1954	20	115	20	210	1/8	38+	61+
10	1974	10	100	10	100	6/8	35	61
11	1957	5	45	70	60	1/8	18	67
12	1967	15	0	30	50	25/7	UNKN	68
13	1966	5	0	5	45	1/8	24	65
14	1965	0	10	0	70+	25/8	25	32
15	1953	0	0	5	35	27/7	5	52+
16	1971	0	0	0	30	23/8	8	71
17	1960	0	0	20+	20	5/8	0	34
18	1964	0	0	0	5	13/8	0	39
19	1970	0	0	5	0	6/8	0	32
20	1956	0	0	0	40	7/9	0	24
21	1969	0	0	0	30	7/9	5	12
22	1955	0	0	5	15	13/9	0	12
23	1975	5	0	5	0	NEVER	0	0

(after Brower, W.A., and H.W. Searby et al., 1977)

Columns 1 & 2 - distance from Point Barrow to ice edge on Aug. 10 and Sept. 15 respectively (ice edge is defined as ice concentrations 1/8 or more).
Columns 3 & 4 - distance from Point Barrow to the boundary of 4/8 ice concentrations on Aug. 10 and Sept. 15 respectively.
Column 5 - Initial date entire sea route to Prudhoe Bay less than or equal 4/8 ice concentration.
Column 6 - number of days entire sea route to Prudhoe Bay ice free.
Column 7 - number of days entire sea route to Prudhoe Bay less than or equal to 4/8 ice concentration.

the last half of September. Through the entire breakup and main open water periods, the ice amounts can vary greatly over the area due to the prevailing winds during a given season.

Further west along the north Alaskan coast the breakup pattern is much slower. The reason for this is that ice continually drifts into the area either from the main polar pack to the north or from the Beaufort Sea area to the east. The variability from season to season along this part of the passage is considerable. During poor years, the ice may be very close to the shore, and, this combined with the shallow coastal waters make passage by larger vessels in ice-free water impossible. In Table 8.55, from Brower and Searby (1977), a summary of the passage between Point Barrow and Prudhoe Bay is shown for a 23-year period. The years are ranked in order of severity of ice conditions with the least severe at the top of the table. As can be seen, a considerable variation in the polar pack positions along this coast is evident with distances offshore for the 4/8ths ice concentrations, for example, ranging from zero to over 200 miles for September 15th. The significance of the "plus" signs in the table was not indicated in the Brower and Searly text. However, it is felt that the "plus" means that the tabular number is the least number of nautical miles or days confirmed by observation. The true value is, therefore, greater than the value shown.

(i) Median Old Ice Concentrations: In Figures 8.51 and 8.52a, the median amounts of old ice are shown for the May 21 to October 22 period in bi-weekly time intervals with the period of time used for the charts being 1959 to 1974. Personal communications with E. Hudson, Officer-In-Charge of the Beaufort Sea Weather Office, have been utilized in the interpretation of these charts.

One interesting feature is the position of the "0" to "T" or "0" to "2" line positions. During late May and early June, this border tends to move northwestward in response to the prevailing east to southeast winds at this time of year. Later, during July, as the shore-fast ice dissipates, small amounts of ice can then drift southward during periods of northwesterly winds. This accounts for the southward movement of this border during July. Finally, as the season progresses into August and September, the warming of the southern Beaufort waters tends to overcome any shoreward ice drift due to wind and on the average allows this border to progressively move northward.

Another point of interest is the "bulge" in the old ice border during most of the period in the 71°-72°N, 130°-135°W region. This is caused by prevailing ocean currents in this area allowing variable amounts of old ice to be transported southward from the main pack.

(ii) Worst Ice Conditions: In Figures 8.53 to 8.55, the maximum reported conditions for all ice are shown. During the May 21 to July 2 periods, the entire area is completely consolidated. During the mid-July to early September period, the openings in the southern Beaufort coastal sections gradually increase followed by a decrease again in later periods. The North Alaskan Coast passage areas remain in the "7" or "F" areas throughout the period with an occasional small "3" area showing in late August and early September.

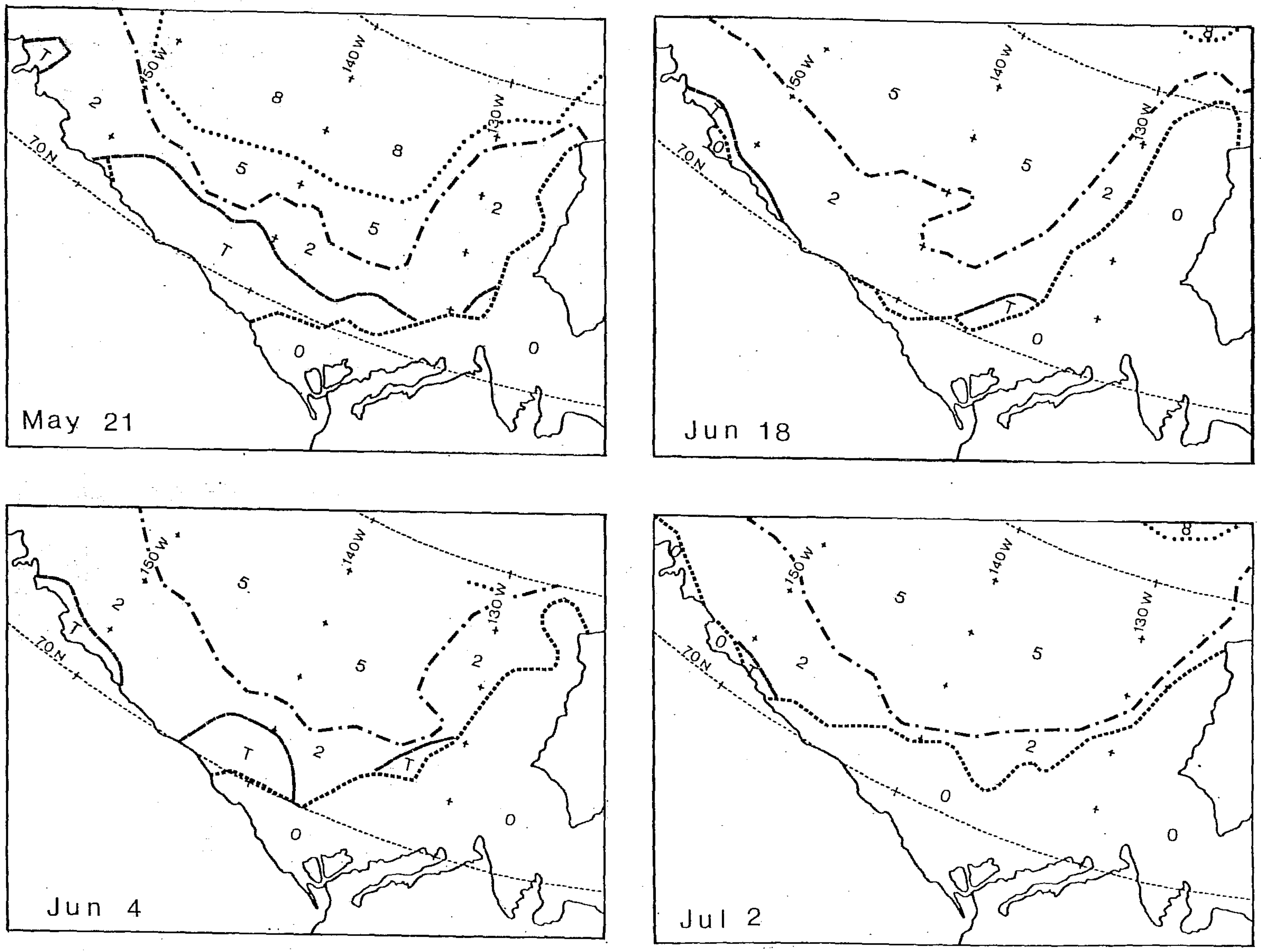


Figure 8.51 Median concentration of old ice, 1959-1974 (after Markham, 1981).

O: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

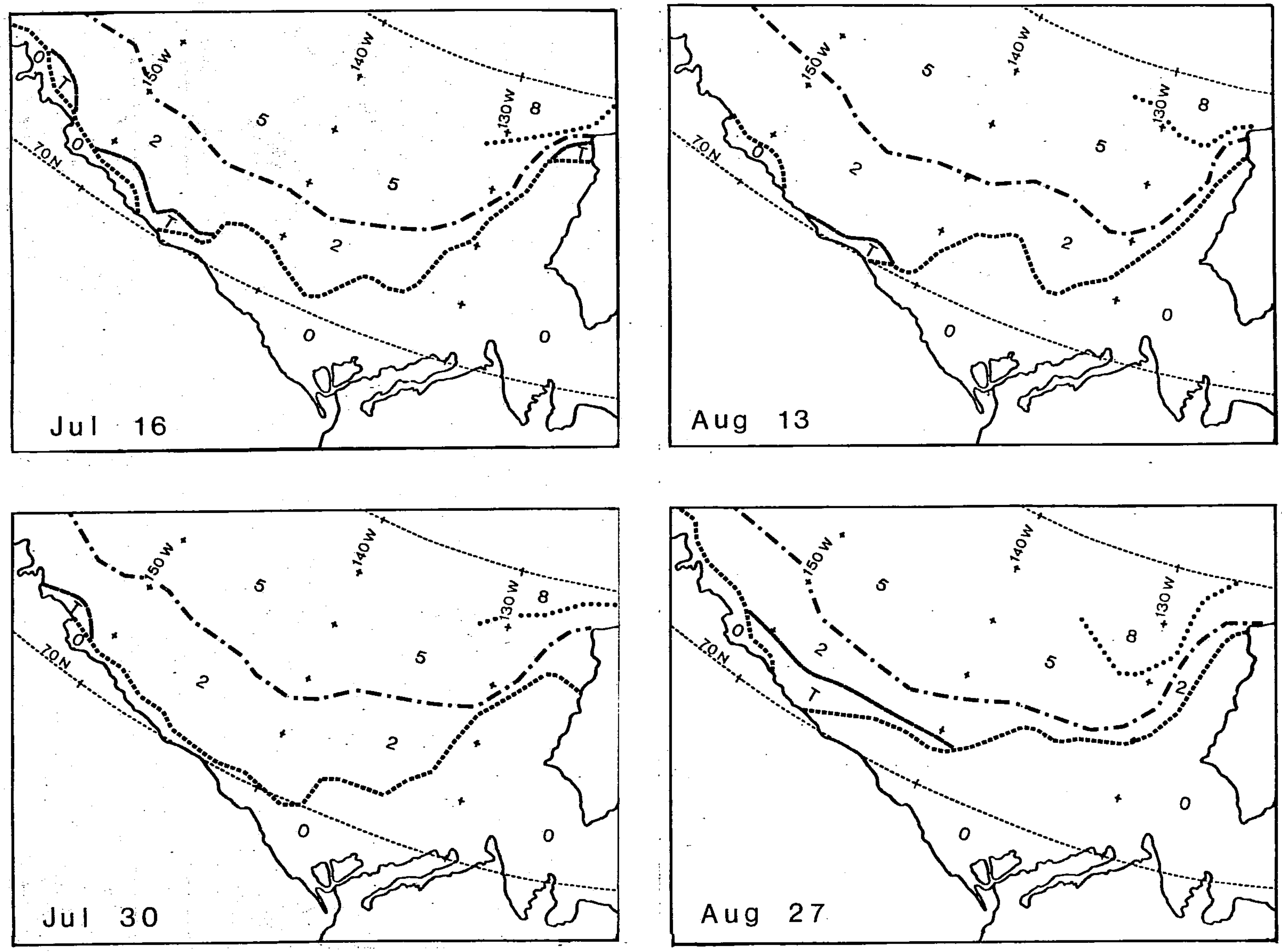


Figure 8.52 Median concentration of old ice, 1959-1974 (after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

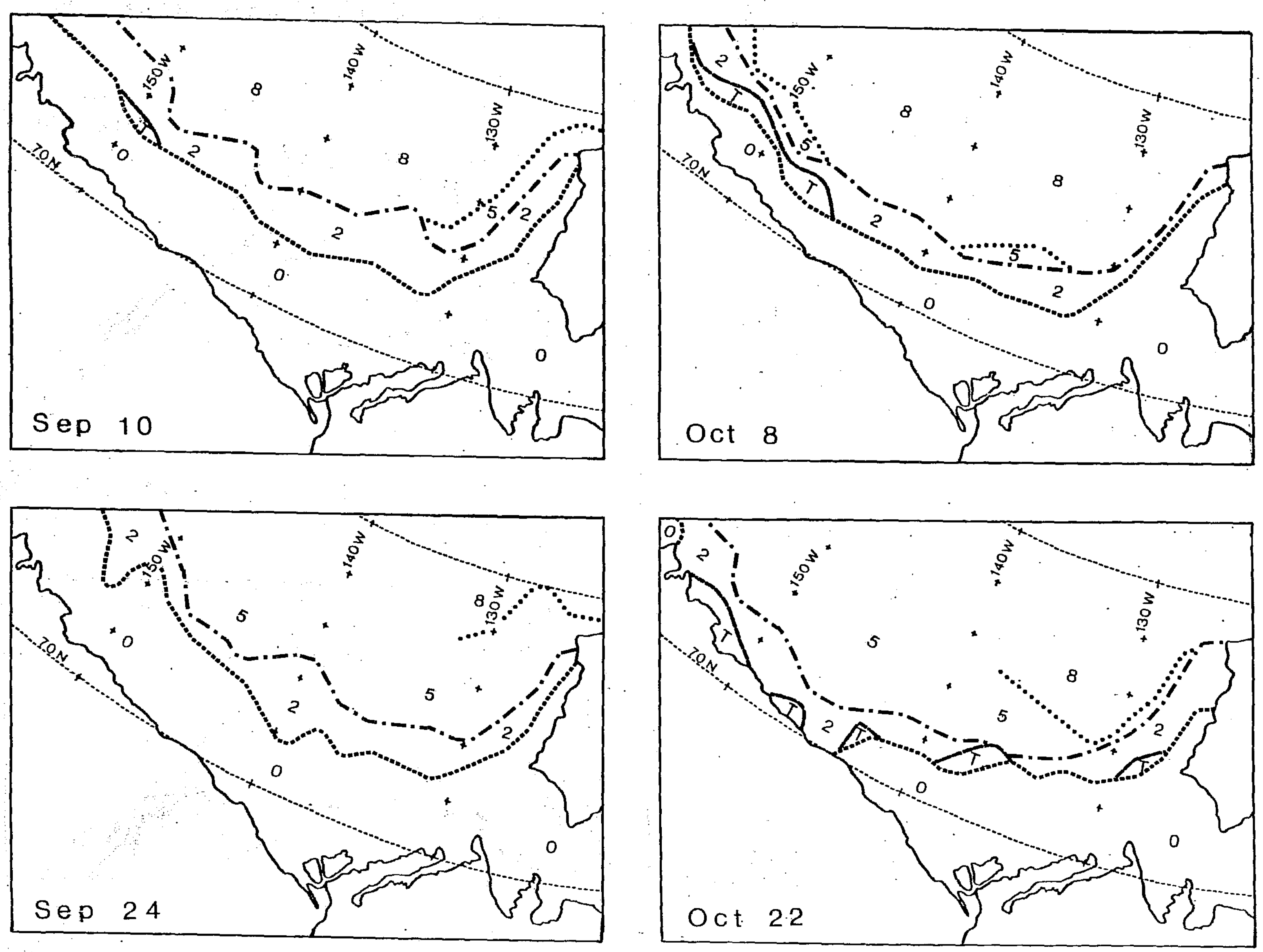


Figure 8.52a Median concentration of old ice, 1959-1974 (after Markham, 1981).

0: No old ice.
T: A few old floes.
2: 1/10-3/10 old ice.
5: 4/10-6/10 old ice.
8: 7/10-9/10 old ice.
F: 10/10 old ice.

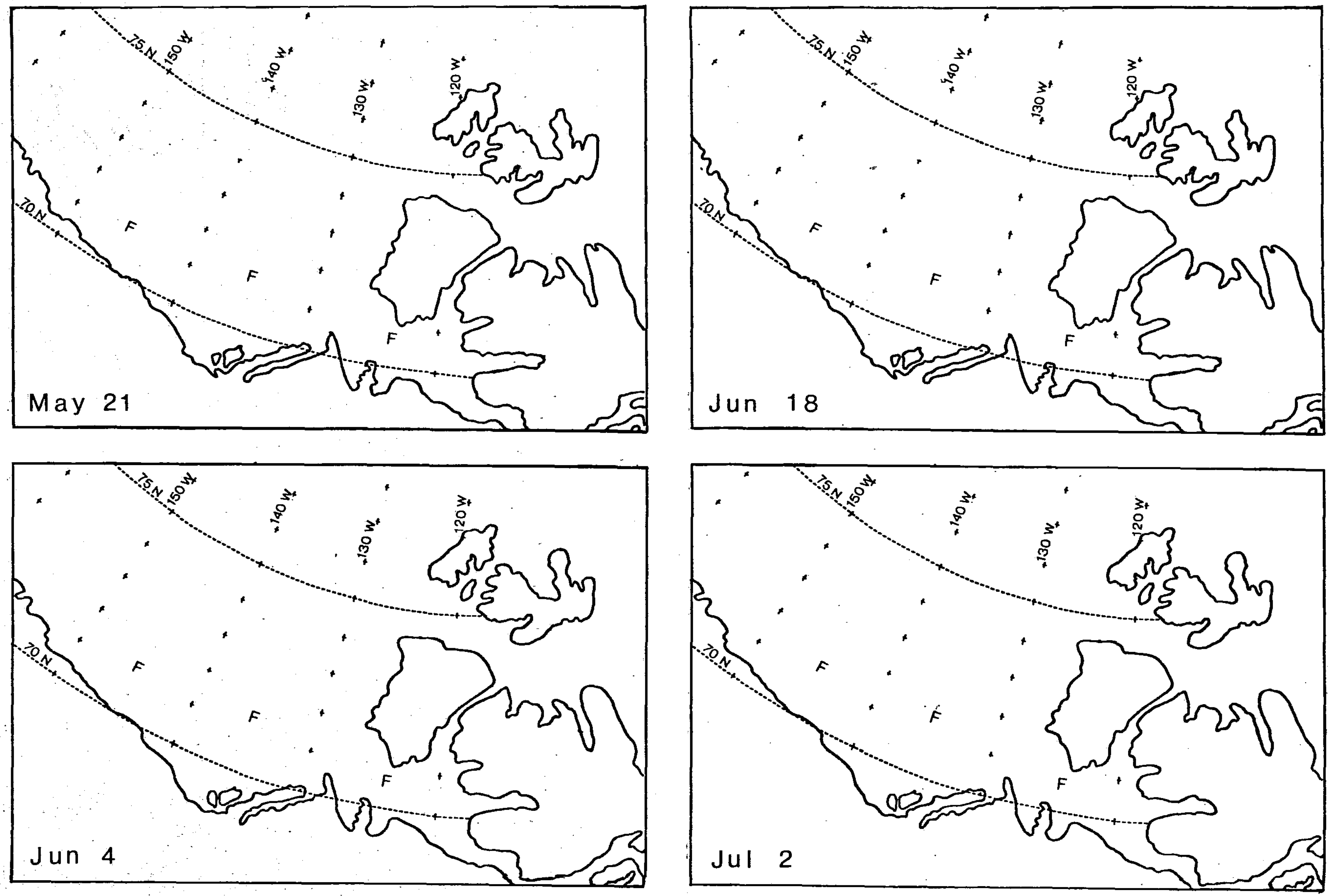


Figure 8.53 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

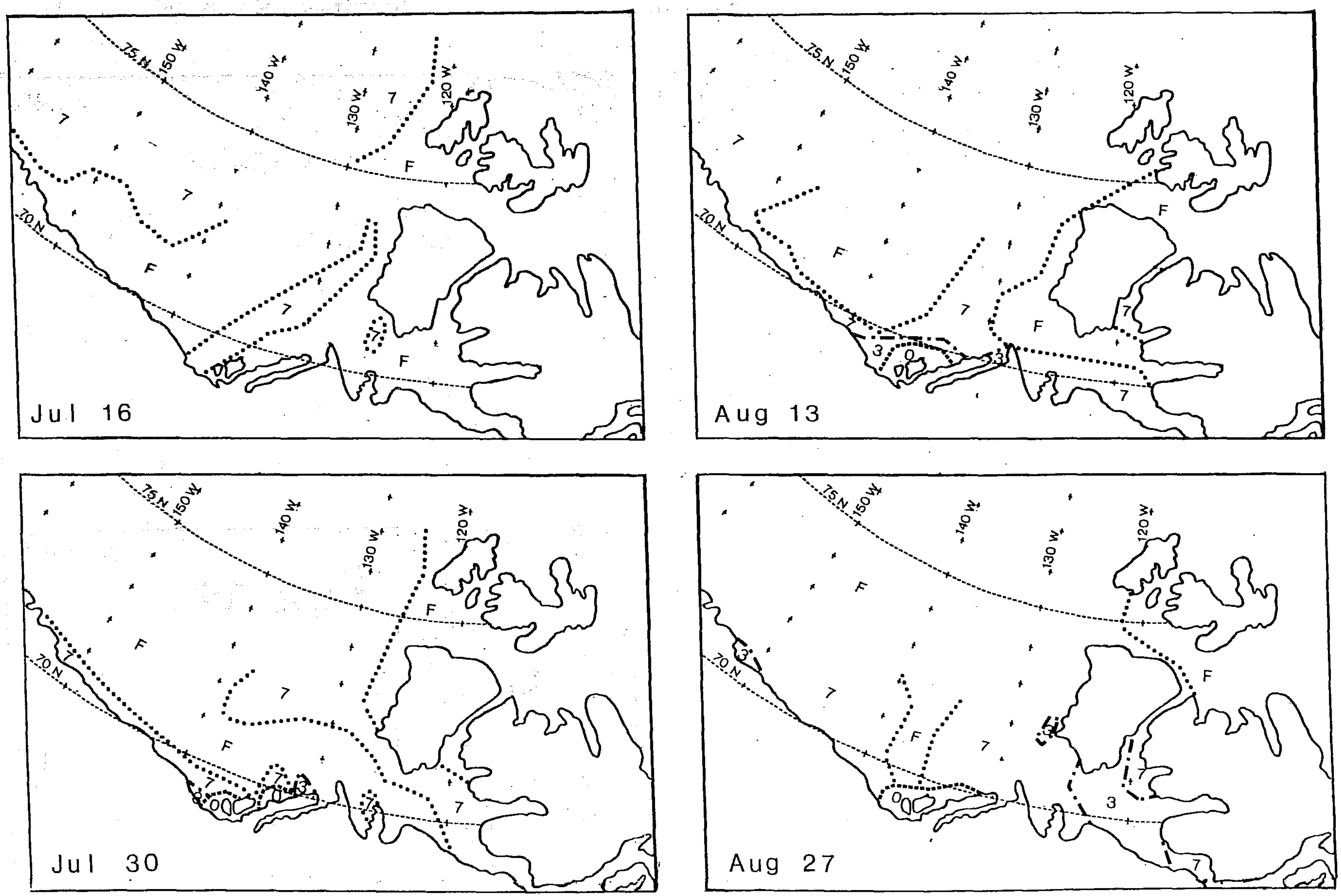


Figure 8.54 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

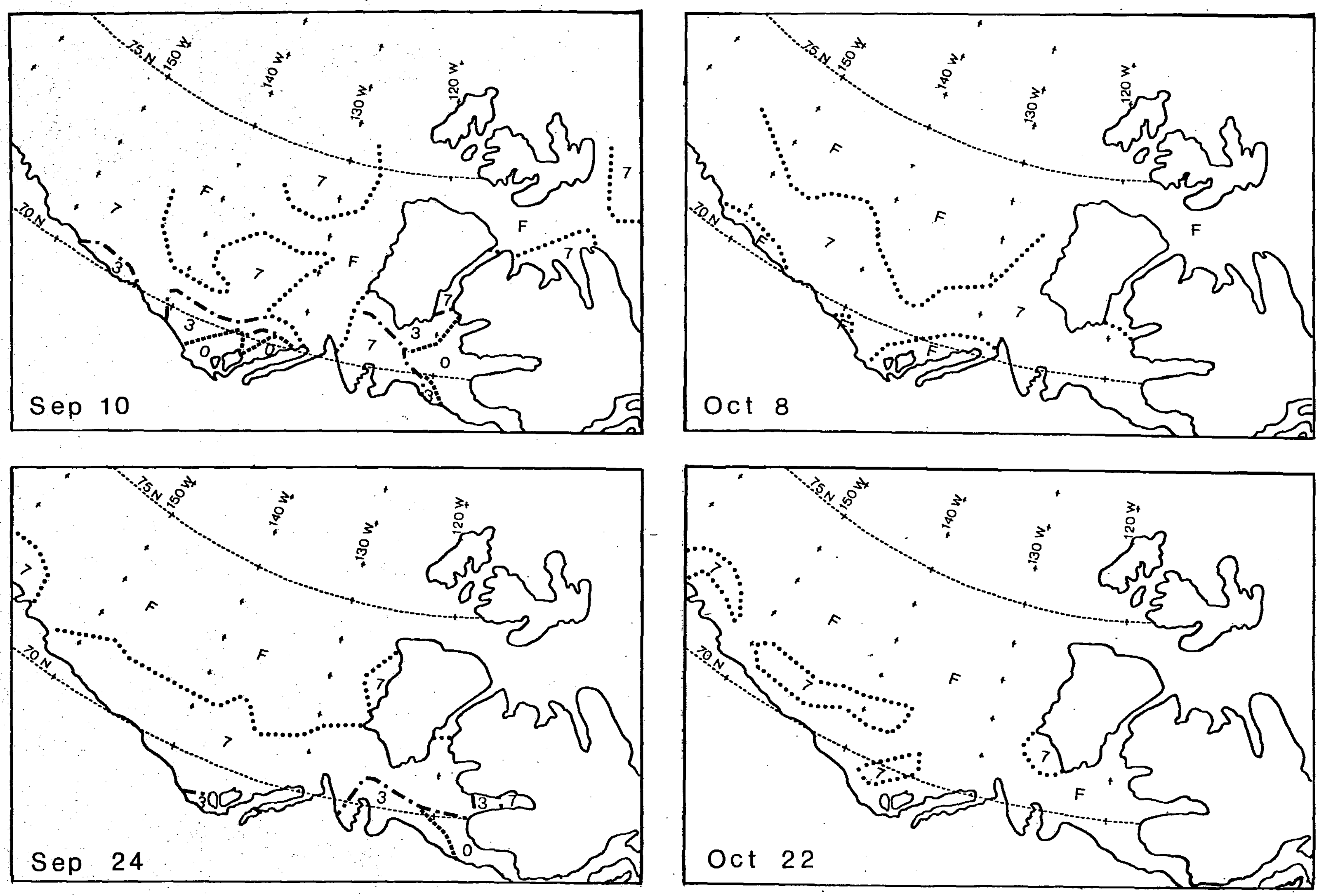


Figure 8.55 Worst ice conditions (after Markham, 1981).

0: Open water.
3: 1/10-5/10 ice.
7: 6/10-9/10 ice.
F: Consolidated ice.

8.5 BEAUFORT SEA COASTAL WEATHER

8.5.1 Introduction

The climate of the mainland coast is generally non-representative of that only a few miles inland. The main reason is, of course, the modifying effect of the Beaufort Sea and the terrain, especially over the northern Yukon where the mountains extend almost to the sea. This section looks at the winds, temperatures and visibilities along the coast from Barter Island to Cape Bathurst. Roses of wind speed and direction are presented in addition to tables of temperature, precipitation and visibilities for a number of coastal sites as well as an inland site for purposes of comparison.

8.5.2 Wind

Terrain plays a dominant role in determining local wind patterns along the Yukon coast and when feasible should be considered when selecting sites for shore-based operations. A more detailed look at winds along the coast from Komakuk to Tuktoyaktuk will be presented to emphasize this fact.

The mountainous terrain of the Yukon extends northward to within a few miles of the coast while the Mackenzie Delta and Tuktoyaktuk peninsula are relatively low land. Figure 8.56 gives a more detailed look at the northern Yukon. The interior plain is separated from the coast by the British and Richadson Mountains and, in general, coastal winds have a strong tendency to blow parallel to these ranges. This relatively simple wind regime is locally modified by a series of passes which provide a link between the coast and interior plain of the Territory. Figures 8.57 and 8.58 show wind roses for Komakuk and Shingle Point and despite the fact they are based on a limited amount of data a number of things are evident. Perhaps the most dramatic is the strong preference for east and west winds at Komakuk, an effect which can be directly attributed to the mountains located just south of the station. On the other hand, although winds at Shingle Point are channelled to predominantly west-northwest and east-southeast directions, there is also a high incidence of southwest winds. These are the result of the Blow River valley which is located southwest of the station.

Figures 8.57 and 8.58 also show maximum wind speed by direction. These indicate that, although there is a preference for strongest winds to correspond with prevailing direction, there may be winds equally as strong from other directions. The October, November, December data for Komakuk (Figure 8.57) show a peak from both the northeast and south while the frequency of winds from these directions is very small. The strong south wind was one isolated case and, although it was not investigated, may be an indication of a foehn wind. Unlike Komakuk, Shingle Point shows a preference for strong southwest winds with the maximum occurring during the winter months. This is at least partially due to the fact that during the winter the Yukon becomes a source region for arctic air, thus providing a reservoir of cold dense air which can drain northward through the Blow River pass.

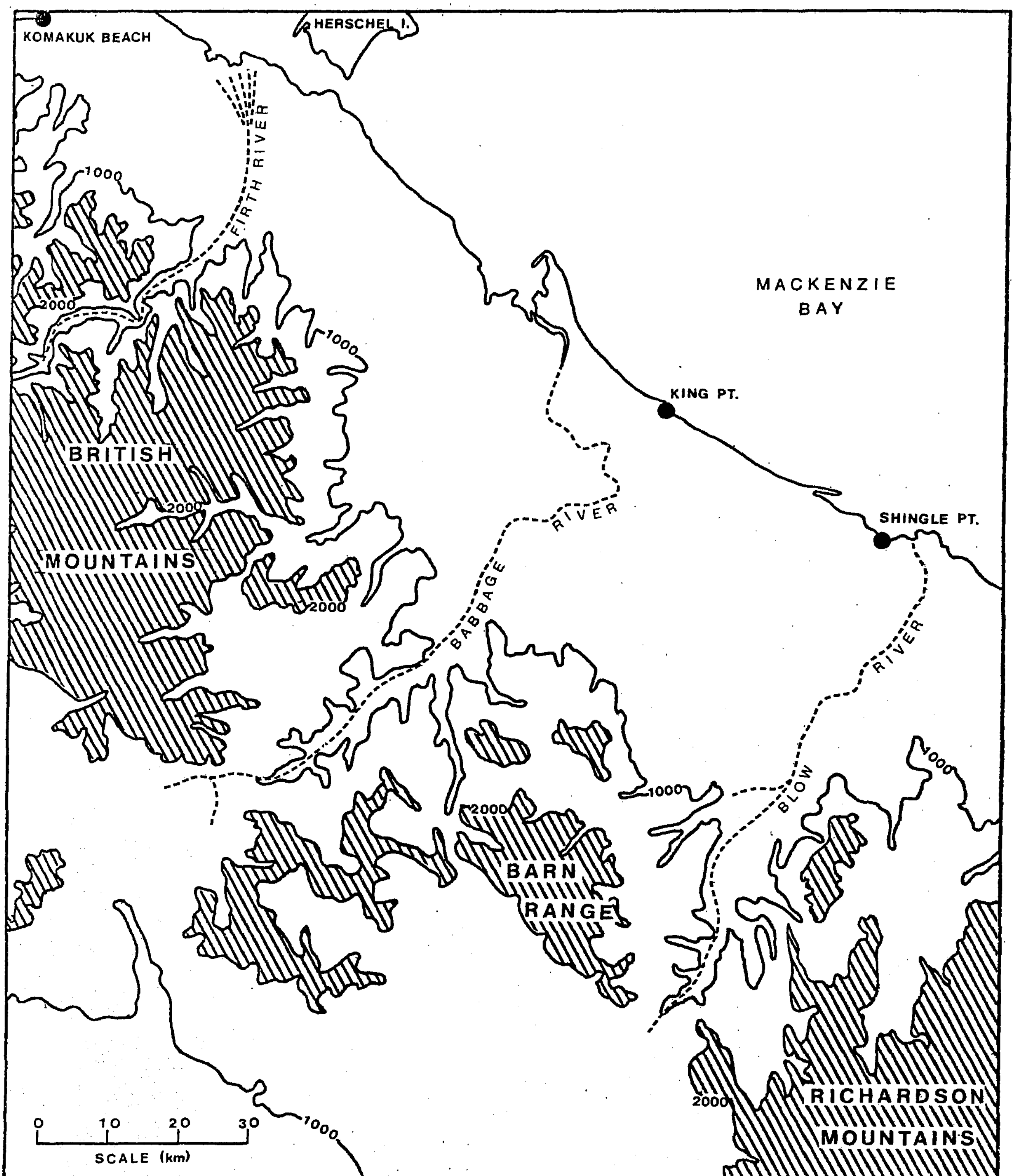


Figure 8.56 Map of north coast of Yukon showing prominent mountain ranges.

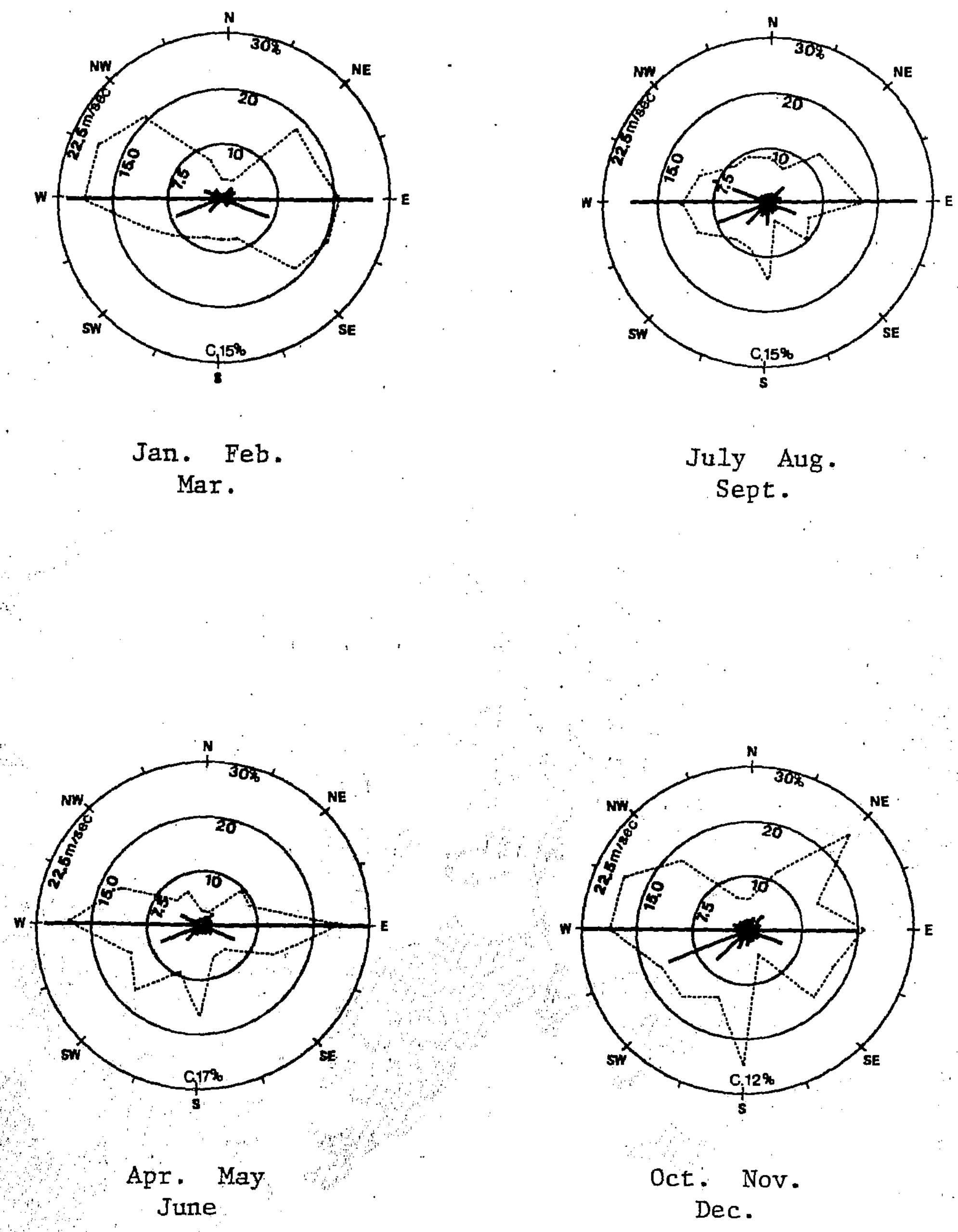
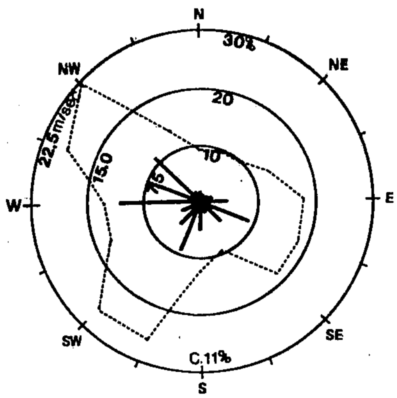
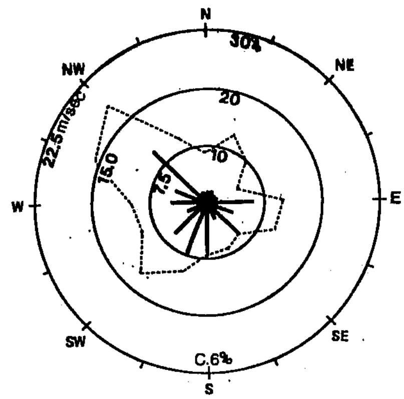


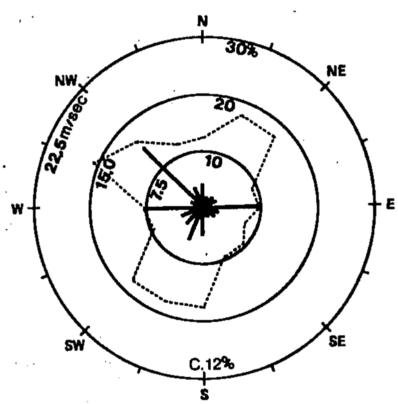
Figure 8.57 Wind roses for Komakuk Beach, Yukon Territory. (Based on limited data between 1961-1971 with 1964 missing).



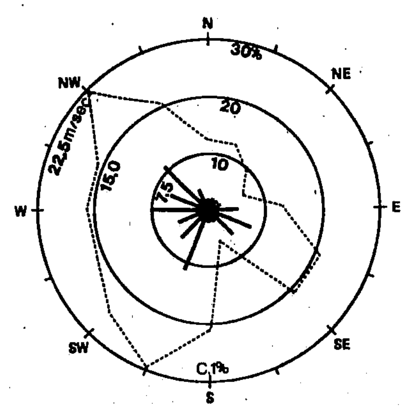
Jan. Feb.
Mar.



July Aug.
Sept.



Apr. May
June



Oct. Nov.
Dec.

Figure 8.58 Wind roses for Shingle Point, Yukon Territory. (Based on limited data between 1961-1971).

Using this information and a topographical map one can then obtain some idea of what the wind regime along other sections of the Yukon coast might be. The King Point area may be a location of increased activity and will be used to demonstrate this technique.

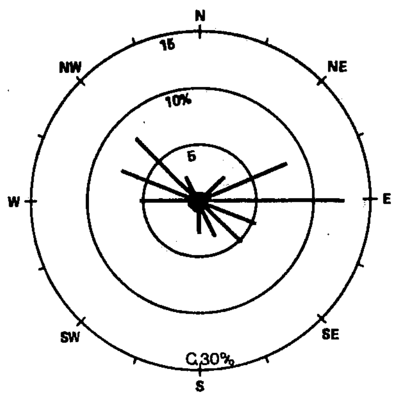
Referring to Figure 8.56, it can be seen that King Point lies some 35 to 40 kilometers to the west-northwest of Shingle Point and, therefore, is likely beyond the main sphere of influence of the Blow River Valley. However, the Babbage River Valley is situated southwest of the site. It would then seem reasonable to expect a speed maximum from the southwest although topographical variations could result in a value higher or lower than that observed at Shingle Point. As with Shingle Point the strongest southwest wind would likely occur during the fall and winter months. For other directons the wind rose would likely be similar to that of Shingle Point. Although occurrences of northeast wind would likely be infrequent the possibility of strong winds from the northeast or other directions still exists. Whether or not King Point experiences occasional foehn winds is not known at this time.

As distance from the mountains increases so does the frequency of winds from other directions. This can be seen in the wind roses for Inuvik and Tuktoyakuk (Figures 8.59 to 8.60a). Both stations show a small frequency of southwest winds. Part of this is due to the proximity of the mountains especially in the case of Inuvik. However, it is interesting to note that the geostrophic wind roses for grid point 12 (Figures 8.39 through 8.42) show similar trends. This then suggests that the basic synoptic patterns do not favour winds from a southwesterly direction. It could be argued that these synoptic patterns are also strongly influenced by terrain; however that is beyond the scope of this study.

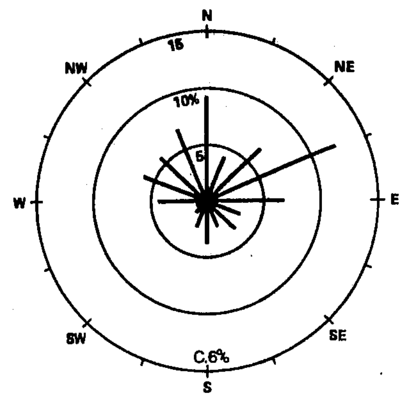
Figure 8.61 shows roses of speed by direction for Tuktoyaktuk. Unlike those for Inuvik they have been separated from the roses of frequency by direction because they use a different data base.

The tendency for the strongest winds to be from the northwest is to be expected. Strong northwest winds generally occur behind lows or cold fronts when the airmass is more likely to be unstable in the low levels, especially during the fall before freeze-up.

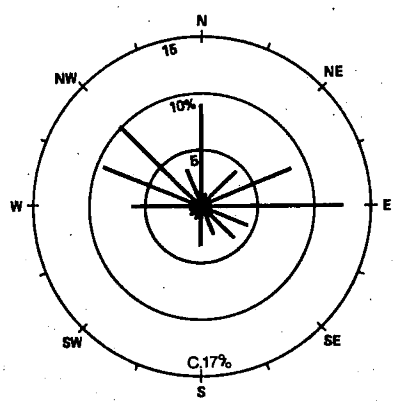
More detail on the wind speed at both Tuktoyaktuk and Inuvik is presented in Tables 8.56 and 8.57 which show the percent frequency of wind speed ranges by month. One fact that stands out is the higher frequency of strong winds at Tuktoyaktuk. This can partially be attributed to the more exposed location of Tuktoyaktuk as compared to Inuvik airport. Another contributing factor is that the more northern location of Tuktoyaktuk places it closer to disturbances moving across the Beaufort Sea.



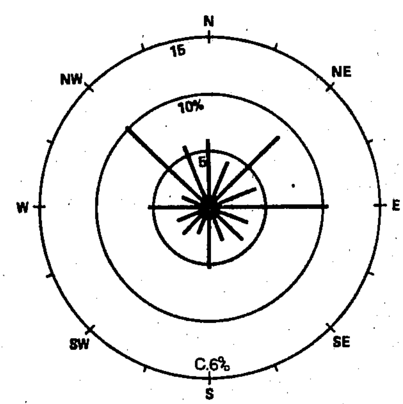
Jan.



May

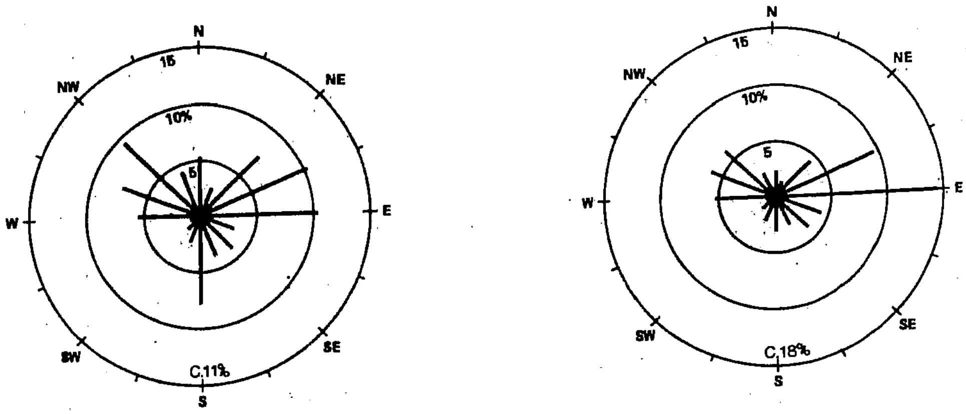


Mar.



July

Figure 8.59 Wind roses for Inuvik, N.W.T. (Based on hourly data from January 1962 to December 1971).



Sept. Nov.

Figure 8.59a Wind roses for Inuvik, N.W.T. (Based on hourly data from January 1962 to December 1971).

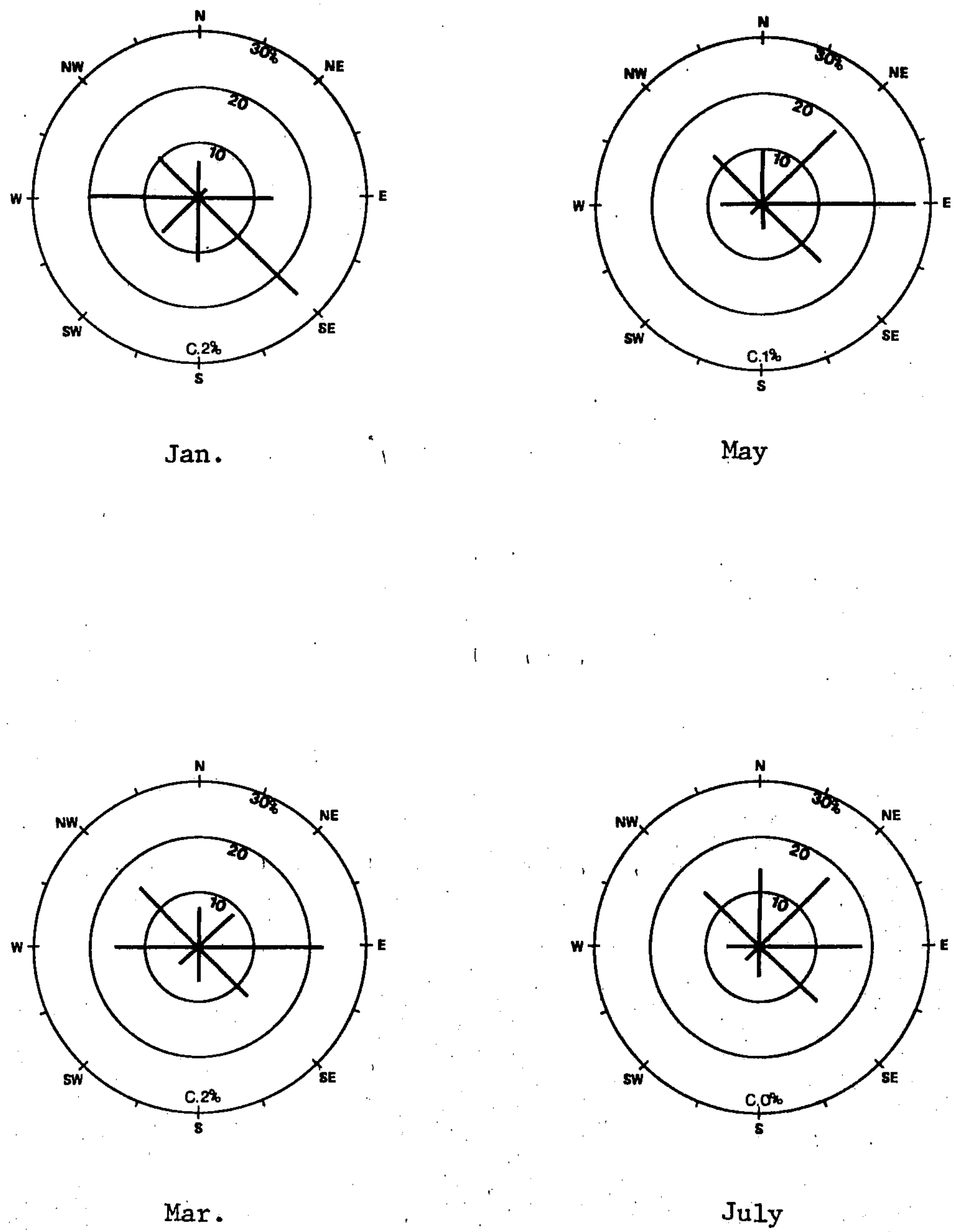
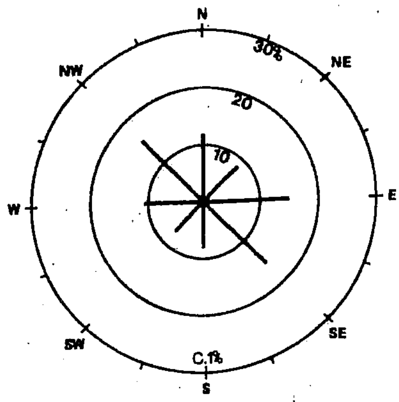
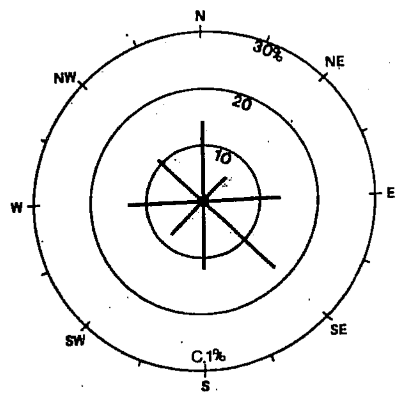


Figure 8.60 Wind roses for Tuktoyaktuk, N.W.T. (Limited data base).



Sept.



Nov.

Figure 8.60a Wind roses for Tuktoyaktuk, N.W.T. (Limited data base).

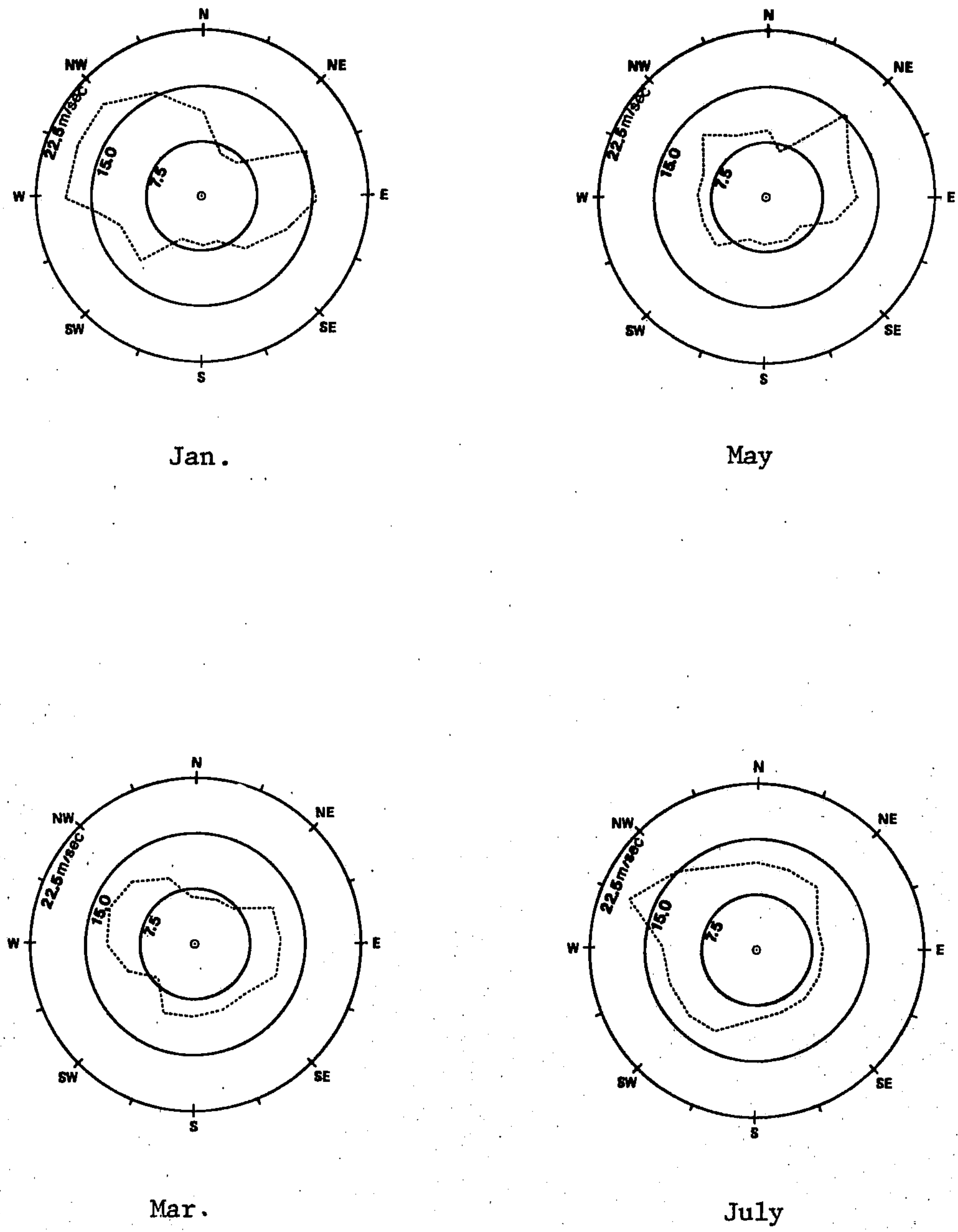
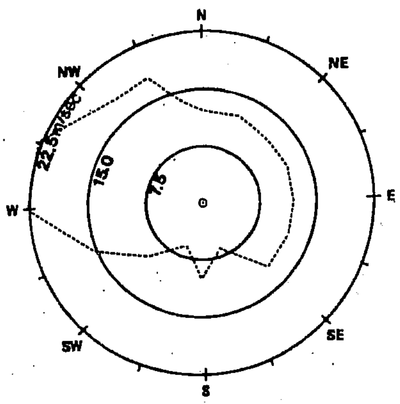
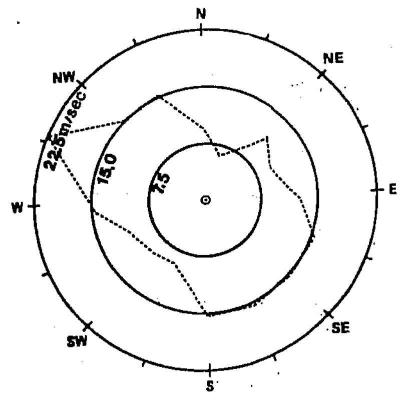


Figure 8.61 Roses of maximum wind speed by direction for Tuktoyaktuk, N.W.T. (Limited data base).



Sept.



Nov.

Figure 8.61a Roses of maximum wind speed by direction for Tuktoyaktuk, N.W.T. (Limited data base).

Table 8.56. Percent frequency wind speed ranges by month for Tuktoyaktuk. Based on limited data between 1970-1976 (original units).

MONTH	WIND SPEED (mph)									
	Calm	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47-54
Jan.	7.7	4.3	16.1	24.1	28.1	9.1	6.4	3.0	.8	
Feb.	10.7	5.1	24.9	30.3	15.3	10.3	3.2	.4		
Mar.	7.6	5.6	25.5	31.6	21.6	6.4	2.0			
Apr.	7.6	6.2	25.8	35.3	18.4	5.9	.9			
May	3.3	5.3	23.6	31.5	27.1	8.1	.9	.1		
Jun.	1.2	2.9	18.2	42.2	28.3	6.4	.8			
Jul.	1.8	3.5	19.6	38.7	25.4	8.8	1.7	.3	.1	
Aug.	2.8	3.2	20.9	36.9	24.2	8.4	2.5	.8	.2	
Sep.	5.7	2.6	15.2	30.5	27.8	12.6	4.4	.5	.5	.1
Oct.	6.2	3.8	19.2	29.2	23.5	13.2	4.6	.3		
Nov.	10.7	6.0	21.6	31.6	19.5	5.7	3.1	1.3	.2	.1
Dec.	13.2	6.3	24.8	28.7	15.8	7.2	2.9	10.6	.2	

Irregular Data Base: Jan 1974-76; Feb/Mar/May 1971-76; Apr/Jun/Jul/Aug/Sep 1970-76; Oct-Dec 1973-76.

Table 8.57. Percent frequency wind speed by month for Inuvik. Based on data from 1962-1971 (original units).

MONTH	WIND SPEED (mph)									
	Calm	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47-54
Jan.	30.1	18.8	31.2	13.1	5.4	1.0	.3			
Feb.	27.3	18.8	37.0	13.3	3.2	.1	.1			
Mar.	16.7	14.6	38.1	22.5	7.1	.7	.1	.1		
Apr.	11.0	9.5	39.6	35.3	11.9	.7	.1			
May	5.6	9.4	38.7	34.1	11.3	.8	.1			
Jun.	4.6	7.0	34.0	40.0	14.2	.6	.1			
Jul.	6.1	9.2	38.3	34.2	11.6	.7	.1			
Aug.	7.7	9.9	40.1	30.0	11.2	.9	.1	.1		
Sep.	10.8	9.2	41.6	29.2	8.5	.4	.1			
Oct.	12.3	14.1	44.3	22.5	6.3	.3	.1			
Nov.	28.4	18.5	33.5	14.1	4.7	.8	.1	.1		
Dec.	30.0	19.8	30.8	12.7	5.3	.9	.3	.1	.1	

8.5.3 Temperatures

Table 8.58 shows the extreme and average temperatures for Komakuk, Shingle Point, Fort McPherson, Aklavik and Tuktoyaktuk. The effect of the Beaufort Sea and mountains on the temperature regime can be seen along the Yukon coast. Average values at Komakuk and Shingle Point are quite similar although summer temperatures are noticeably warmer at Shingle Point. This is likely due to the higher frequency of warmer southwest winds. As one moves inland the summer averages and maxima show marked increases with Fort McPherson having an average July temperature of 14.8 compared to 7.3 at Komakuk. Wintertime averages and minima are lower as distance from the coast increases. Tuktoyaktuk, being more exposed to the open sea, shows lower summer temperatures than Aklavik. However, readings are still above those along the Yukon coast due to a higher frequency of southerly winds.

8.5.4 Precipitation

Tables 8.59 and 8.60 show mean monthly rainfall and snowfall at selected sites along the coast and the lower Mackenzie Valley. The highest amounts occur southwest of the Mackenzie Delta with a decrease occurring to the northeast and along the Yukon coast. Greatest 24-hour snowfall and rainfall are presented in Tables 8.61 and 8.62. Amounts decrease toward the northeast; however maximum rainfall remains relatively high along the Yukon coast which would be a result of the mountains enhancing the precipitation.

8.5.5 Visibility

Table 8.63 presents percent frequency of visibility by range for Tuktoyaktuk. Information for other areas was not available for comparison but some general comments can be made. The frequency of onshore winds along the Yukon coast is higher than that at Tuktoyaktuk. Thus, during much of the year, the frequency of fog would likely be slightly higher than that at Tuktoyaktuk, while less fog would be expected at inland locations. During the winter months, the main restriction to visibility is ice fog and/or ice crystals. As the number of personnel and wintertime activity increases in the Tuktoyaktuk area one would expect a corresponding increase in the amount of ice fog observed. Continuous ice breaking during the winter months would also increase the amount of fog and ice fog observed offshore. Onshore winds could then carry this over the settlement or airport, possibly hampering air or sea operations.

Table 8.58. Monthly average and extreme temperatures.(°C)

Komakuk 10-14 Years Data

	J	F	M	A	M	J	J	A	S	O	N	D	YR
XTRM MAX	8.3	-0.6	2.8	7.8	15.0	25.6	27.2	25.6	23.3	13.3	8.3	7.2	27.2
AVERAGE	-24.3	-27.9	-24.7	-17.6	-5.1	2.9	7.3	5.9	0.8	-8.4	-17.6	-23.9	-11.1
XTRM MIN	-46.7	-47.8	-47.7	-35.6	-25.0	-9.4	-5.6	-7.8	-17.8	-29.4	-38.9	-44.4	-47.8

Shingle Point 10-14 Years Data

	J	F	M	A	M	J	J	A	S	O	N	D	YR
XTRM MAX	1.7	0.6	5.0	8.9	20.0	28.3	27.8	28.9	18.3	15.0	7.8	1.7	28.9
AVERAGE	-24.9	-27.3	-23.5	-16.3	-4.2	5.0	10.6	8.2	1.7	-7.9	-18.9	-24.1	-10.1
XTRM MIN	-51.1	-52.2	-42.2	-38.9	-30.6	-8.9	-6.7	-5.6	-13.3	-30.0	-42.8	-47.2	-52.2

Fort McPherson 30 years Data

	J	F	M	A	M	J	J	A	S	O	N	D	YR
XTRM MAX	8.9	10.0	9.4	16.7	28.3	31.1	32.2	33.3	27.2	17.2	8.9	8.3	33.3
AVERAGE	-29.4	-27.9	-21.5	-11.1	1.4	11.5	14.8	11.4	3.5	-7.0	-20.3	-26.9	-8.5
XTRM MIN	-55.6	-55.0	-48.9	-44.4	-25.6	-6.7	0.0	-6.7	-15.0	-37.2	-46.7	-50.0	-55.6

Aklavik 30 Years Data

	J	F	M	A	M	J	J	A	S	O	N	D	YR
XTRM MAX	6.7	9.4	9.4	13.9	25.0	30.0	33.9	31.1	24.4	12.8	6.7	10.0	33.9
AVERAGE	-28.6	-27.4	-22.3	-12.7	-0.4	9.6	13.8	10.8	3.6	-7.1	-19.5	-27.3	-9.0
XTRM MIN	-50.6	-52.2	-48.9	-42.2	-25.6	-6.7	-1.1	-3.9	-11.1	-30.0	-45.6	-47.8	-52.2

Tuktoyaktuk 10-14 Years Data

	J	F	M	A	M	J	J	A	S	O	N	D	YR
XTRM MAX	-3.9	-2.8	1.1	5.6	18.9	27.2	27.8	30.0	21.7	10.0	6.1	-2.2	30.0
AVERAGE	-27.2	-29.2	-24.9	-16.9	-4.6	4.7	10.3	8.7	2.3	-6.9	-19.3	-25.2	-10.7
XTRM MIN	-45.0	-50.0	-41.7	-38.3	-27.2	-11.1	-2.2	-1.7	-10.6	-31.1	-38.9	-43.9	-50.0

Table 8.59. Mean monthly rainfall (mm).

MONTH	Komakuk	Shingle Point	Aklavik	Inuvik	Fort McPherson	Tuktoyaktuk	Nicholson Peninsula
Jan.	.3	0.0	0.0	0.3	0.0	0.0	0.0
Feb.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr.	0.0	0.0	T	T	0.3	T	0.0
May	1.0	2.3	1.5	5.1	2.8	1.5	1.8
Jun.	9.4	18.0	17.3	10.7	22.1	17.3	8.1
Jul.	27.9	39.1	33.8	34.0	26.4	33.8	20.6
Aug.	25.9	35.8	35.1	38.4	42.7	35.1	31.0
Sep.	7.4	13.5	10.4	10.9	19.8	10.4	10.7
Oct.	0.5	1.5	1.0	2.0	1.3	1.0	0.8
Nov.	0.5	0.0	0.0	T	0.0	0.0	0.0
Dec.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	72.9	110.2	99.1	101.4	115.4	99.1	73.0

Table 8.60. Mean monthly snowfall (cm).

MONTH	Komakuk	Shingle Point	Aklavik	Inuvik	Fort McPherson	Tuktoyaktuk	Nicholson Peninsula
Jan.	4.6	9.4	11.9	21.6	20.6	5.1	2.3
Feb.	2.3	3.0	10.7	11.9	19.6	5.3	2.3
Mar.	3.0	6.9	11.2	18.5	25.7	3.6	3.3
Apr.	2.5	8.9	8.1	15.0	23.1	4.8	3.6
May	2.8	6.1	6.6	14.0	12.2	4.1	2.0
Jun.	2.0	1.3	1.0	2.3	0.5	3.3	2.0
Jul.	0.3	0.0	T	0.3	0.0	0.3	T
Aug.	5.1	3.6	1.0	4.3	0.8	0.5	0.8
Sep.	5.6	8.4	9.7	11.4	11.7	4.1	4.3
Oct.	14.5	22.6	31.2	34.5	46.5	11.9	10.2
Nov.	5.3	8.9	21.1	18.5	35.6	5.1	4.1
Dec.	3.6	4.1	24.4	21.6	25.9	7.6	3.0
Total	51.6	83.2	136.9	173.9	222.2	55.7	37.9

Table 8.61. Greatest 24-hour snowfall (cm).

MONTH	Komakuk	Shingle Point	Aklavik	Inuvik	Fort McPherson	Tuktoyaktuk	Nicholson Peninsula
Jan.	10.2	15.2	20.3	11.4	17.8	10.2	5.1
Feb.	3.0	5.1	25.4	13.7	15.2	7.6	5.1
Mar.	2.5	10.2	25.4	13.0	15.2	6.4	5.1
Apr.	12.4	14.0	25.4	17.8	22.9	8.9	5.1
May	7.6	12.7	10.7	24.9	24.1	5.1	2.5
Jun.	6.9	2.5	20.8	10.2	5.1	11.4	10.2
Jul.	1.5	0.0	1.0	1.3	T	4.1	1.3
Aug.	15.2	7.6	14.5	22.6	10.7	3.6	7.6
Sep.	7.6	12.7	16.0	12.2	27.2	12.7	7.6
Oct.	7.6	14.0	18.8	13.5	35.6	6.4	6.9
Nov.	7.6	17.8	20.8	10.4	17.8	7.6	8.1
Dec.	10.2	7.6	15.2	12.2	20.3	6.6	2.8

Table 8.62. Greatest 24-hour rainfall (mm).

MONTH	Komakuk	Shingle Point	Aklavik	Inuvik	Fort McPherson	Tuktoyaktuk	Nicholson Peninsula
Jan.	1.3	0.0	0.0	1.5	0.0	0.0	0.0
Feb.	0.0	0.0	0.0	T	0.0	0.0	0.0
Mar.	0.0	0.0	T	T	T	0.0	0.0
Apr.	0.0	T	0.8	0.3	5.1	T	T
May	T	7.6	50.8	19.3	18.5	12.4	7.6
Jun.	28.7	12.7	29.7	14.0	37.3	19.1	18.3
Jul.	44.5	27.9	40.9	22.1	66.0	20.3	27.9
Aug.	44.5	33.5	44.2	33.0	50.8	29.5	20.3
Sep.	10.4	22.9	14.7	9.7	28.2	12.7	11.9
Oct.	4.3	12.7	6.9	13.2	9.9	2.8	8.4
Nov.	6.9	0.0	T	0.8	T	1.0	0.0
Dec.	0.0	0.0	0.0	0.0	3.8	0.0	0.0

Table 8.63. Tuktoyaktuk percent frequency for visibility ranges (km) 1970 - 1979.

Month/Range	0 to .7	.8 to 1.6	1.6 to 3.1	3.2 to 4.7	4.8+
Jan.	4.3	1.8	2.8	2.1	89.0
Feb.	1.9	2.4	3.9	3.5	88.2
Mar.	1.2	1.6	3.5	2.1	91.6
Apr.	1.4	1.8	3.3	1.8	91.7
May	3.5	1.7	2.6	1.3	90.9
Jun.	2.0	2.4	2.2	1.6	91.8
Jul.	1.1	.9	.8	.8	96.4
Aug.	1.2	.8	1.2	.4	96.4
Sep.	2.4	1.3	2.1	.8	93.4
Oct.	1.6	1.1	4.8	3.1	89.4
Nov.	.7	2.0	4.3	2.8	90.2
Dec.	1.8	1.9	2.8	2.1	91.4

8.5.6 Blowing Snow

Table 8.64 shows the percent frequency of blowing snow at Inuvik for the period 1962-1971. Similar data were not available for the Yukon coast or Tuktoyaktuk although it is expected values would be greater in these areas due to a higher frequency of strong winds.

Table 8.64. Percent frequency of blowing snow for Inuvik (1962-71).

Jan.	Feb.	Mar.	Apr.	May.	Sep.	Oct.	Nov.	Dec.
10%	.6%	.8%	.8%	.2%	<.1%	.3%	.6%	1.5%

8.6 WESTERN ALASKAN WATERS MARINE AREA

Figure 8.62 shows a map of the western Alaskan waters with the gridpoint locations and marine regions.

8.6.1 Winds

(i) FNOC Gridpoint Results: In Figures 8.63 to 8.67 the wind roses for gridpoints GP14 to GP16 are shown. The annual wind roses show a prevalence of east to northeast winds for all gridpoints. For the seasonal roses, it can be seen that the January, May and September cases agree with the annual pattern, while the July pattern shifts to more south to west as the predominant directions.

The extreme wind data by month are shown in Figure 8.68. Here it may be seen that for all gridpoints there is a tendency for the strongest winds to be either approximately east to northeast or south to west. It is also of interest to note that in most cases the highest wind speeds occur from the seasonally predominant wind directions. However, there are exceptions to this, notably the May maximum speeds for gridpoints GP15 and GP16 from the west to west-southwest directions while the wind rose indicates an east to northeast wind as the dominant direction. Thus, the strongest wind speeds do not always occur from the direction of the highest frequency. Another point concerning the extreme winds is the tendency for the highest values to occur in the fall and winter seasons for all three gridpoints.

In Tables 8.65 to 8.67, the percentage frequencies for each of the wind speed ranges are shown by month. Here again the fall and winter months stand out as the windiest months while the summer months show the weakest winds. There appears to be little difference among the three points except for a tendency toward lighter winds for all months for gridpoint GP14.

In Figure 8.69, the annual wind speed durations are shown for each gridpoint. As is evident, there is a large range between the annual maximum and minimum 6-hour durations for the 33-year sample. It may be seen that gridpoints GP14 and GP15 show comparable durations with these in turn being larger than those for gridpoint GP16.

Return periods for the wind speeds and durations are shown in Figures 8.70 and 8.71. Again the stronger winter winds and lighter summer winds are evident from the speed return periods. Gridpoint GP14 exhibits the lowest speeds for a given return period while the other two points are nearly equal. As well, for a given return period, the durations for wind speeds greater than 20 to 25 m/s are greater for gridpoints GP15 and GP16. However, for less than 20 to 25 m/s wind speeds, longer durations occur for point GP16.

(ii) Marine Observations: In Figures 8.72 to 8.76, the wind roses for the marine areas M 1 and M 2 are shown. For area M 2, a preference toward east to northeast and westerly winds is evident. A comparison of the July and September wind roses for both marine area M 2 and gridpoint GP14 data shows similarities in the high east to

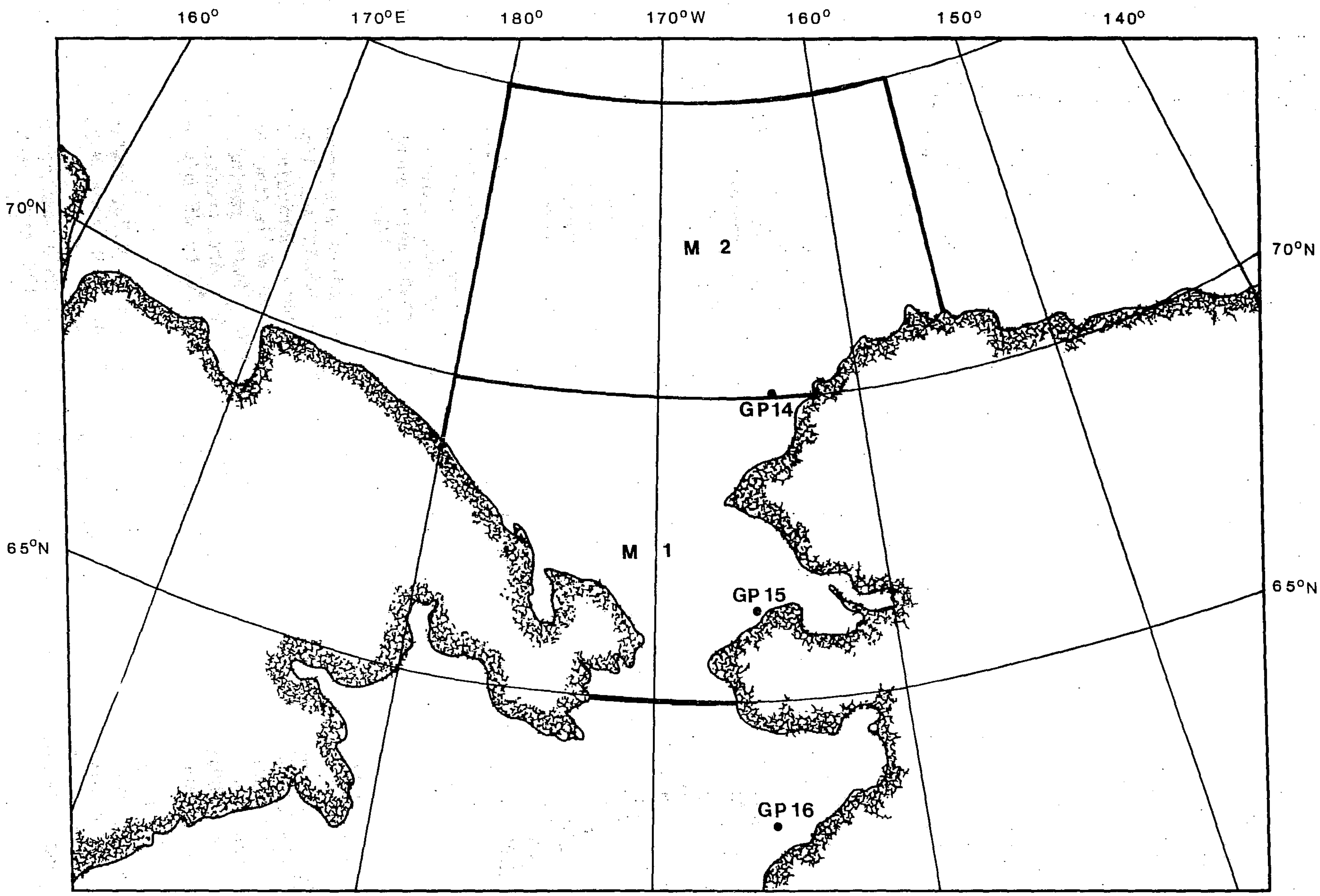


Figure 8.62 Western Alaska waters marine areas.

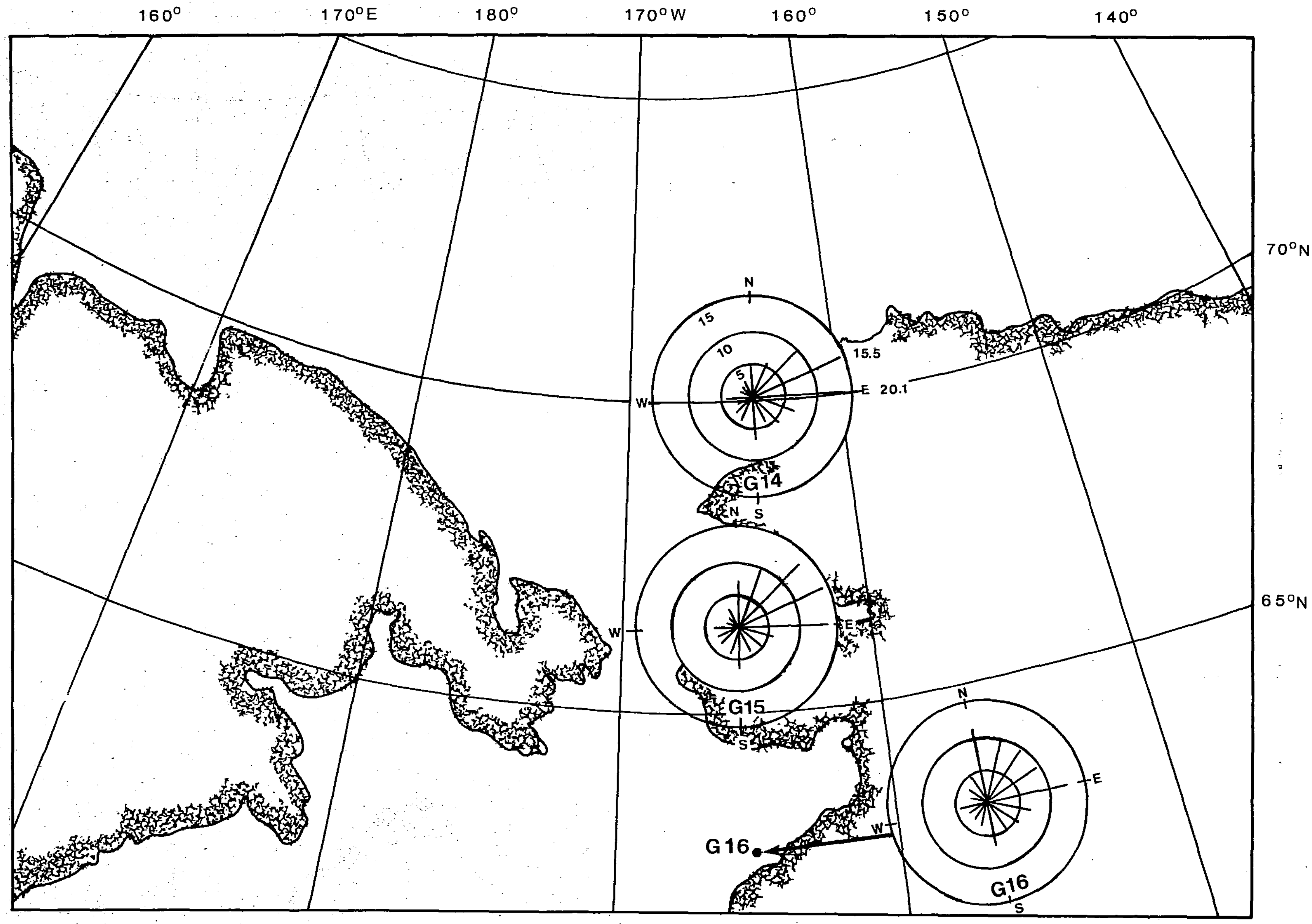


Figure 8.63 Gridpoint wind roses - annual.

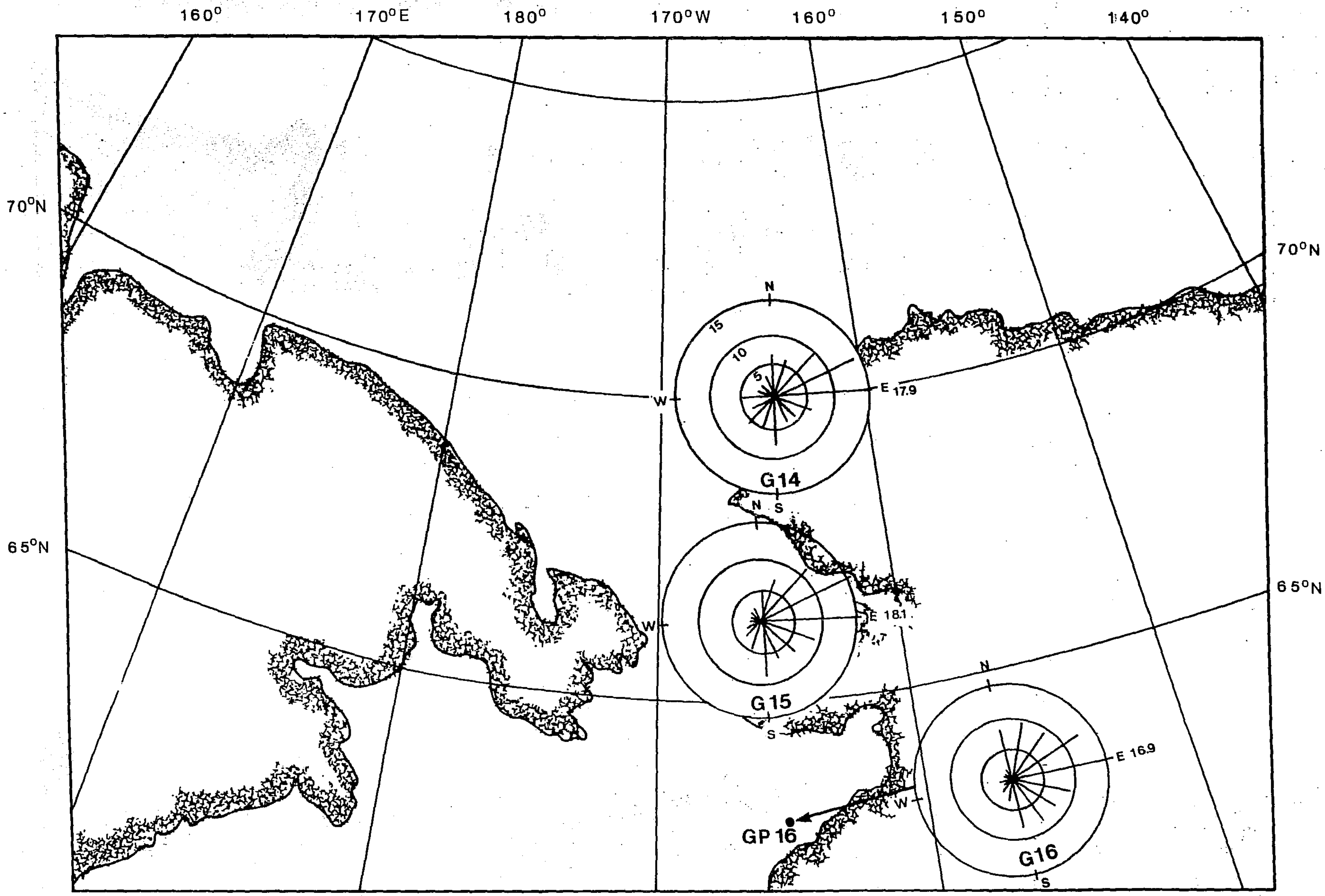


Figure 8.64 Gridpoint wind roses - January.

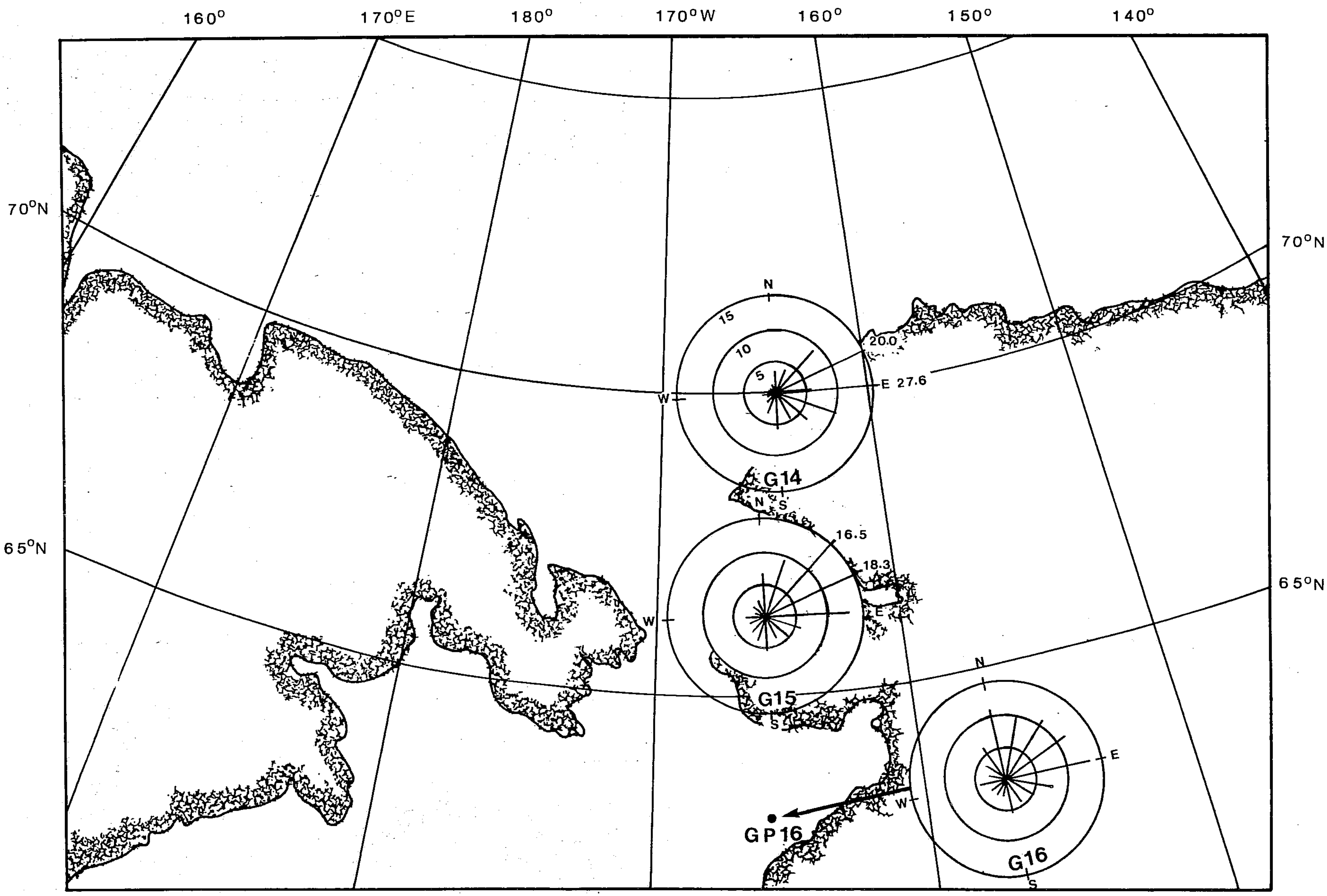


Figure 8.65 Gridpoint wind roses - May.

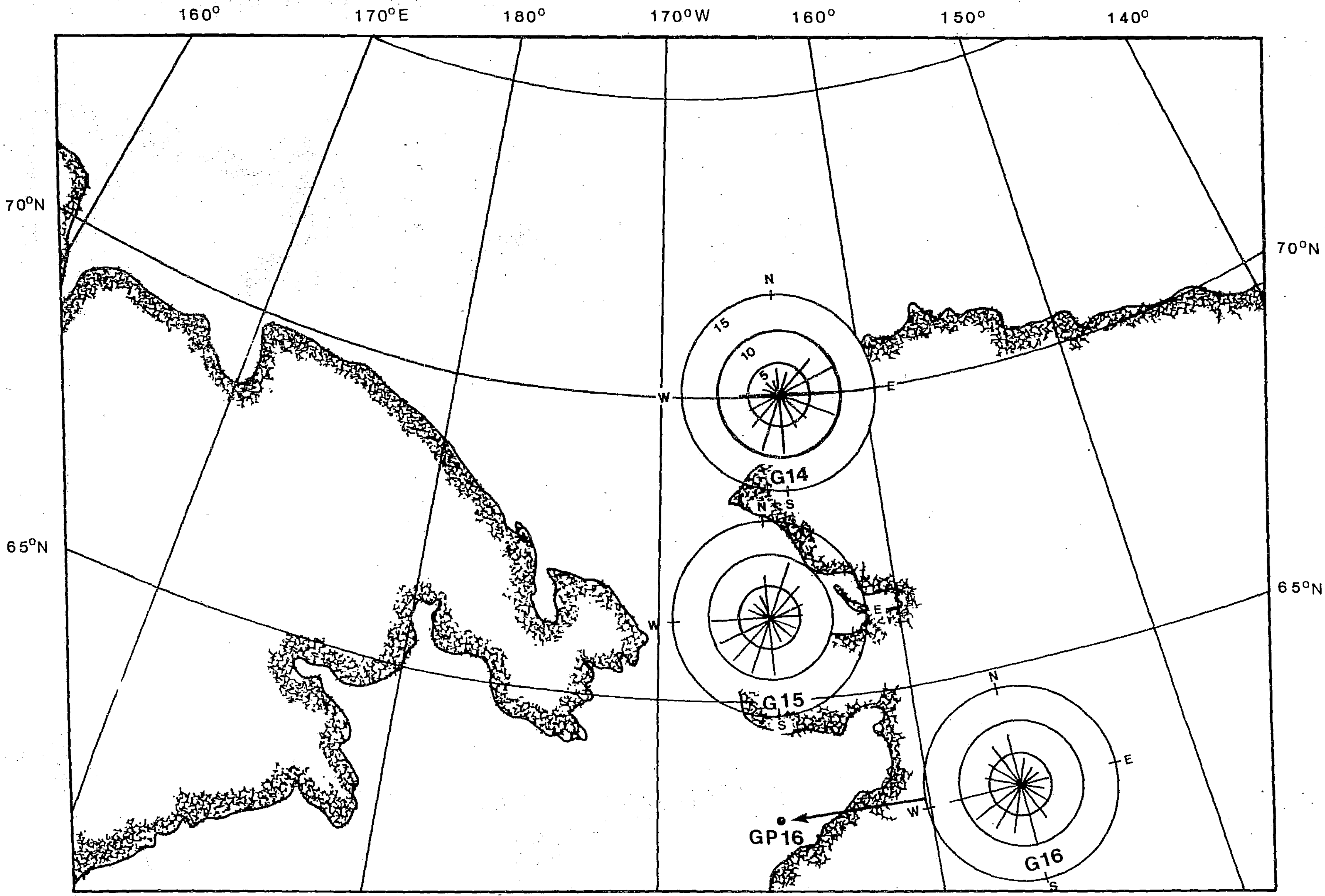


Figure 8.66 Gridpoint wind roses - July.

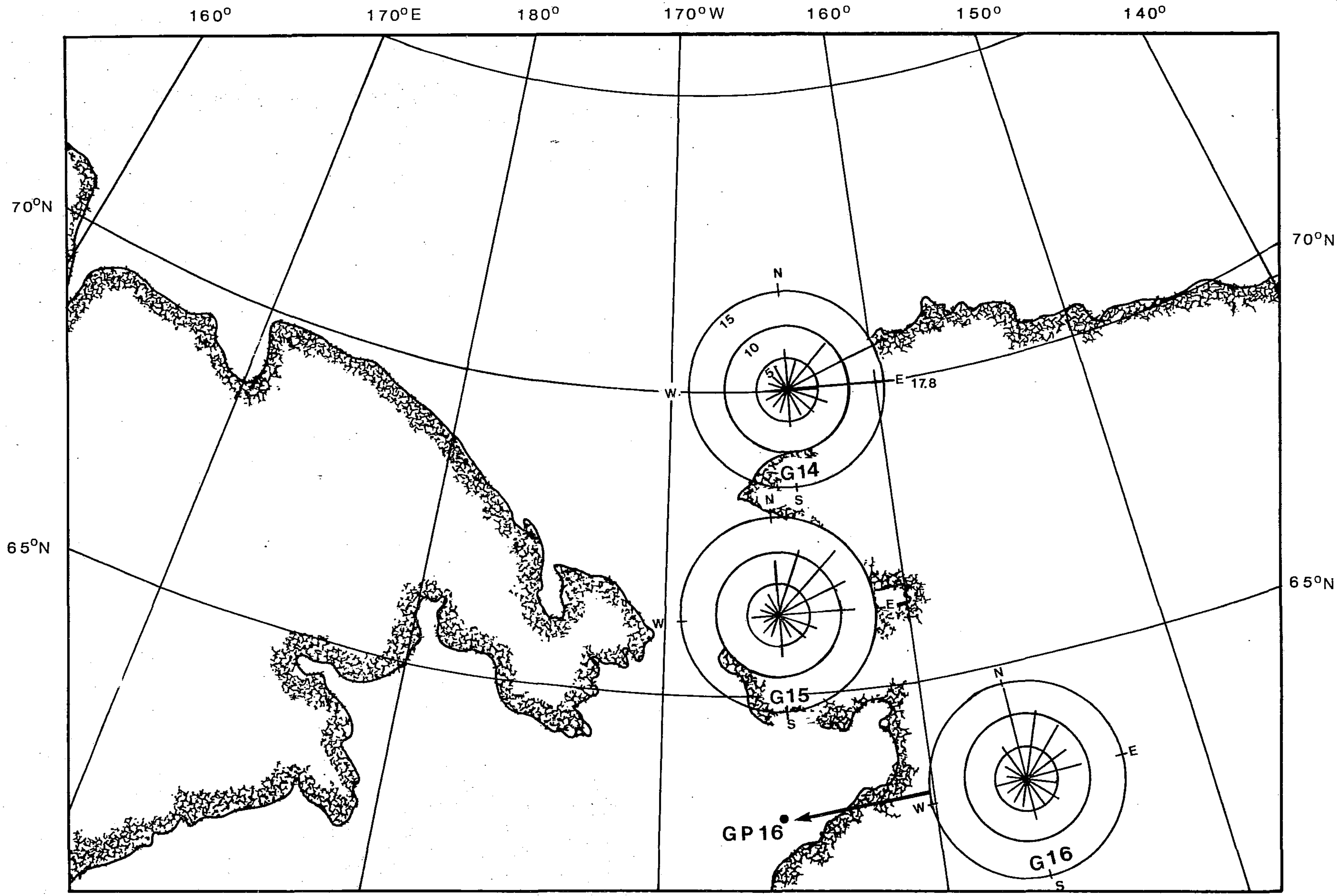


Figure 8.67 Gridpoint wind roses - September.

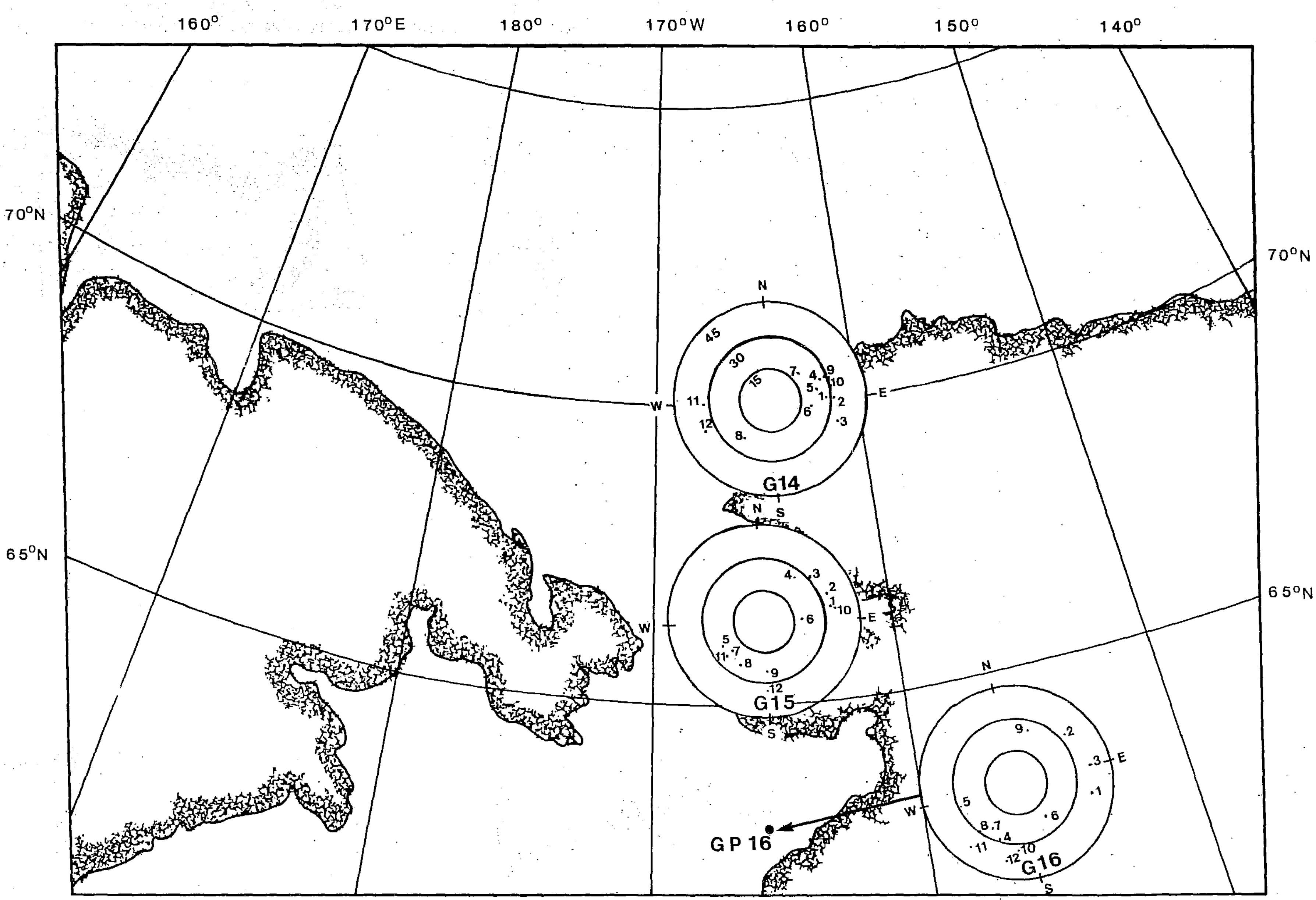


Figure 8.68 Direction and speed of maximum wind by month for Gridpoints 14-16. (Months shown by number; i.e., Jan = 1).

Table 8.65. Gridpoint wind speed percent frequency by month.

		Gridpoint GP16			(Metres/Second)			
MONTH	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
Jan.	11.1	26.7	34.5	19.9	6.7	1.1	-	-
Feb.	8.7	28.4	36.9	19.0	5.9	0.9	0.1	-
Mar.	17.1	34.7	31.1	13.1	3.4	0.5	0.1	-
Apr.	16.4	40.1	32.3	9.7	1.3	0.1	-	-
May	29.6	47.8	18.9	3.4	0.2	0.1	-	-
Jun.	43.3	46.8	9.3	0.5	0.1	-	-	-
Jul.	46.5	44.7	7.9	0.8	0.1	-	-	-
Aug.	36.6	47.1	14.5	1.6	0.1	0.1	-	-
Sep.	26.4	44.4	21.9	6.3	1.0	0.1	-	-
Oct.	17.0	39.3	29.5	10.9	3.1	0.2	-	-
Nov.	13.5	32.2	29.8	17.4	5.6	1.1	0.2	-
Dec.	11.0	29.9	34.6	18.4	4.9	1.0	0.1	-
Annual	23.2	38.6	25.0	10.0	2.7	0.4	-	-

Table 8.66. Gridpoint wind speed percent frequency by month.

		Gridpoint GP15			(Metres/Second)			
MONTH	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
Jan.	11.2	31.2	30.9	18.6	6.9	1.0	0.1	-
Feb.	10.3	30.4	35.6	17.0	5.4	1.2	0.1	-
Mar.	17.0	35.6	29.9	13.3	3.8	0.5	-	-
Apr.	18.8	38.2	31.0	10.5	1.4	0.1	-	-
May	31.2	43.7	21.3	3.6	0.2	-	-	-
Jun.	51.8	40.9	6.9	0.5	-	-	-	-
Jul.	51.1	41.2	7.3	0.4	-	-	-	-
Aug.	42.3	46.3	10.3	0.9	0.1	-	-	-
Sep.	27.7	46.3	21.0	4.5	0.6	-	-	-
Oct.	20.4	39.7	27.5	9.9	2.7	0.4	0.1	-
Nov.	14.1	33.6	29.9	16.6	4.8	0.8	0.2	-
Dec.	13.6	31.2	31.1	17.6	5.5	1.0	0.1	-
Annual	15.9	35.8	30.7	13.9	3.2	0.4	-	-

Table 8.67. Gridpoint wind speed percent frequency by month.

	Gridpoint GP14				(Metres/Second)			
MONTH	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40
Jan.	15.9	35.8	30.7	13.9	3.2	0.4	-	-
Feb.	12.6	37.6	34.4	12.4	2.6	0.3	-	-
Mar.	20.1	38.7	28.1	11.5	1.3	0.2	0.1	-
Apr.	22.9	40.2	26.5	8.2	2.0	0.1	-	-
May	28.9	46.5	21.1	3.2	0.4	-	-	-
Jun.	43.7	45.4	10.0	1.0	-	-	-	-
Jul.	44.3	46.3	9.2	0.2	-	-	-	-
Aug.	44.1	44.1	10.4	1.4	-	-	-	-
Sep.	30.8	43.9	20.8	4.1	0.3	0.1	-	-
Oct.	23.3	41.3	25.9	7.2	2.0	0.2	-	-
Nov.	16.2	36.1	29.1	13.8	3.9	0.8	0.1	-
Dec.	17.1	35.8	31.2	13.0	2.5	0.4	0.1	-
Annual	26.8	41.0	23.0	7.5	1.5	0.2	-	-

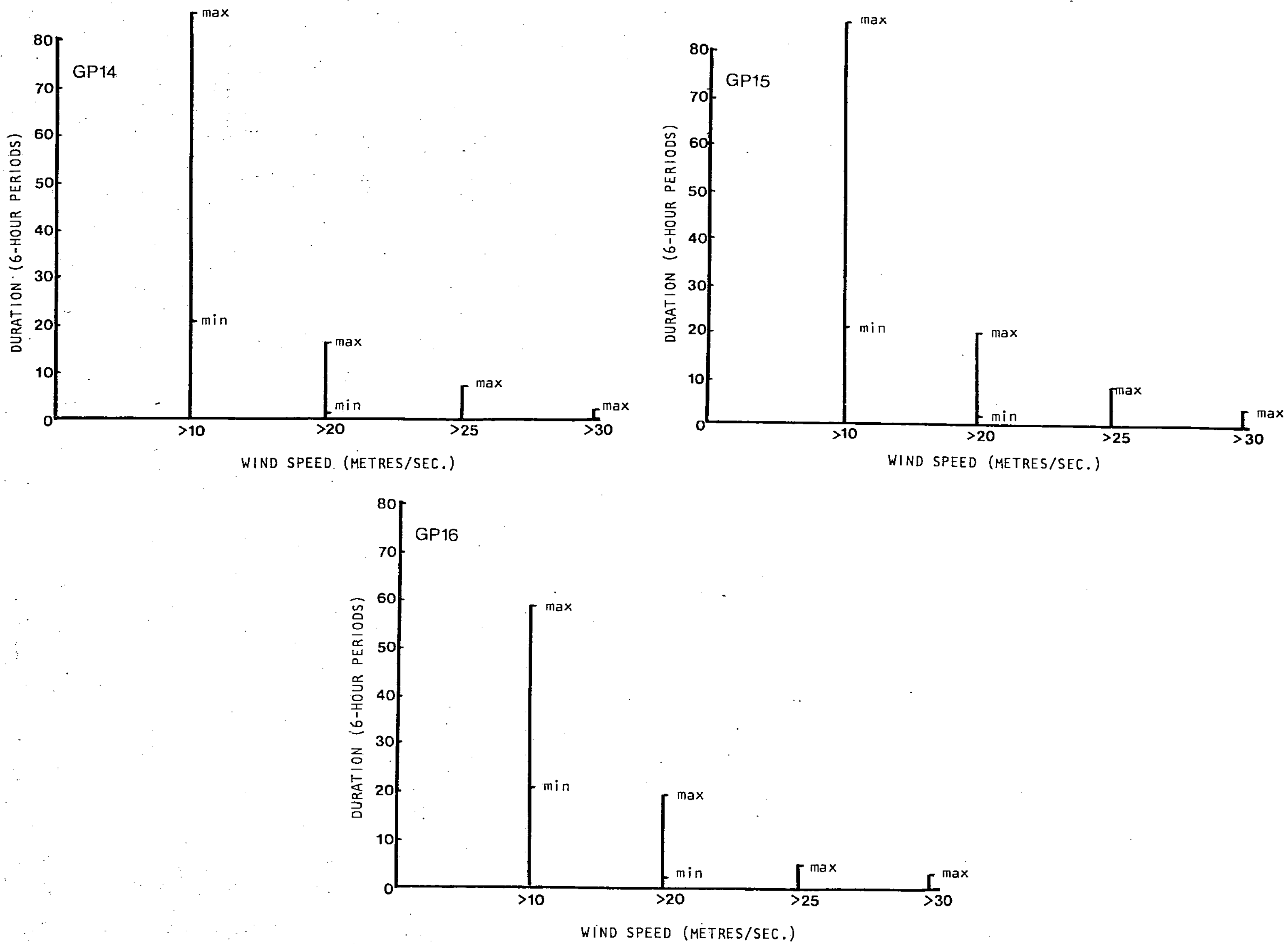


Figure 8.69 Duration (No. of 6-hr periods) for yearly maximum wind speed at Gridpoints 14-16. (The extreme event for any given year lies at or between the Max and Min points).

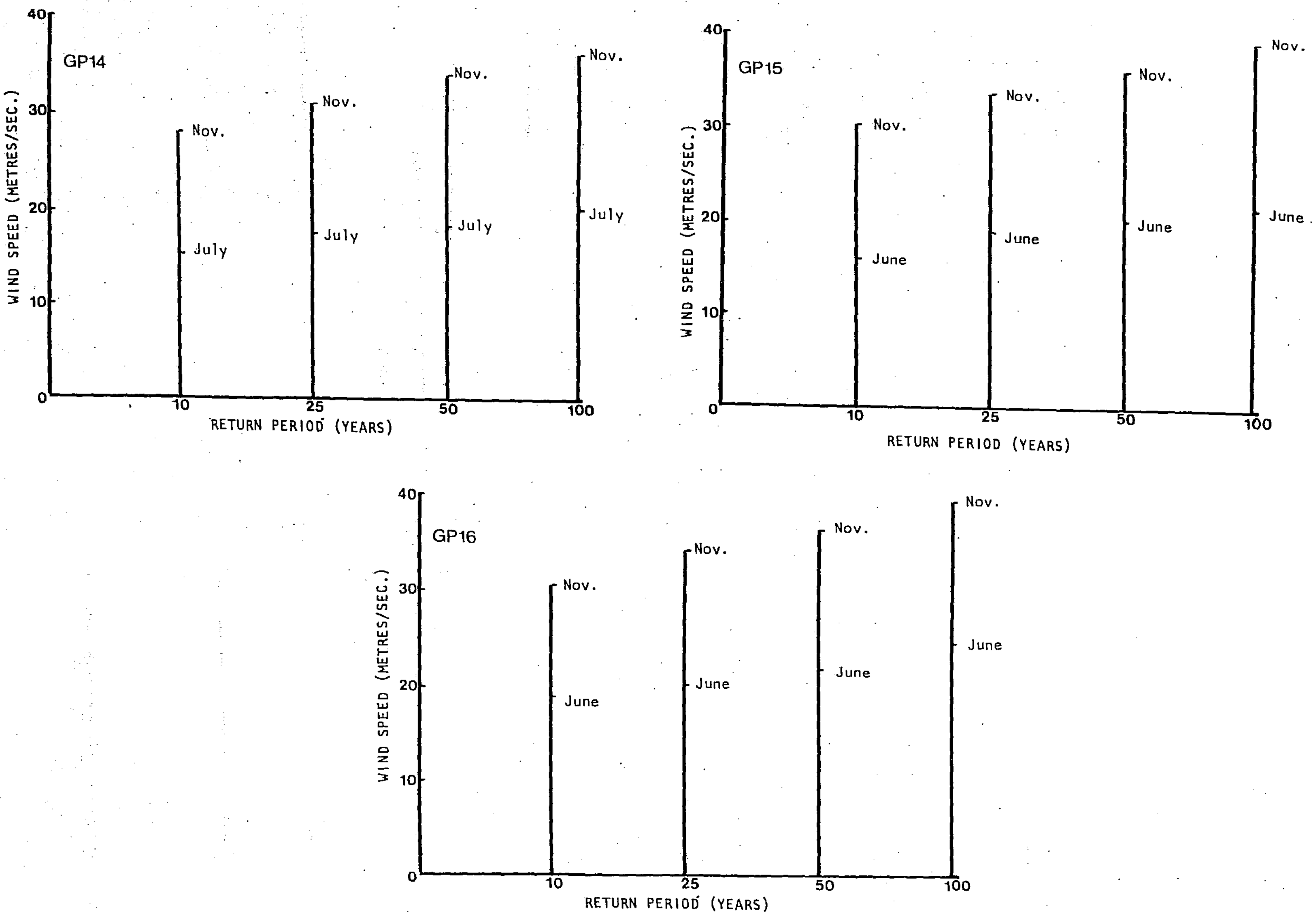


Figure 8.70 Return period for maximum wind speed by month for Gridpoints 14-16. (All values lie at or between the two points).

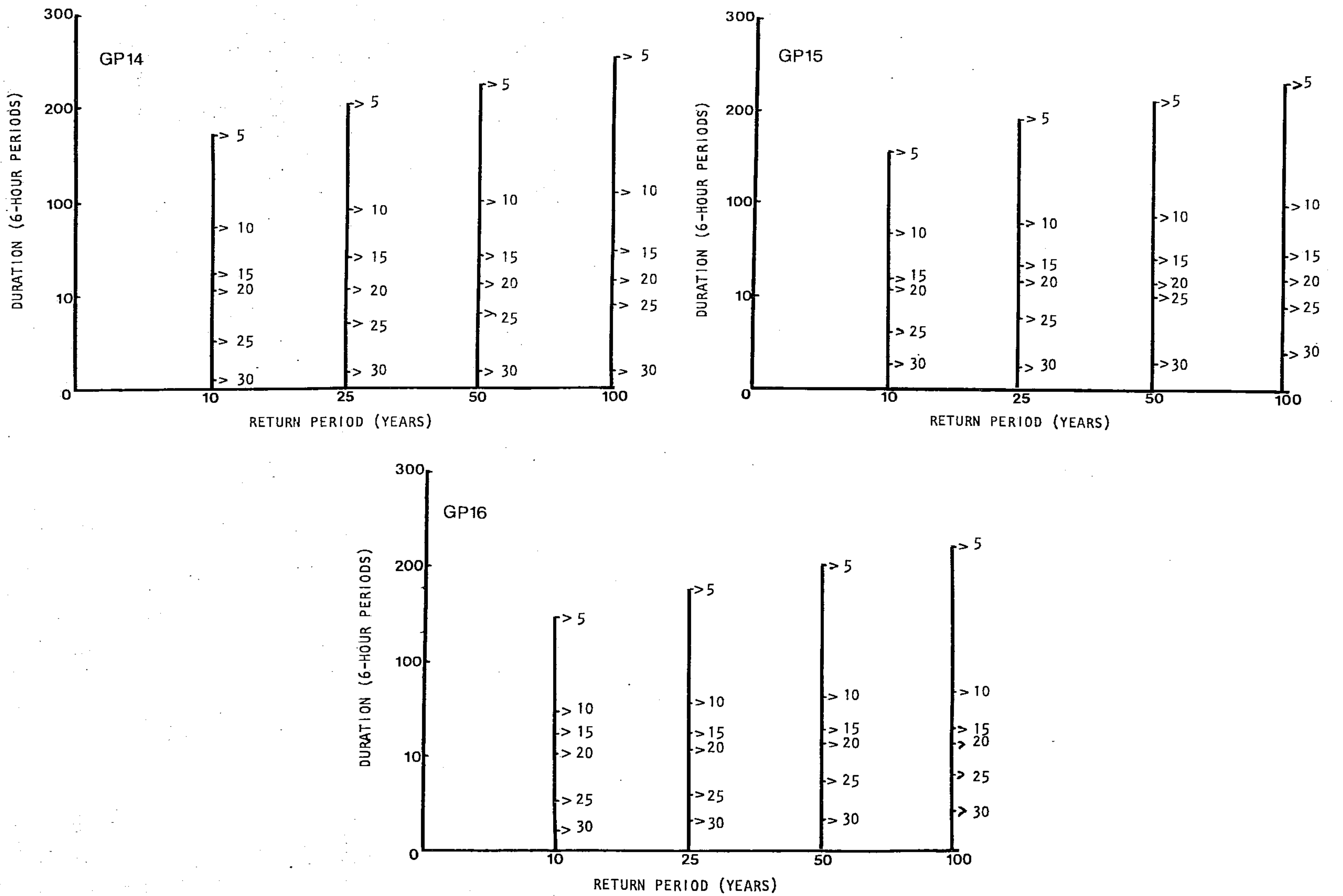


Figure 8.71 Return period for maximum wind speed events of specific duration for Gridpoints 14-16.

northeast percentages with poorer agreement in the westerly winds. For marine area M 1 the wind rose patterns are similar for June to September with the north and south directions being predominant. In the October rose, the northwest through northeast winds are more evident. Comparing the July area M 1 marine wind rose with gridpoints GP15 and GP16 for the same period, similarities in the south to southwesterly and northerly directions are evident while the agreement is poorer in the westerly direction. For September the agreement is good.

The marine area percentages of occurrence of wind speeds by month are shown in Tables 8.68 and 8.69. The higher percentages in the wind speeds greater than 11.0 m/s are notable for area M 1. Note also the increasing percentages for higher wind speeds in the late summer and fall periods.

Table 8.68. Percent frequency of wind speed for Marine Area M 2.

		Wind Speed (Metres/Second)			
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
May (144)	60	37	3	1	0
Jun. (68)	67	27	4	1	0
Jul. (1298)	55	39	7	*	0
Aug. (2741)	55	37	8	1	0
Sep. (1367)	44	40	13	2	*
Oct. (232)	57	32	10	1	*

* = < 1%.

Table 8.69. Percent frequency of wind speed for Marine Area M 1.

		Wind Speed (Metres/Second)			
MONTH (#OBS)	0.0-5.0	5.5-10.5	11.0-16.5	17.0-23.5	24+
May (80)	43	38	13	7	0
Jun. (267)	57	37	6	1	0
Jul. (1883)	46	42	10	1	*
Aug. (1923)	46	41	12	1	*
Sep. (1522)	43	40	15	2	*
Oct. (513)	32	40	21	6	*

* = < 1%.

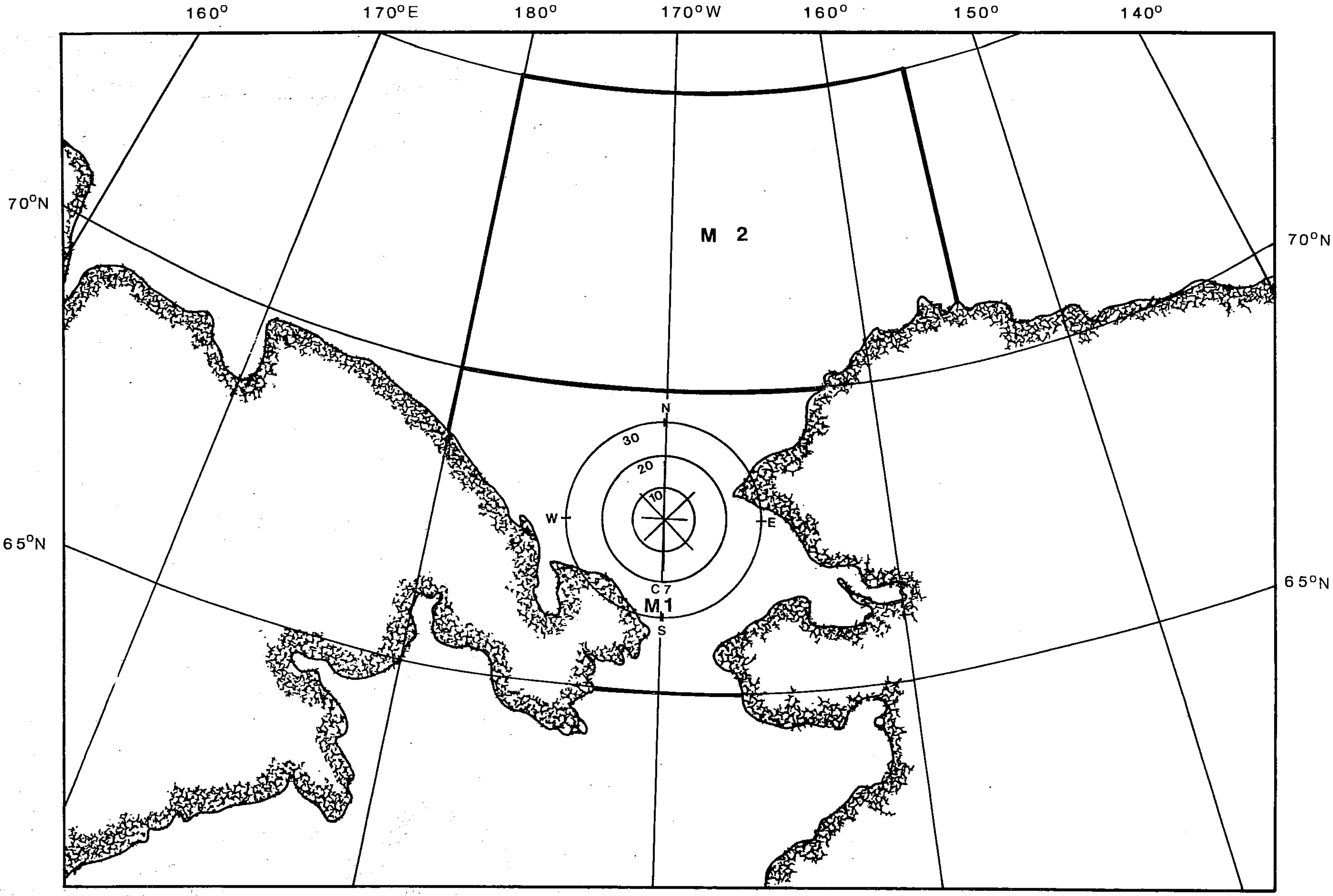


Figure 8.72 Marine Area wind rose - June.

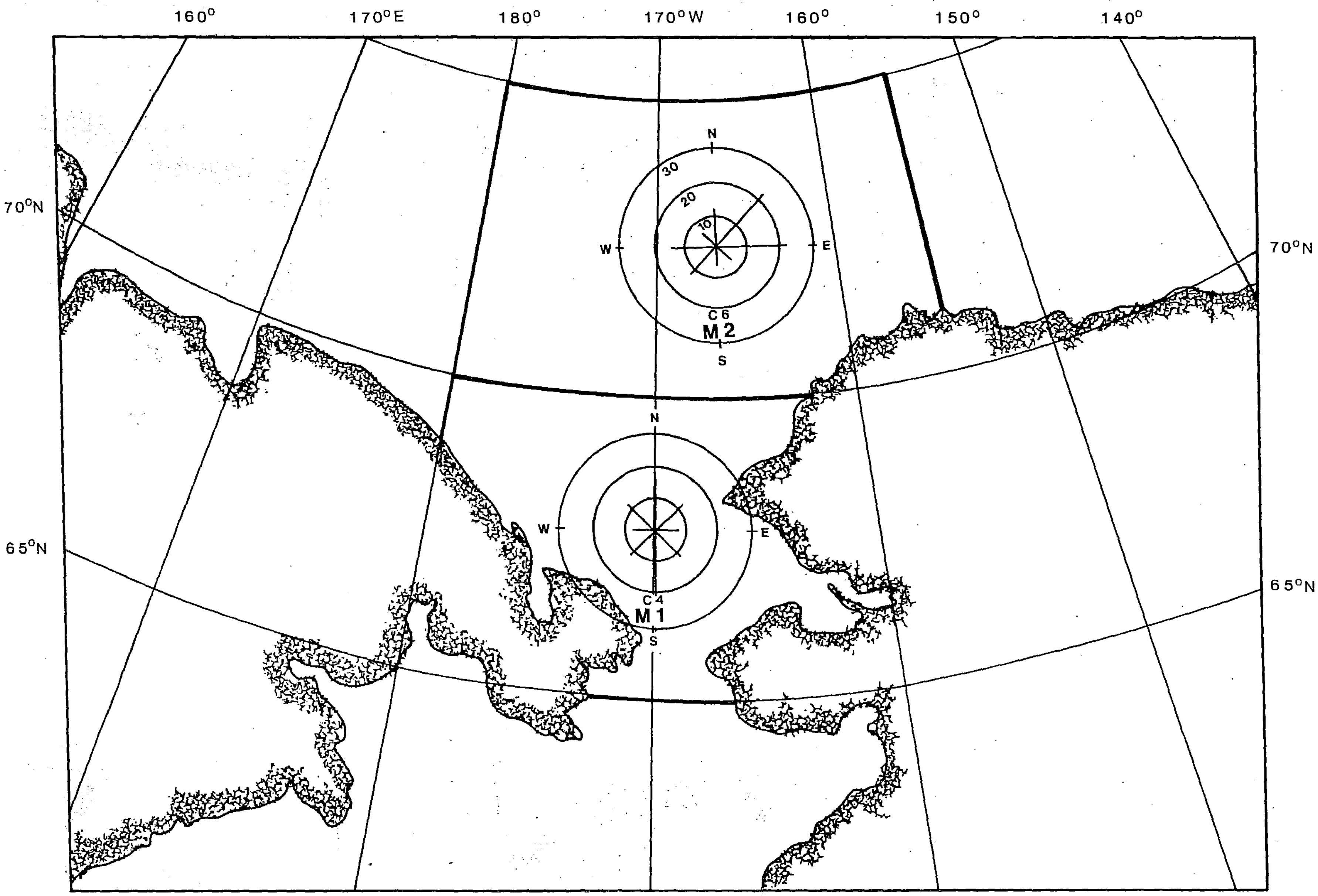


Figure 8.73 Marine Area wind roses - July.

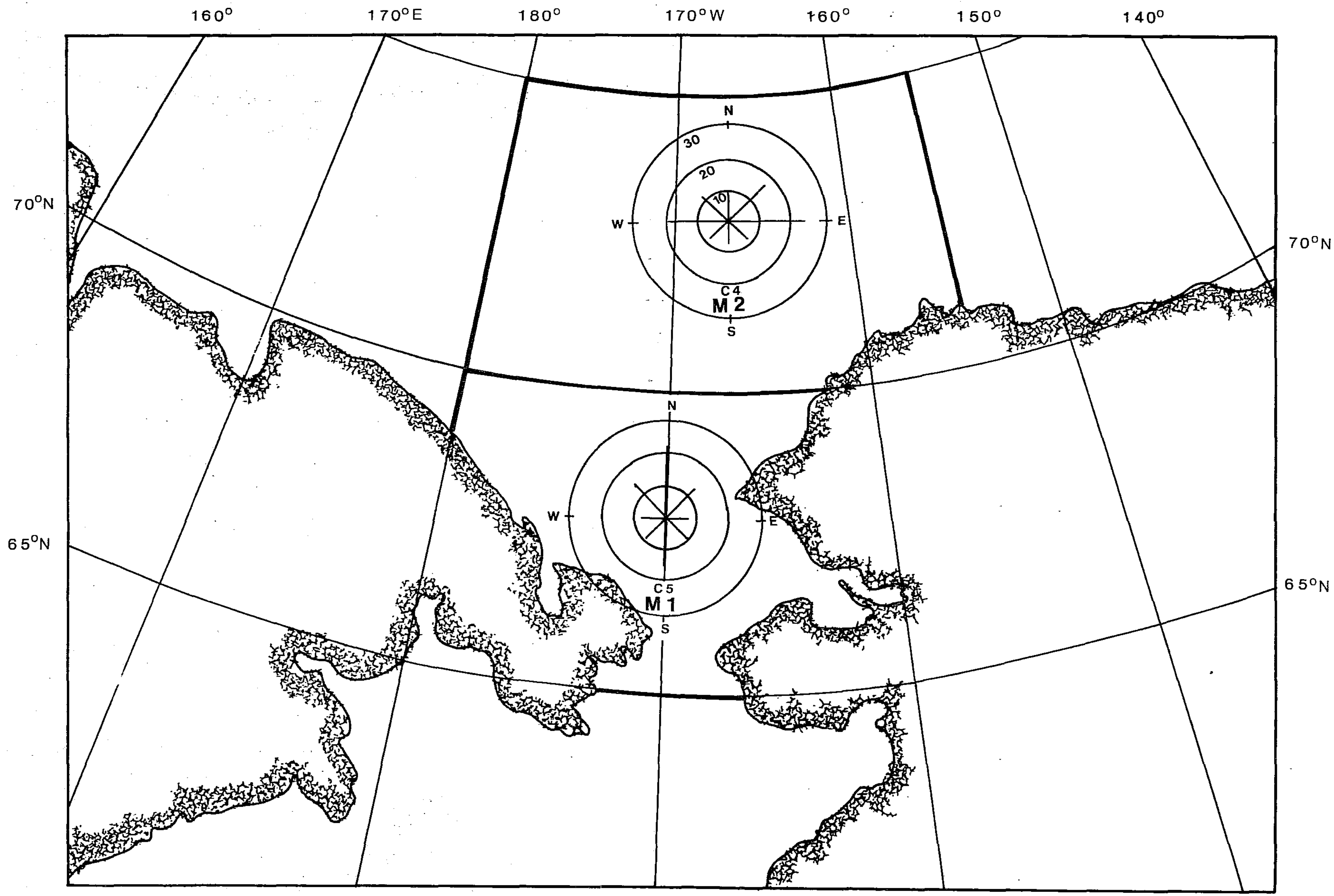


Figure 8.74   Marine Area wind roses - August.

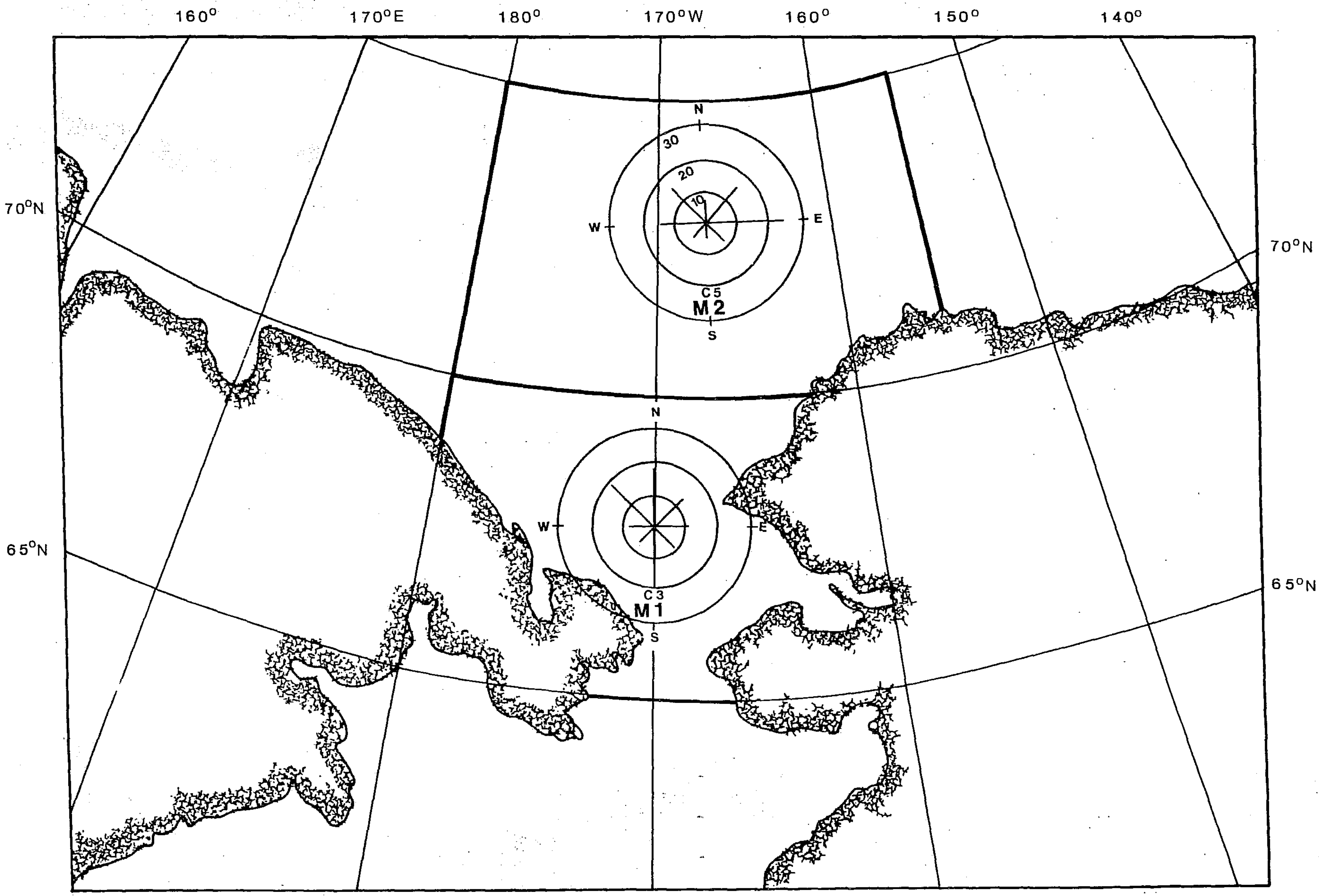


Figure 8.75 Marine Area wind roses - September.

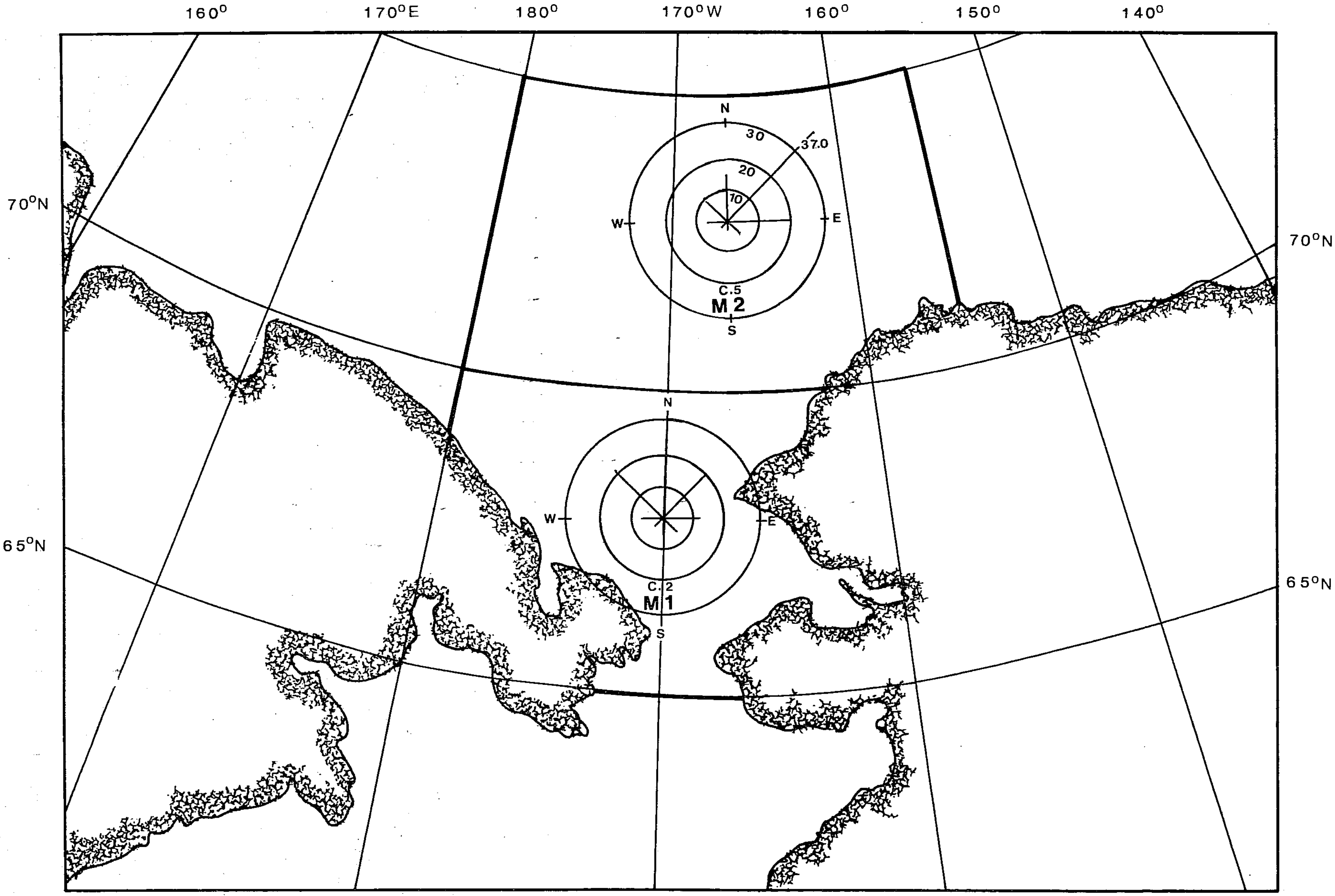


Figure 8.76 Marine Area wind roses - October.

8.6.2 Waves

In Tables 8.70 and 8.71, the percentage frequency of the wave height ranges (feet) are shown for the two western Alaskan waters marine areas. A tendency toward higher waves in the later summer and early fall is evident. Also, area M 1 shows the higher waves.

Table 8.70. Percent frequency of wave heights for Marine Area M 2 (after Brower, et al, 1977): original unit retained.

		Wave Heights (Feet)					
MONTH	(#OBS)	0-2	3-6	7-9	10-12	13-19	20+
Jul.	(427)	76	21	2	*		
Aug.	(1128)	76	21	3	1	*	
Sep.	(626)	61	32	5	1	1	*
Oct.	(81)	67	25	9			

* =<1%.

Table 8.71. Percent frequency of wave heights for Marine Area M 1 (after Brower, et al, 1977): original units retained.

		Wave Heights (Feet)					
MONTH	(#OBS)	0-2	3-6	7-9	10-12	13-19	20+
May	(42)	57	43				
Jun.	(160)	69	28	3			
Jul.	(1185)	49	42	7	1	*	
Aug.	(1107)	41	44	10	3	1	*
Sep.	(1033)	32	46	16	3	2	*
Oct.	(285)	29	41	24	5	*	1

* =<1%.

8.6.3 Visibilities

The percentage frequency of visibility ranges by month is shown in Tables 8.72 and 8.73 for marine areas M 1 and M 2. The higher percentages of the low visibility range less than 0.9 km during the early summer months is evident for both marine areas. This is likely caused by a mixture of ice and water during breakup or by puddling on the ice surface.

Table 8.72. Percent frequency of visibilities for Marine Area M 1 (after Brower, et al, 1977).

		Percent Frequency of Visibilities (Kilometers)					
MONTH	(#OBS)	< 0.9	0.9<1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
May	(83)	2	1	2	2	91	3
June	(282)	12	3	1	9	24	51
Jul.	(1758)	14	3	3	6	26	48
Aug.	(1809)	11	2	3	9	26	49
Sep.	(1338)	3	3	1	8	40	45
Oct.	(477)	3	2	8	10	42	35

Table 8.73. Percent frequency of visibilities for Marine Area M 2 (after Brower, et al, 1977)

		Percent Frequency of Visibilities (Kilometers)					
MONTH	(#OBS)	< 0.9	0.9 <1.9	1.9<3.7	3.7<9.3	9.3<18.5	18.5+
May	(146)	12	1	6	8	35	38
Jun.	(66)	9	5	4	10	28	44
Jul.	(1346)	19	6	5	8	31	31
Aug.	(2746)	10	4	4	9	35	38
Sep.	(1212)	8	3	6	8	50	35
Oct.	(175)	8	1	1	11	46	33

8.6.4 Freezing Spray

Freezing spray is generally a fall phenomenon since ice cover suppresses wave development during the winter and spring. Conditions favourable for freezing spray are most likely to develop between September and the time when ice begins to limit the fetch. The more extreme cases are also likely to occur behind systems moving northward across western Alaska or moving eastward across the Beaufort Sea. These situations frequently result in strong northerly winds moving cold air southward thus satisfying two conditions for freezing spray. For example a wind of 20 m/s and an air temperature of -5°C will produce an accumulation rate of about 10 cm/24 hrs if the water temperature is +3°C. The authors do not consider these values unrealistic, since air temperatures can drop to extreme values for October ranging from -24°C near Point Barrow to -12°C across the Bering Strait. Such extremes may have occurred during years when ice conditions were also heavier than average so it is not advisable to indiscriminately apply the nomograms to the extreme values for wind, air and sea temperatures.

8.6.5 Ice

For this section on ice over the western Alaskan marine area, the emphasis will be placed on the position of the main ice pack edge. Source of this information is the Climatic Atlas of the outer Continental Shelf Waters and Coastal Regions of Alaska. 1977. Volume III, by Brower and Searby. In Figures 8.77 to 8.79, these positions are shown with an ice concentration of one-eighth or greater defining the edge. No distinction as to type or age of the ice is considered. It should be noted that the period of data coverage for these figures is maximum from 1954 to 1970 with several time intervals having data periods considerably less. In particular, the information for the late May to late June period is very limited.

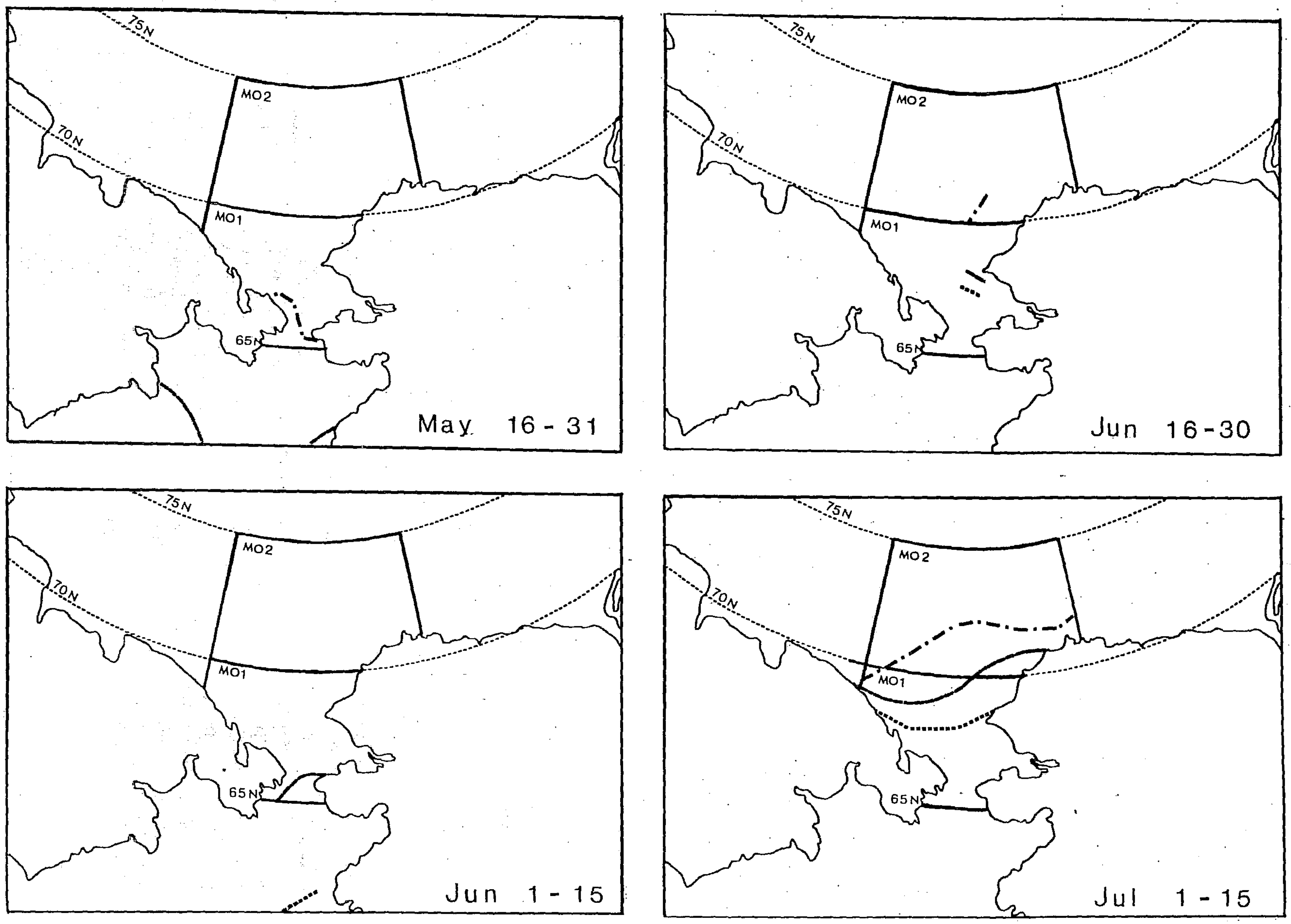


Figure 8.77 Edge of pack ice (after Brower and Searby, 1977).

median position of 15-day mean.
extreme south pack edge.
extreme north pack ice edge (1 octa).

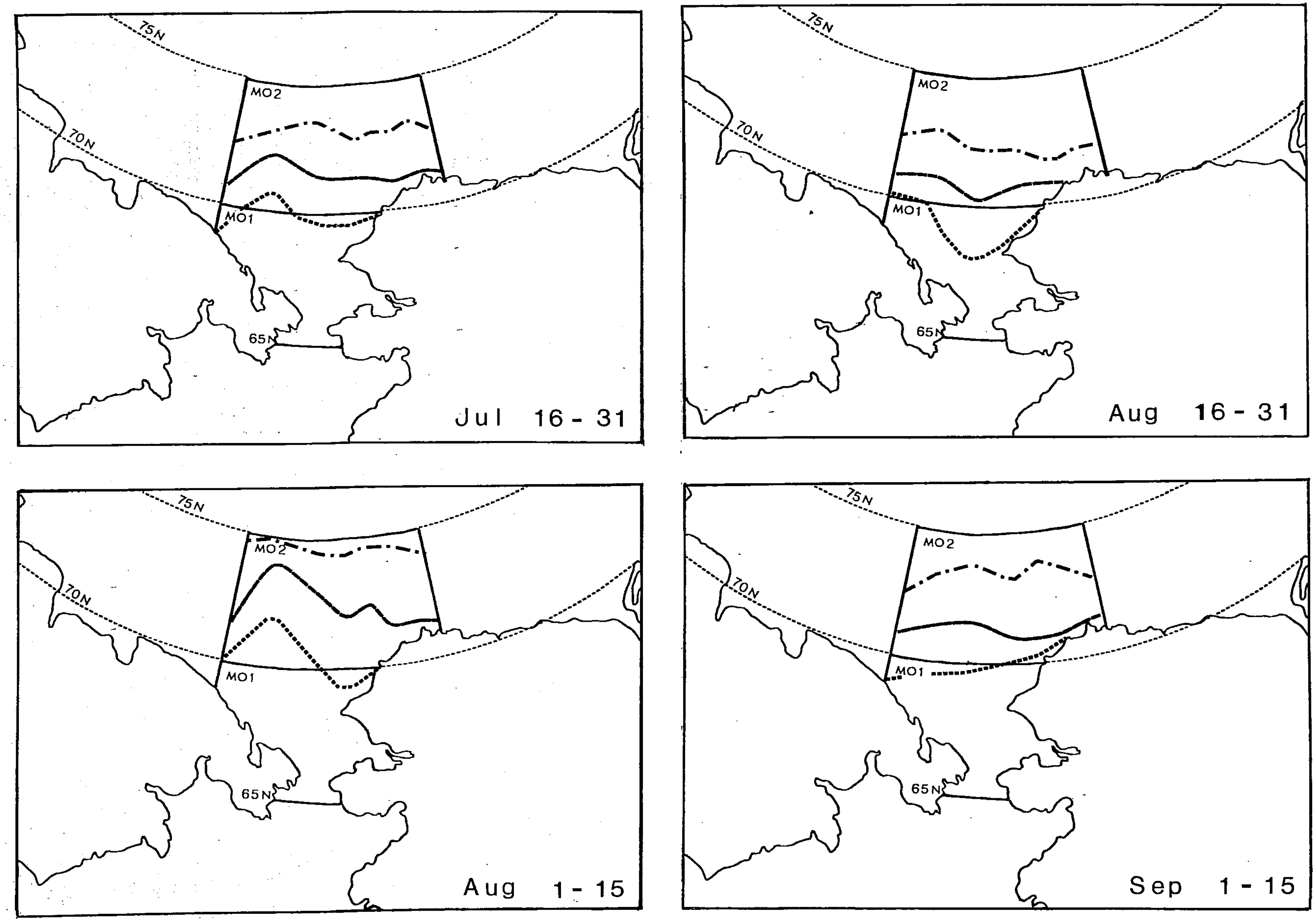


Figure 8.78 Edge of pack ice (after Brower and Searby, 1977).

median position of 15-day mean.
extreme south pack edge.
extreme north pack ice edge (1 octa).

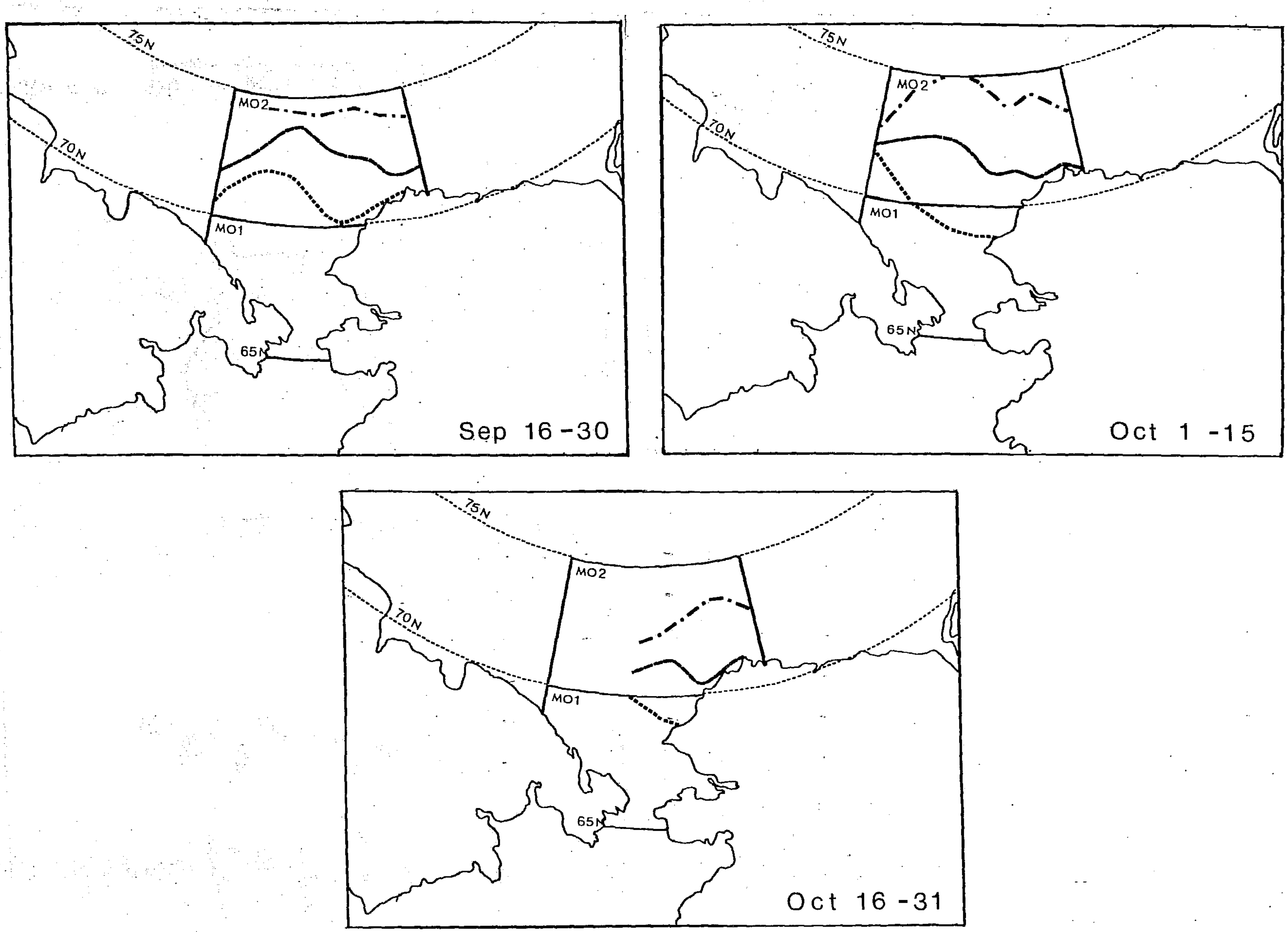


Figure 8.79 Edge of pack ice (after Brower and Searby, 1977).

median position of 15-day mean.
extreme south pack edge.
extreme north pack ice edge (1 octa).

9. SCENARIOS

9.1 INTRODUCTION

In this section scenarios will be developed showing some of the worst conditions along the northern section of the Alaskan shipping route as well as the route through the Northwest Passage. In addition, the Beaufort Sea production area will be examined in order to identify potential problem areas.

9.2 THE ALASKAN ROUTE

The worst shipping conditions along this route are expected to be encountered during those years in which the polar pack lies along or very near the coast from Point Barrow to Herschel Island. Table 8.55 presents observed ice conditions along this section of the coast for a period of 23 years. One important fact is that no trend is obvious in the ranking of the various years.

During a "bad ice year" tankers would be forced to operate through the southern edge of the polar pack. This would require navigation through an area containing multi-year ice, ice ridges and possibly portions of ice islands.

Even though such obstacles may have been observed and catalogued they could make navigation difficult. Wintertime transit could be further hampered by snow and blowing snow which, when combined with very low temperatures, could make outside activity dangerous if not impossible.

9.3 THE NORTHWEST PASSAGE ROUTE

As with the Alaskan route ice will present the main problem to year-round shipping through the Northwest Passage. One area of concern is the western portion of Viscount Melville Sound. Stasyshyn (1981) of Ice Reconnaissance Division of Atmospheric Environment Service revealed that in 1978 an ice ridge of considerable size was detected in eastern M'Clure Strait. Subsequent investigation showed that this ridge most likely developed when a 95-km wide area of new ice was compressed to 30 kilometres. The movement of this ridge was followed for two seasons and eventually it moved across the northern entrance to Prince of Wales Strait. The frequency of occurrence of such ridges is unknown but should such a pressure ridge block Prince of Wales Strait it could represent a major obstacle to marine traffic along the passage and may be a worst case. Such ridges in other areas of Viscount Melville Sound or Barrow Strait may not pose as great a problem due to the greater width of these channels.

In areas east of Barrow Strait, the main concern will be the detection and avoidance of icebergs rather than icebreaking. Waves and freezing spray will also be not as significant a problem in this area as compared to further south where waves are considerably larger.

9.4 BEAUFORT SEA PRODUCTION AREA

Once freeze-up has occurred the main problems are seen as the continuous cold and the occasional blizzard. Increased icebreaking activity will lead to an increase in ice fog because of additional combustion products and larger open water areas. This could be a potential problem on the production and loading atolls.

The summer and fall seasons bring problems associated with moving ice. Persistent onshore winds will result in a bad ice year. During such a year the production area can be subjected to intrusions of multi-year ice or possibly a piece of an ice island. Either of these may be sufficient to move a ship off station; however, the main threat may be from scouring damage to underwater facilities. A storm such as that of September 1970 could cause damage to facilities located on or near a beach due to flooding and wave action with this damage greatly enhanced in the presence of ice.

Another consideration is the spring breakup of the southern Beaufort Sea. The effect of the Mackenzie River on the clearing pattern of Mackenzie Bay has been previously discussed. Any significant reduction in the amount of water discharged into Mackenzie Bay would alter the breakup in Mackenzie Bay and may alter the clearing east-northeastward across western Amundsen Gulf. Such changes could be brought about by dams on tributaries reducing downstream water level during spring and summer run-off.

The effect that a large number of artificial islands and/or production and loading atolls could have on the breakup pattern is another unknown. A hypothetical case in which the area became dotted by such structures would help anchor the shore-fast ice. However, the current and projected number of sites may be of minimal significance.

9.5 WEATHER IMPACT ON MARINE ACCIDENTS

For the purposes of this discussion an accident will be defined as either a disabled vessel or an oil spill.

During any season of the year reduced visibilities could play a major role in the aftermath of an accident. Initial assistance would likely be by air, and either fog or blowing snow could curtail flying. In winter, blizzards can last three to four days, and besides hampering flying, can severely restrict outside activity due to the extreme windchill values. Fog can have a curtailing effect on aviation but surface activity would not be as severely restricted. During the fall months, heavy seas, freezing spray, low visibilities and aircraft icing in low cloud could present problems in accident assistance along most sections of the routes but, in particular, Baffin Bay, Davis Strait and the Bering Strait.

A worst case oil spill could develop if a blowout occurred during a fall storm which caused the arctic pack to move across the drill site preventing any capping operations. Should the following year be a "bad ice year" there could be further delays in capping and cleanup operations.

Another scenario would be a major oil spill occurring in the production area during or just prior to a storm such as that of September 1970. Wind driven currents and the accompanying storm surge could not only foul the beaches but could move oil a considerable distance inland.

10. OBSERVATIONAL AND FORECASTING SYSTEMS

10.1 INTRODUCTION

It is assumed that the use of icebreaking tankers to transport hydrocarbons from the Arctic will require expanded marine and ice programs. This section details a program to support routine operations and a second program to deal with emergencies such as an oil spill. The following recommendations are those of the authors and in no way reflect AES policy.

10.2 SUPPORT FOR ROUTINE OPERATIONS

10.2.1 Forecast Services

Forecast requirements to support offshore exploration and production and marine transportation, in particular, those operating within ice-infested waters, are substantially different from those of the aviation industry and general public. This fact is already recognized and during the offshore drilling season a forecast office is staffed at Tuktoyaktuk. This office forecasts specifically for the Beaufort Sea exploration area and is able to give specialized service not normally available from a major Weather Centre. The remainder of the Arctic marine areas are handled by the Arctic Weather Centre in Edmonton.

It is suggested that once icebreaking tankers begin to operate in the Arctic on a year-round basis, the production area and entire northern marine transportation industry could best be served by one dedicated team of meteorologists. Besides a knowledge of arctic meteorology, members of the team should also have a knowledge of oceanography and ice. Such a system should not only result in better forecasts but would establish a resource group for research, consultation and further training. To prepare for the arrival of the icebreaking tanker, it is recommended that:

a) steps be taken to upgrade the knowledge of arctic meteorologists in both oceanography and ice;

b) the current marine forecasting program be examined to determine if it reflects the needs of the icebreaking tanker;

c) the existing marine forecast regions be examined to see if alterations are possible so they can better describe the actual transportation route;

d) plans be developed for extending the Beaufort Weather Office to a year-round operation;

e) the ice observing program be expanded during the winter months so that better climatology of wintertime ice conditions can be developed;

f) research be continued into obtaining more information on both ice and arctic weather conditions through the use of remote sensing.

10.2.2 Basic Data Requirements

Forecasts and research require a good data base. In order to provide a basic forecast program in support of normal year-round operations it is recommended that:

a) there be no reduction in the current observational programs across the Canadian Arctic. This also includes the current upper air program;

b) coverage be increased along the transportation route by the installation of automatic weather stations on northern Banks Island and southern Devon Island;

c) the current observational programs at Sachs Harbour, Komakuk Beach and Shingle Point be increased to 24 hours. This could be accomplished through the use of automatic stations;

d) the deployment of automatic buoys on the polar pack be continued;

e) each tanker be equipped with an automatic weather station to ensure 24-hour coverage;

f) each tanker be required to file main synoptic weather reports.

10.2.3 Communications

A system to allow rapid and dependable dissemination of forecasts and warnings is essential. It should also have the flexibility to provide for two-way communication on demand.

10.3 SUPPORT FOR EMERGENCY OPERATIONS

10.3.1 Forecast Services

If an accident or major oil spill were to occur along a transportation route or in the production and loading area, it would be necessary to issue accurate, site-specific forecasts for both the short and long term. Although the normal forecast team should be capable of responding to such a situation, it may, depending on the situation, be advantageous to have a meteorologist available at the site. This would provide on-site interpretation of forecasts and consultation services to those involved in the operation.

10.3.2 Basic Data Requirements

Meteorological support for an accident will require an increase in data in the immediate area of the accident. To cope with such an emergency it is recommended that:

a) a plan be developed that can rapidly deploy a number of automatic meteorological stations near the accident site;

b) if deemed necessary and feasible, a trained observer be available to send to the site;

c) in the absence of an observer, at least one ship in the area be designated to supply extra observations. These must include at least pressure and wind;

d) depending on the situation, it should be feasible to begin a mini-sonde program at the site;

e) there be a capability to provide increased ice reconnaissance as required.

10.3.3 Communications

The communication system must at least have the capability of that required to support normal operations. The requirement for two-way communication is even more imperative during an emergency situation.

11. AREAS OF FURTHER STUDIES

Several areas for future work have become evident during the present study:

a) A more detailed comparison of the FNOC geostrophic winds and the actual reported winds would be useful. This would involve the computation of the geostrophic winds from the FNOC data at a sea reporting station such as a stationary Beaufort Sea reporting platform or at a winter ice drilling station. Better correlations between the FNOC geostrophic and actual surface winds could be obtained for various stability categories. These correlations could then be applied to other areas. The FNOC pressure analyses could be compared to hand-drawn maps in order to determine the accuracy of the FNOC data in depicting pressure patterns.

b) An update and extension of the climatology records for offshore locations and coastal stations is required. This would especially apply to the Beaufort Sea area where during the last several years large amounts of climate data have been accumulated. Currently, the SSMO data included as the marine information in this study ends in 1973.

c) A detailed study could be made of the main Arctic Ocean icepack. Although the generally accepted large-scale movement of the pack from ice island trajectories is in a clockwise direction, recent tracking of buoy locations has revealed that this may not always be the case for smaller scale motions (Hudson (1981)). A study of these buoy movements may yield locally different trajectories which are dependent on the weather patterns.

d) The depiction of the areas of maximum ice concentration requires further attention. The maximum amounts that have been presented are based on the worst ice amounts reported at each point over the entire period of data. A regional division of the marine areas could be made and the worst of the ice conditions in each area shown for a single time period rather than a composite of the worst conditions over several years. This would give a better impression of what the worst year ice conditions over a given area would be.

e) For future shore-based operations in areas of unknown weather conditions, it is suggested that an automatic station be deployed to the area. This would help pinpoint any unusual wind patterns at the site. In Chapter 3.4, an example of this variation in wind over a short distance was seen.

f) An analysis of the frequency of occurrence and size distributions of ice ridges is required for various portions of the proposed marine transportation route.

g) An examination of the individual ship reports in a given marine area should be carried out to determine the representativeness of the SSMO tables for depiction of marine conditions. The possibility of ships reporting more frequently in port or near coasts could be examined.

h) More use of the SSMO tables to summarize weather conditions over marine areas could be made in order to assist marine forecasting for these areas.

i) The use of ship reports should be utilized to study the local wind fields in fiords and near coastal valleys or hills to determine unusual patterns.

j) Several possibilities for case studies over the marine areas are seen. Detailed discussions of blizzards over the Central marine area including weather elements such as blizzard length, temperatures, ice conditions, wind chills, and wind speeds could be presented. As well, case studies could be done depicting the weather and ice conditions that have occurred during past unusual seasons including unusually early or late break-up or freeze-up situations.

k) Case studies involving local weather phenomenon at a meso-scale level are possible. These could include detailed wind field depictions at local sites anticipated as future port facilities.

l) Another area of study involves analogue classification of synoptic weather patterns over the Arctic areas, especially the Beaufort Sea, to assist in forecasting.

m) Studies concerning freezing spray are another possibility to determine how well previously-developed forecasting nomograms perform. Encouragement of the offshore Beaufort Sea drilling sites to report freezing spray events would be of considerable assistance.

12. REFERENCES

American Meteorological Society, Boston, Mass. 1959. Glossary of Meteorology.

Anonymous. Oceanography for the Navy Meteorologist 1960. U.S. Navy Weather Research Facility NWRF 32-0360-030.

Ball, F.K. 1956. The Katabatic winds of Adélie Land and King George V Land. Tellus, Vol. 9.

Berry, Owens and H.P. Wilson. 1953. Arctic Weather Maps. Bureau of Aeronautics Project ARAWA., Norfolk, Va.

Brower, W.A., and H.W. Searby et al. 1977. Vol. III. Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska. Arctic Environmental Information and Data Center, University of Alaska, Anchorage, Alaska.

Buckler, S.J. 1969. The Vertical Wind Profile of Monthly Mean Winds Over the Prairies. Canada Dept. of Transport, Met. Branch, Tech. Memo. 718, 16 pp.

Burns, B.M. 1973. The Climate of the Mackenzie Valley - Beaufort Sea. Vol. 1, Climatological Studies #24, Atmospheric Environment Service, Downsview, Ontario.

Burns, B.M. 1974. The Climate of the Mackenzie Valley - Beaufort Sea. Vol. II, Climatological Studies #24, Atmospheric Environment Service, Downsview, Ontario.

Campbell, N.J. and A.E. Collin. 1956. A preliminary report on some oceanography features of Foxe Basin. Joint Committee on Oceanography, Manitoba.

Campbell, N.J. 1958. The oceanography of Hudson Strait. Fish. Res. Board, Canada, Man. Rep. Ser. No. 12.

Collin, A.E. 1963. Waters of the Canadian Arctic Archipelago. 139 pp in: Proceedings of the Arctic Basin Symposium, Oct. 1962. Arctic Institute of North America, Washington, D.C. 313 pp.

Davenport, A.G. 1960. Rationale for Determining Design Wind Velocities. J. Structural Divis., Proceedings of Amer. Soc. of Civil Eng. 86, No. ST5, pp 39-68.

Defant, F. 1951. In Compendium of Meteorology, p. 679.

Dickey, W.W. 1961. A study of the Topographic Effect on Wind in the Arctic. Journal of Meteorology. 18 pp. 790-883.

Dunbar, M. and K. Greenaway. 1956. Arctic Canada from the Air. Canada Defence Research Board.

Dunbar, M.J. 1951. Eastern Arctic Waters. J. Fish. Res. Board Canada, 88, 1-131.

Environment Canada. Canadian Normals Vol. 1-SI. Temperature 1941-1970. Atmospheric Environment Service, Downsview, Ont.

Environment Canada. Canadian Normals Vol. 2-SI. Precipitation 1941-1970. Atmospheric Environment Service, Downsview, Ont.

Fathauer, T.F. 1978. A Forecast Procedure for Coastal Floods in Alaska, NOAA Technical Memorandum NWS AR-23.

FENCO. 1975. Analytical Study of Ice Scour on the Sea Bottom. A.P.O.A. Review March 1980.

Fichaud, R.J. 1959. Wind Waves and Prognostic Wave charts. Royal Canadian Navy Publication (unnumbered).

Fleagle, R.G. 1950. A theory of Air Drainage. Journal of Meteorology 7, 227-232.

Fraser, D.B. 1959. Unstable Character of Northeasterly Winds at Resolute, N.W.T. AES. TEC 300.

Fraser, D.B. 1968. A Meso Scale Wind System in the Canadian Arctic, Arctic Weather Centre, Edmonton. Unpublished.

Glossary of Meteorology. 1959. American Meteorological Society. Boston, Mass.

Gross, E. 1970. The Air Pollution Forecast Program. Weather Bureau Technical Memorandum, WBTM-NMC43, National Meteorological Centre, Suitland, Maryland, 8 pp.

Headley, A.H. 1979. Climatic Analysis of Dundas Harbour, N.W.T. Atmospheric Environment Service. Report No. 79-16.

Henry, R.F. 1975. Storm Surges. Beaufort Sea Project, Dept. of the Environment, Victoria, B.C., Beaufort Sea Technical Report #24.

Henry, R.F. and N.S. Heaps. 1976. Storm Surges in the southern Beaufort Sea. J. Fish. Res. Board Can. 33: 2362 - 2376.

Herlinveaux, R.H. 1974. Surface movements in Canadian Arctic Waters with some accompanying temperature and salinity observations. Unpublished manuscript, Pacific Marine Science Report, Marine Sciences Directorate, Pacific Region, Environment Canada, Victoria, B.C.

Hess, S.L. 1959. Introduction to Theoretical Meteorology. Henry Holt and Company, New York.

Hudson, E. 1981. 1980 Beaufort Weather Office Report. Atmospheric Environment Service reports Western Region.

Kiilerich, A.B. 1939. A theoretical treatment of the hydrographic observational material, the Godthaab expedition. Meddelelson om Groenland 78, 5, 1-148.

Kovacs, A., D. Dickens and B. Wright. 1975. An Investigation of Multi-Year pressure Ridges and Shore Pile-Ups. Norcor Engineering and Research Ltd. Reviewed.
- Arctic Petroleum Operators Assoc., March 1980, Vol. 3, No. 1.
- 1975. Analytical Study of Ice Scour on the Sea Bottom. Fenco.

Lachapelle, P.A., 1981. "Winds and Waves in Lancaster Sound and North-western Baffin Bay". Canadian Climate Centre Report Series, Atmospheric Environment Service, Downsview, Ontario (To be published).

Landsberg, H. 1968. Physical Climatology. Gray Printing Co. Inc., Dubois, Penn.

Markham, W.E. 1981. Ice Atlas Canadian Arctic Waterways. Canadian Government Publishing Centre, Supply and Services Canada, Hull, P.Q., Canada, K1A 0S9.

Maxwell, J.B. 1980. The Climate of the Canadian Arctic Islands and Adjacent Waters. Vol. 1, Climatological Studies Number 30, Atmospheric Envirnment Service, Downsview, Ontario.

Maxwell, J.B., P.J. Duck, R.B. Thomson and G.G. Vickers. 1980. The Climate of Northwestern Baffin Bay.

Morgan, M.R. 1971. The Analysis and Forecasting of Sea and Swell Conditions in Deep Water. Atmospheric Environment Service, TEC. 763.

Munn, R.E., J. Tomlain and R.L. Titus. 1970. A Preliminary Climatology of Ground-based Inversions in Canada. Atmosphere, Vol. 8, pp 52-68.

Neumann, C. and W.J. Pierson, Jr. 1966. Principles of Physical Oceanography. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Parker, M.N. 1981. Personal knowledge.

Portelli, R.V. 1977. Mixing Heights, Wind Speeds and Ventilation Coefficients for Canada. Climatological Studies, No. 31. Atmospheric Environment Service of Canada, Downsview, Ont.

Reimnitz, E. and D.K.Maurer. 1979. Effects of storm surges on the Beaufort Sea coast, northern Alaska. Arctic Institute of North American. pp. 329-344.

Roots, E.F. Environment Canada (1979). Environmental Aspects of Arctic Marine Transportation and Development. Marine Transportation and High Arctic Development. Policy Framework and Priorities. Symposium Proceedings. Montebello, Que.

Schram, G.R. 1981. Personal communication.

Siple, P.A., and C.F. Passel. 1945. Measurements of Dry Atmospheric Cooling in Sub-Freezing Temperatures. Proc. Amer. Phil. Soc. 89, pp. 177-179.

Stackpole, J.D. 1967. The Air Pollution Forecast Program. Weather Bureau Technical Memorandum, WBTM-NMC43, National Meteorological Centre, Suitland, Maryland, pp 8.

Stasyshyn, E. 1981. Personal communication.

Stewart, R.W. 1969. The Atmospheric and the Ocean. Scientific American. Vol. 221, No. 3, pp 76-86.

Streten, N.A., N. Ishikawa and G. Wendler. 1971. Some observations of the local wind regime on an Alaskan Glacier. Geophysical Institute, University of Alaska, Fairbanks, Alaska.

Swail, V.R. 1982. "Geostrophic Wind Climatology of Canadian Marine Areas", CCC Report Series. (To be published).

Timofeyev, V.T. 1960. Vodriye Massy Arkticheskogo Basseina. Gidrometeorologicheskoe Izdaklstvo, Leningrad, pp 19. (translated by L.K. Coachman, Univ. of Washington, Seattle, June 11.)

Walker, E.R. 1977. Aspects of Oceanography of the Archipelago. Inst. of Ocean Sciences, Patricia Bay, Victoria, B.C.

Williams, Jerome. 1962. Oceanography. Little Brown and Company, Boston, Mass.

Wilson, H.P. 1971. An interesting storm. Unpublished. Can., Arctic Weather Centre, Edmonton.

Wilson, H.P. 1973. A Study Guide for Arctic Weather Forecasters. Arctic Weather Centre, Edmonton.

Wilson, H.P. 1974. Winds and Currents in the Beaufort Sea. Arctic Institute of North America. Proceedings of a symposium on Beaufort Sea Coast and Shelf Research.

Wilson, H.P., S.W. Dewar, W.E. Markham and H.A. Thompson. 1953. Weather in the Canadian Arctic. Meteorological Division, Department of Transport, Canada. TEC 170.

Wise, J.L. and A.L. Comiskey. 1980. Superstructure Icing in Alaskan Waters. Pacific Marine Environmental Laboratory, Seattle, Wash.

Author Unknown. Ice Growth, Deformation and Disintegration. Unpublished. Lecture, Ice Forecasting Central. Atmospheric Environment Service, Ottawa, Ontario.