POSSIBLE TELECONNECTIONS BETWEEN NORTH PACIFIC SEA SURFACE TEMPERATURES AND EXTENDED DRY SPELLS AND DROUGHTS ON THE CANADIAN PRAIRIES

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ABSTRACT

This thesis examines the possible teleconnections between North Pacific sea surface temperatures and synoptic extended dry spells and droughts on the Canadian Prairies. Dry spells are a natural occurrence on the Canadian Prairies. It is also a well known fact that extended dry spells often lead to droughts. The major synoptic cause of extended dry spells and droughts on the Canadian Prairies includes the presence of a quasi-stationary mid-tropospheric ridge over the area. What causes this ridge to become quasi-stationary is not certain. Some previous studies have shown that sea surface temperature anomalies over the North Pacific Ocean may be a significant factor in affecting upper atmospheric long wave patterns and abnormal weather conditions over North America.

The main objective of this study is to determine if there is a significant statistical relationship between anomalous North Pacific sea surface temperatures and the occurrence of extended dry spells and droughts on the Canadian Prairies during the agricultural growing season (May - August) for the period 1948-1988. Individual extended dry spells are identified and then ranked in terms of their severity. Results show a significant correlation between these extended dry spells and a positive sea surface temperature anomaly gradient located in the east central North Pacific. This gradient consists of a region of anomalously cold water located in the east-central North Pacific in the area bounded by 30°N to 40°N latitude and 165°W to 135°W longitude and a region of anomalously warm water found along the west coast of North America bounded by the coordinates 45°N to 55°N latitude and 130°W to 125°W longitude. A probability model shows that the longer this gradient persists, the greater the probability of a major extended dry spell. A conceptual model is also constructed and shows a distinctive pattern in sea surface temperature anomalies and 50 kPa anomalies associated with the major extended dry spells.

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CHAPTER 1

INTRODUCTION

1.1 SIGNIFICANCE OF STUDY

The term dry spell is often used to describe a period of prolonged precipitation deficiency. The length of this period can differ depending on the study and on the area under consideration. It is also well known that extended dry spells often lead to drought (Dey, 1973). However, the term drought is not so easily defined.

Drought has different meanings for different people. To a climatologist, a drought is often referred to as a long term lack of precipitation over a particular region or as a water shortage within the soil. A climatological drought may be studied by examining precipitation, temperature, evapotranspiration, and upper air circulation patterns (Street and Findlay, 1981). To a hydrologist, the term drought refers to a prolonged period of unusually low surface runoff and ground water levels over a large area. An agriculturist often defines drought as a period during which soil moisture is insufficient to support crops (Dracup et al., 1980). Another definition that has been used to describe drought is an unusual shortage of water that produces an adverse effect on society and the economy. This is known as a socio-economic drought (Ripley, 1988).

The definition of dry spells and droughts also varies considerably depending on the area under consideration. For example, in a humid environment where precipitation is normally evenly distributed throughout the growing season, a summer dry period of a week or two may constitute a drought. On the other hand, in persistently drier areas such as the Sahelian zone of western Africa, droughts are recognized only after two or more rainy seasons without precipitation (Olapido, 1985).

The Canadian Prairies periodically experience prolonged dry spells as a normal characteristic of their climate. Occasionally, however, serious effects on agriculture and other sensitive water resource activities result from unusually severe or prolonged dry periods (Street and Findlay, 1981). Therefore, extended dry spells and droughts can be very costly to the Canadian Prairies. As a result, the ability to predict these events could provide many economic benefits to the Prairie region (Ripley, 1988).

The synoptic climatological causes of extended dry spells and droughts on the Canadian Prairies have been well documented. Chakravarti (1972), Dey (1973), Dey and Chakravarti (1976), Dey (1982), and Knox and Lawford (1990) all observed a direct relationship between a quasi-stationary mid-tropospheric ridge centred over the Prairies and extended dry spells and droughts over the same area. What causes this ridge to become quasi-stationary is not certain. However, some previous studies have shown that sea surface temperature anomalies over the North Pacific Ocean may have a significant effect on upper atmospheric long-wave patterns and abnormal weather conditions over North America (Namias, 1972,1982; Wick, 1973; Dey, 1982).

A few studies have been carried out relating North Pacific sea surface temperatures to winter weather conditions over North America. They indicate that the simultaneous occurrence of a large area of anomalously cold water in the central North Pacific, and an area of anomalously warm water off the coasts of California and Central America, is associated with a long-standing (Rossby) wave pattern that produces warm, dry conditions in the western part, and cold wet conditions in the eastern part of North America (Namias, 1969,1972,1978,1986; Wick, 1973). Namias (1972) also stated that if these sea surface temperature anomalies are reversed, then the weather patterns over North America will be reversed as well. To date, only one study has attempted to relate North Pacific sea surface temperatures with summer dry spells and droughts over North America. Namias (1982) observed that these sea surface temperatures are contemporaneously associated with Great Plains drought in the United States. These previous results imply that there is some association between North Pacific sea surface temperatures and long term weather patterns over North America.

1.2 OBJECTIVES OF STUDY

Although a few studies have been carried out relating anomalous North Pacific sea surface temperatures to abnormal weather patterns in the United States, relatively little attention has been given to the effect of these temperatures on dry spells and droughts on the Canadian Prairies. Also, past work for North America has dealt mainly with the winter season. The Canadian Prairies receive up to two thirds of their annual precipitation during the agricultural growing season (Dey, 1973). As a result, dry spells and droughts during this time period can be very damaging to the Canadian Prairie economy. Therefore, the two principal objectives of this study are as follows:

a. Determine if there is a significant relationship between anomalous North Pacific sea surface temperatures and the occurrence of extended dry spells and droughts over the Canadian Prairies during the growing season (May - August).

b. Construct a conceptual model and a probability model showing the relationship between North Pacific sea surface temperatures and severe extended dry spells leading to drought on the Canadian Prairies. The models may aid in the forecasting of these drought events.

CHAPTER 2

LITERATURE REVIEW

The following chapter involves a review of relevant literature pertaining to this study. It is presented in two major categories. These include: (i) dry spells and droughts on the Canadian Prairies and, (ii) teleconnections of North Pacific sea surface temperatures with weather patterns over North America.

2.1 DRY SPELLS AND DROUGHTS ON THE CANADIAN PRAIRIES

The definition of a dry spell or drought varies considerably depending on the investigation and on the area in question. For the Canadian Prairies, a few different definitions have been used. Some of these include the Palmer Drought Index and the Crop Moisture Index. These indices take into account precipitation, soil moisture, temperature, and evapotranspiration (Knox and Lawford, 1990). Other definitions such as the one applied by Knox and Lawford (1990), divided the Canadian Prairies into different zones and used monthly precipitation anomalies to define dry spells within these zones.

Dey (1973) defined a dry spell as a succession of dry days. For the agricultural area of the Canadian Prairie

Provinces, he suggested that a dry spell of seven or more days would harm young crops. Therefore, in Dey's investigation, a succession of seven or more days, during which no measurable precipitation is received on any one day, was used as the definition of a dry spell. To provide a definition which takes into account the areal extent of dry spells on the Canadian Prairies, Dey redefined a dry spell as a period of at least seven consecutive days during which 68% or more of the stations within the Prairies report no measurable precipitation.

A number of studies have also been carried out on the synoptic causes of dry spells and droughts on the Canadian Prairies. Early investigations that dealt specifically with the Prairies suggested that major circulation patterns accompanying drought situations in the Great Plains of North America (which includes the Canadian Prairies) involve abnormally strong westerlies persisting for one or more months, relatively high pressure over the Great Basin and southern plateaus, and a northward displacement of the usual cyclone path across the central plains (Borchert, 1950; Currie, 1953; Villmow, 1956; Bryson, 1966).

More recent studies have determined that widespread dry conditions over the Canadian Prairies are related to the extension of the subtropical high pressure cell over the north-eastern Pacific Ocean and the presence of a quasi-stationary 50 kPa ridge with its north-south axis across the

Prairies. These flow patterns create 'blocking action' displacing the jet stream, cyclonic tracks, and associated moist air masses and fronts northward, thus creating dry conditions on the Canadian Prairies (Chakravarti, 1972; Dey, 1973; Chakravarti, 1976; Dey and Chakravarti, 1976; Dey, 1982). These results were also confirmed using 70 kPa analysis (Dey, 1979,1982).

The blocking ridges situated over the Canadian Prairies can be divided into two main types. The first is a cellular pattern that includes an upper-level high at the centre which extends throughout the troposphere. The second type is an upper-air ridge of large amplitude also extending throughout the troposphere. This second pattern is part of the planetary (Rossby) wave system which includes cold troughs separated by warmer ridges. Over the Canadian Prairies, the ridge commonly assumes the shape of the Greek letter omega and thus is often referred to as omega blocking. These ridges are known to intensify drought conditions through low-level divergence and the resultant subsidence of air (Dey, 1982; AES Drought Study Group, 1986).

Knox and Lawford (1990) analyzed spring and early summer dry months on the Canadian Prairies using circulation anomalies in the mid-troposphere. They attributed these dry months to positive height anomalies suggesting upper-level ridges over the Prairies. These ridges are often associated with a circulation anomaly known as the Pacific North America or PNA pattern. The typical PNA pattern consists of negative upper-atmospheric height anomalies over the eastern North Pacific Ocean and eastern Canada, and positive anomalies over western Canada (Knox and Lawford, 1990).

2.2 TELECONNECTIONS OF NORTH PACIFIC SEA SURFACE TEMPERATURES

The term teleconnection is commonly used to describe significant correlations between simultaneous temporal fluctuations in climatological parameters at widely separated points on the earth's surface. Teleconnection patterns are of considerable interest because they can often provide evidence concerning the transient behaviour of planetary waves (Wallace and Gutzler, 1981). The important effects of atmosphere - ocean teleconnections have been outlined by Barnett (1979) and Namias and Cayan (1981). The atmosphere acts on the ocean mainly through the mechanism of wind stress while the ocean acts on the atmosphere principally through its surface temperatures. Sea surface temperature anomalies are primarily produced by changes in winds and solar radiation absorption. Due to the huge heat capacity of the oceans, sea surface temperature anomalies, once produced, tend to persist for several months. As a result, any global climatic response to these anomalies can also be expected to persist for a comparable time (Ripley, 1988).

A few studies have been carried out in which researchers attempted to describe some of the observed teleconnections between anomalous sea surface temperatures in the North Pacific and the associated atmospheric circulation patterns over North America. Many of these investigations dealt with the winter season and found that unusual winter weather conditions over North America are related to an anomalous sea surface temperature gradient in the North Pacific Ocean. In fact, it was found that whenever there was an area of anomalously warm water off the coast of California, and simultaneously, an area of anomalously cold water in the central North Pacific, this sea surface temperature gradient was associated with a diversion of the jet stream to the north over western North America and to the south over eastern North America. This in turn produced warm, dry conditions in the west and cool, wet conditions in the east (Namias, 1969,1972; Wick, 1973; Walsh and Richman, 1981). When these sea surface temperature anomalies were reversed, the weather patterns over North America were reversed as well (Namias, 1972).

The possible reasons for this association between anomalous North Pacific sea surface temperatures and persistent unusual winter weather conditions over North America have also been suggested. Namias (1976) reported that anomalously warm sea surface temperatures in the sub-Aleutian area of the North Pacific during summer are significantly associated with an intensified Aleutian Low during the following autumn. He postulated that a strong Aleutian Low in autumn would drive cyclones north of the United States border and contribute to an upper-level ridge over western North America and a trough over eastern North America. On the other hand, a weak or absent Aleutian Low would result in less cyclonic activity and thus a tendency for an upper-level trough to develop over western North America and a ridge over eastern North America. Therefore, anomalously warm sea surface temperatures in the sub-Aleutian area during summer will often be associated with higher than normal autumn temperatures over the western United States and lower than normal temperatures in the east. Anomalously cold water in this area during summer will have the exact opposite effect i.e. higher than normal autumn temperatures over the eastern United States and lower than normal temperatures in the west (Namias, 1976).

An anomalous sea surface temperature gradient in the North Pacific Ocean was associated with the abnormal winter of 1976-77. This winter was characterized by unusually cold weather in eastern North America and simultaneously, unusually warm weather in western North America (Canby, 1977). A west-east zonal sea surface temperature gradient located near 140°W was evident over the North Pacific Ocean during the autumn of 1976. This gradient aided in the production of a meridional upper-level flow which steered cyclones northward rather than taking on their normal eastward course. As a result, abnormal weather conditions were observed over North America during the following winter (Namias, 1978).

As is shown by the previous investigations, summer and autumn North Pacific sea surface temperatures can be significant predictors of North American winter weather conditions. These same results were also reported by Harnack (1979), Namias (1986), and Dixon and Harnack (1986). Harnack (1979) attempted to predict area-averaged winter temperatures for various areas in the eastern United States by using November sea surface temperatures in the eastern North Pacific Ocean. He found that his sea surface temperature model was able to distinguish correctly between the relatively mild winter of 1975-76 and the cold winters of 1976-77 and 1977-78. As an explanation, he suggested that North Pacific sea surfaces temperatures may be a primary factor in determining winter surface temperature conditions, and by implication, large scale winter circulation patterns over the eastern United States. Namias (1986) showed that many persistent 70 kPa height anomaly patterns over North America tend to have maximum occurrence during winter. He also suggested that these persistent patterns are probably due in part to the influence of North Pacific sea surface temperatures. Dixon and Harnack (1986) used tropical and North Pacific sea surface temperatures to predict area-averaged temperature anomalies for United States winters. They found statistically significant results using winter sea surface temperatures from 1950-1979.

The association of North Pacific sea surface temperatures with summer weather conditions over North America has not been extensively researched. Namias (1982) found drought patterns over the United States Great Plains to be related to contemporaneous North Pacific sea surface temperatures. This included significant contemporaneous correlations between air temperatures over the United States Great Plains and sea surface temperatures over the North Pacific during the spring and summers of 1947-1980. In cases of established United States Great Plains drought, an anomalously warm pool of water was likely to be located near the northern and western parts of the North Pacific subtropical high pressure cell, while anomalously cold water extended from near Hawaii northeastward to the west coast of North America. Namias (1982) suggested that this anomalously cold ocean pool may have assisted in the development of a stronger than normal subtropical high pressure cell over the North Pacific. Through long-wave amplifications, the west coast trough, Great Plains ridge, and east coast trough were all intensified. This stronger than normal Great Plains ridge was then responsible for drought conditions in this region (Namias, 1982,1983).

Finally, Namias et al. (1988) studied the persistence of North Pacific sea surface temperature anomalies and atmospheric flow patterns over North America. Their analysis indicated that the most persistent sea surface temperature patterns exhibited negative anomalies in the central North Pacific and positive anomalies along the west coast of North America. Associated with this sea surface temperature anomaly pattern were highly persistent 70 kPa negative height anomalies centred off the west coast and positive height anomalies over much of the rest of North America. On average, North Pacific sea surface temperature anomaly patterns have lifetimes of three to five months and are most persistent in winter when the mixed layer of the ocean is deepest.

In all of the previous investigations, references were made to the associations between anomalous North Pacific sea surface temperatures and large scale circulation patterns over North America. However, the majority of these studies analyzed the winter season. There have been very few investigations that have examined relationships between North Pacific sea surface temperature anomalies and summer weather conditions over North America. Those that have, either dealt specifically with the United States (Namias, 1982,1983) or generally attributed drought conditions over North America (including the Canadian Prairies) to phenomena such as El Nino or La Nina which occur in the tropical Pacific Ocean (Trenberth et al., 1988). This is the first study to deal directly with possible teleconnections between anomalous North Pacific sea surface temperatures and growing season dry spells and droughts on the Canadian Prairies.

CHAPTER 3

STUDY AREA, DATA SOURCES, AND METHODOLOGY

This chapter describes the different methodologies used in this investigation. It begins with a brief description of the study area. The data sources and methodology are discussed in three separate sections. These include: (i) precipitation data for the Canadian Prairies, (ii) upper-air circulation over the Prairies, and (iii) sea surface temperatures in the North Pacific Ocean. Each section describes the nature of the data and the different methodological techniques used in the analysis.

3.1 STUDY AREA

The study area chosen for this investigation was the agricultural area of the Canadian Prairies which includes the southern portions of the provinces of Alberta, Saskatchewan, and Manitoba (Figure 3.1). The study area is bounded on the east by the Manitoba-Ontario border and on the west by the foothills of the Rocky Mountains. To the north, this region is bounded by forested lands of low agricultural potential and lower temperatures; while the United States border forms the southern boundary. The area chosen for the sea surface temperature analysis was the North-Central Pacific Ocean.

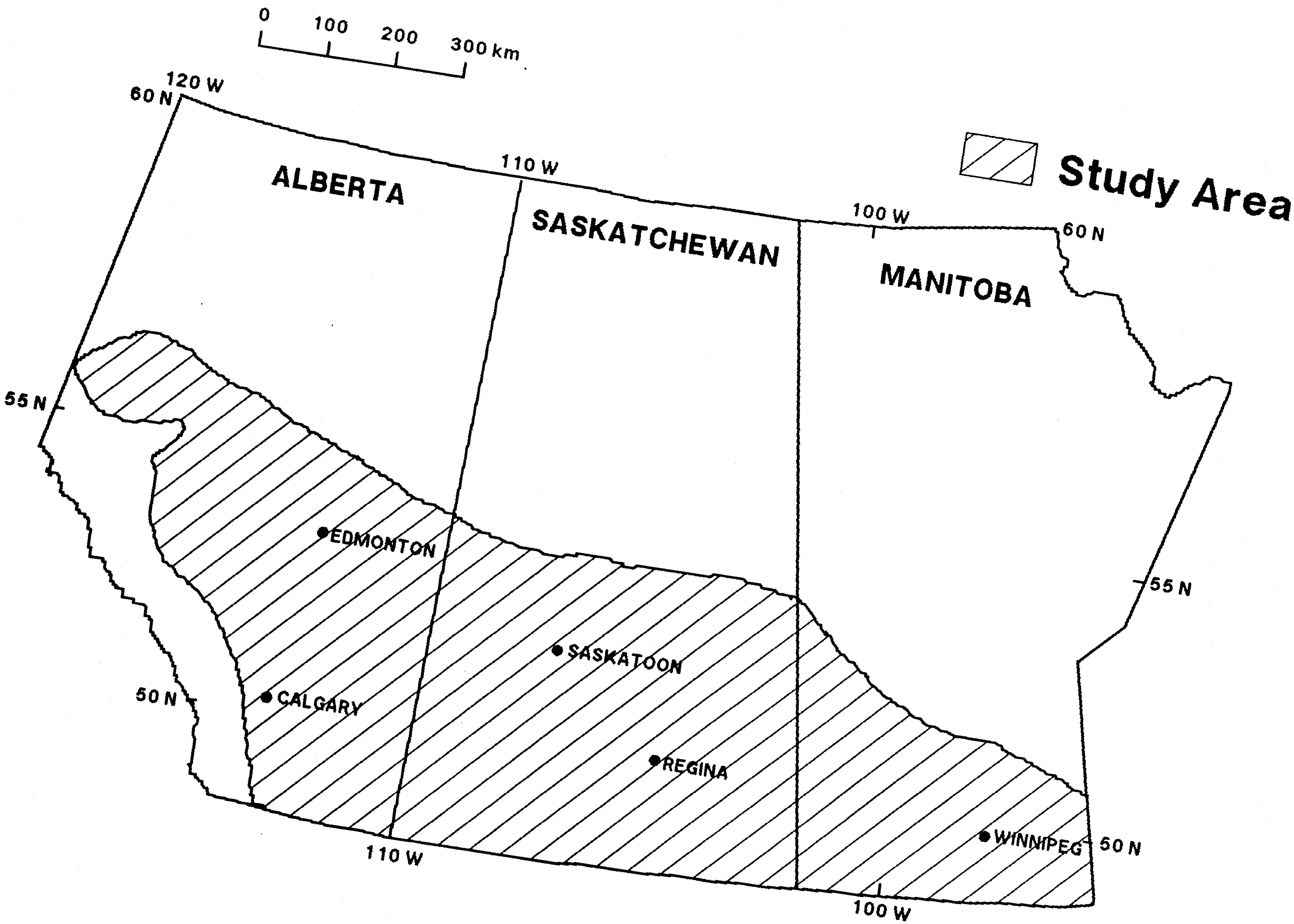

Figure 3.1: Canadian Prairie Study Area.

Based on previous investigations of sea surface temperature anomalies in this region (e.g. Namias, 1970; Davis, 1976; Namias et al., 1988), this area is defined as the part of the Pacific Ocean lying between 20°N to 60°N latitude and 120°E to 110°W longitude (Figure 3.2).

3.2 METHODOLOGY

This thesis investigates the possible teleconnections between North Pacific sea surface temperatures and extended synoptic dry spells and droughts on the Canadian Prairies. The analysis is carried out for the agricultural growing season (May to August) for the period 1948-1988. This time period was chosen because at the time of this study, comprehensive sea surface temperature data for the North Pacific Ocean was available only during these years. Also, this 41-year period is long enough to allow for reliable statistical analysis.

The first step in this study is to identify and describe individual extended dry spells over the Canadian Prairies. These spells are ranked in terms of their severity and then correlated with sea surface temperature anomaly patterns in the North Pacific Ocean.

3.2.1 PRECIPITATION DATA FOR THE CANADIAN PRAIRIES

3.2.1.1 NATURE OF THE PRECIPITATION DATA

In order to determine extended dry spells over the

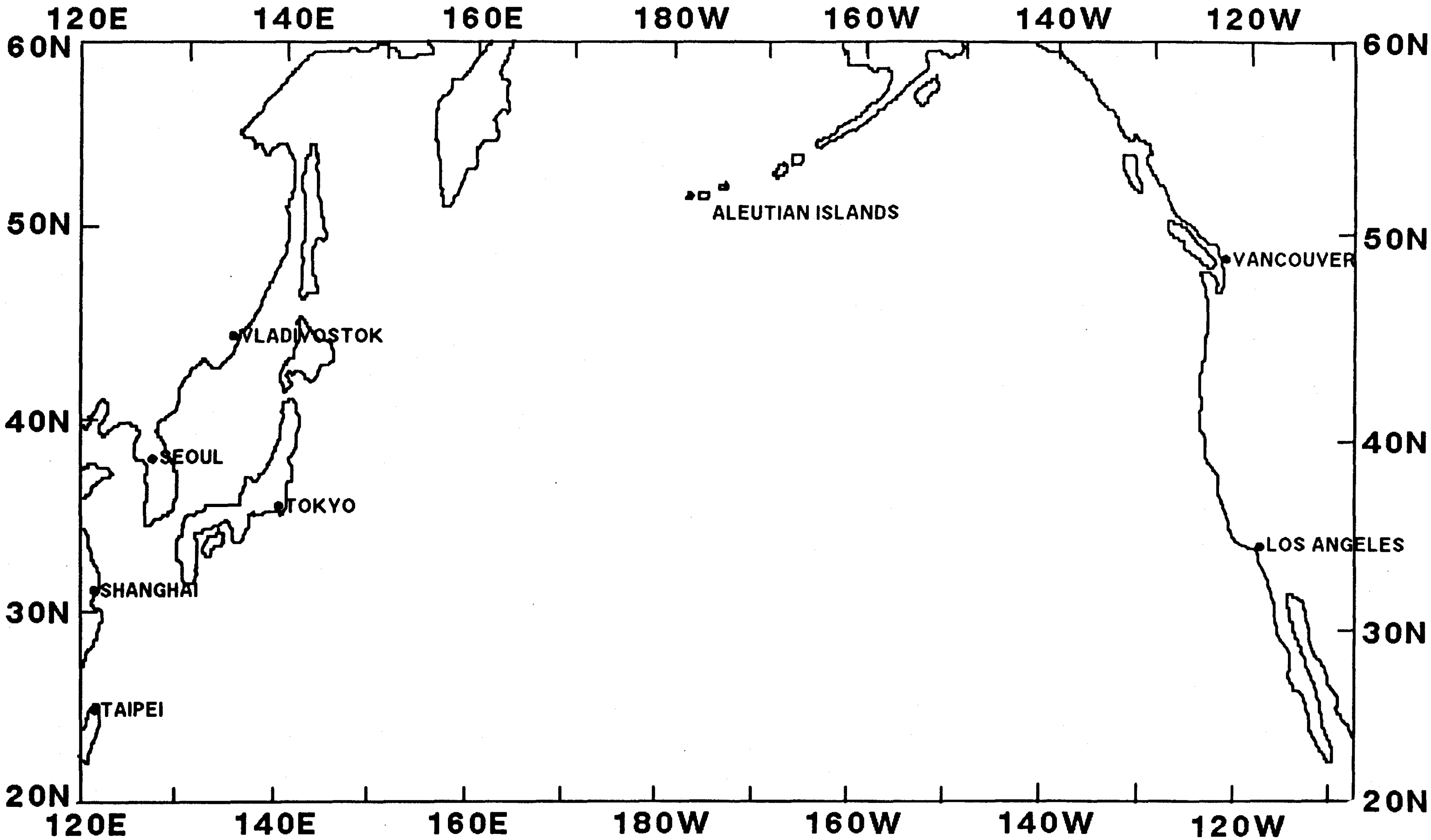

Figure 3.2: North Pacific Ocean Study Area.

Canadian Prairies, a continuous record of daily precipitation amounts during the study period were required. The precipitation data were obtained from 63 individual stations across the Prairie study area (Figure 3.3). These stations were chosen to provide the most uniform coverage of the study area. In the south, the stations are generally uniformly distributed. However, in the north, they are slightly less evenly spaced. The requirement that each station have a continuous precipitation record for the period 1948-1988 made uniform coverage even more difficult. Also, observation sites at some stations changed locations but remained within the same community. A list of these stations along with their station numbers and the time periods for which their observations were used is given in Appendix A - Table A.1.

Most of the daily precipitation data were obtained from the Atmospheric Environment Service Archives located in Downsview, Ontario. Once the data were obtained, a file was produced for each growing season. Each file consisted of a station number followed by a series of binary numbers. The number '0' indicated that no measurable precipitation occurred on that given day while the number '1' indicated that some measurable precipitation occurred on that day. Note that a trace of precipitation was considered to be no measurable precipitation. Each day during the growing season (May 1 - Aug 31) was represented in the data file. The number '9' indicated that the data for that particular day were

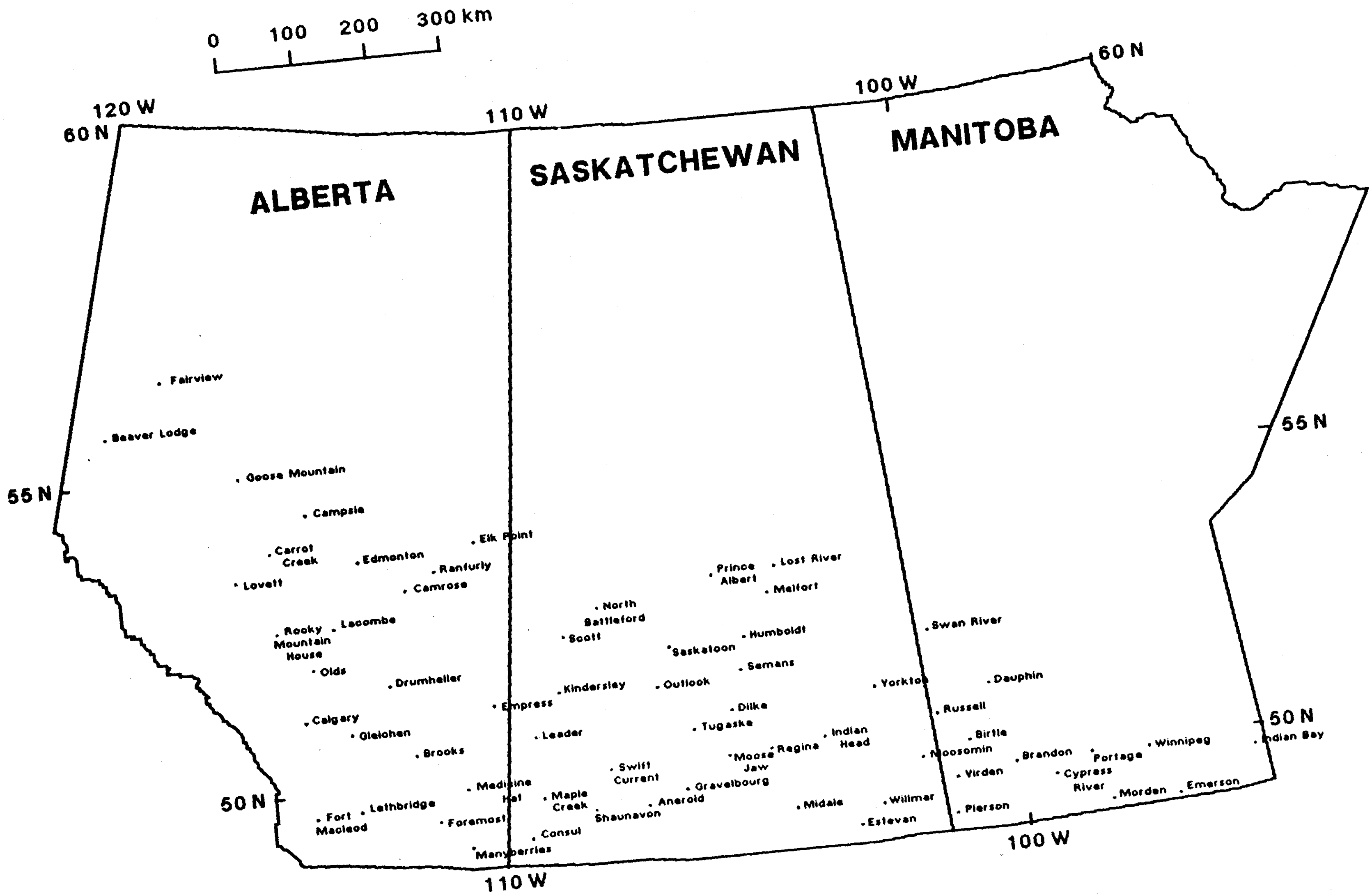

Figure 3.3: Precipitation Stations Used in this Study.

missing. An example of a data file is given in Appendix A - Table A.2.

Some of the precipitation values for certain stations were missing. The problem of missing data was handled by selecting the nearest station with data, to that for which data were missing. This station's precipitation value was then inserted into the existing station's data base. As a result, every station had a complete data time series for the period 1948-88. The insertion of replacement precipitation values for some of the stations should not have a significant effect on the identification of dry spells due to the fact that large area synoptic dry spells were being identified. Since the replacement stations were located within close proximity to the actual stations, large area precipitation patterns should remain the same. A list of these replacement stations along with the time periods over which they were used and their distance from the actual station is given in Appendix A - Table A.3. The missing data were obtained from Canada, AES Monthly Record Meteorological Observations. These complete precipitation data sets were then used to identify individual extended dry spells as discussed in the next chapter.

3.2.2 UPPER-AIR CIRCULATION AND DRY SPELLS

As discussed earlier, the major synoptic climatological cause of Canadian Prairie extended dry spells and droughts is a quasi-stationary upper-level ridge located over the Prairie region. Many studies have used the 50 kPa level when examining these ridges (Chakravarti, 1972; Dey and Chakravarti, 1976; Dey, 1982; Knox and Lawford, 1990). Therefore, once individual extended dry spells had been determined, the 50 kPa circulation pattern associated with each spell was examined.

3.2.2.1 NATURE OF THE UPPER-ATMOSPHERIC DATA

The upper-atmospheric circulation data consisted of daily (1200 UTC) 50 kPa height values for the Northern Hemisphere on a 5° latitude by 10° longitude grid. The major portion of the record, 1948-81, was obtained by Knox et al. (1988) from the National Centre for Atmospheric Research and the remainder, 1982-88, from the Canadian Meteorological Centre in Montreal. There were a few cases of missing data throughout the record. Shorter gaps (1-2 days), were filled by interpolation. Longer gaps (of the order of a week), were filled by digitizing hand drawn maps obtained from the United States Weather Bureau Historical Map Series (Knox et al., 1988). The Northern Hemisphere database consisted of 455 points. However, for the purpose of this study, only the 12 grid points that were located closest to the study area were used. A map showing the location of these 12 grid points is given in Figure 3.4.

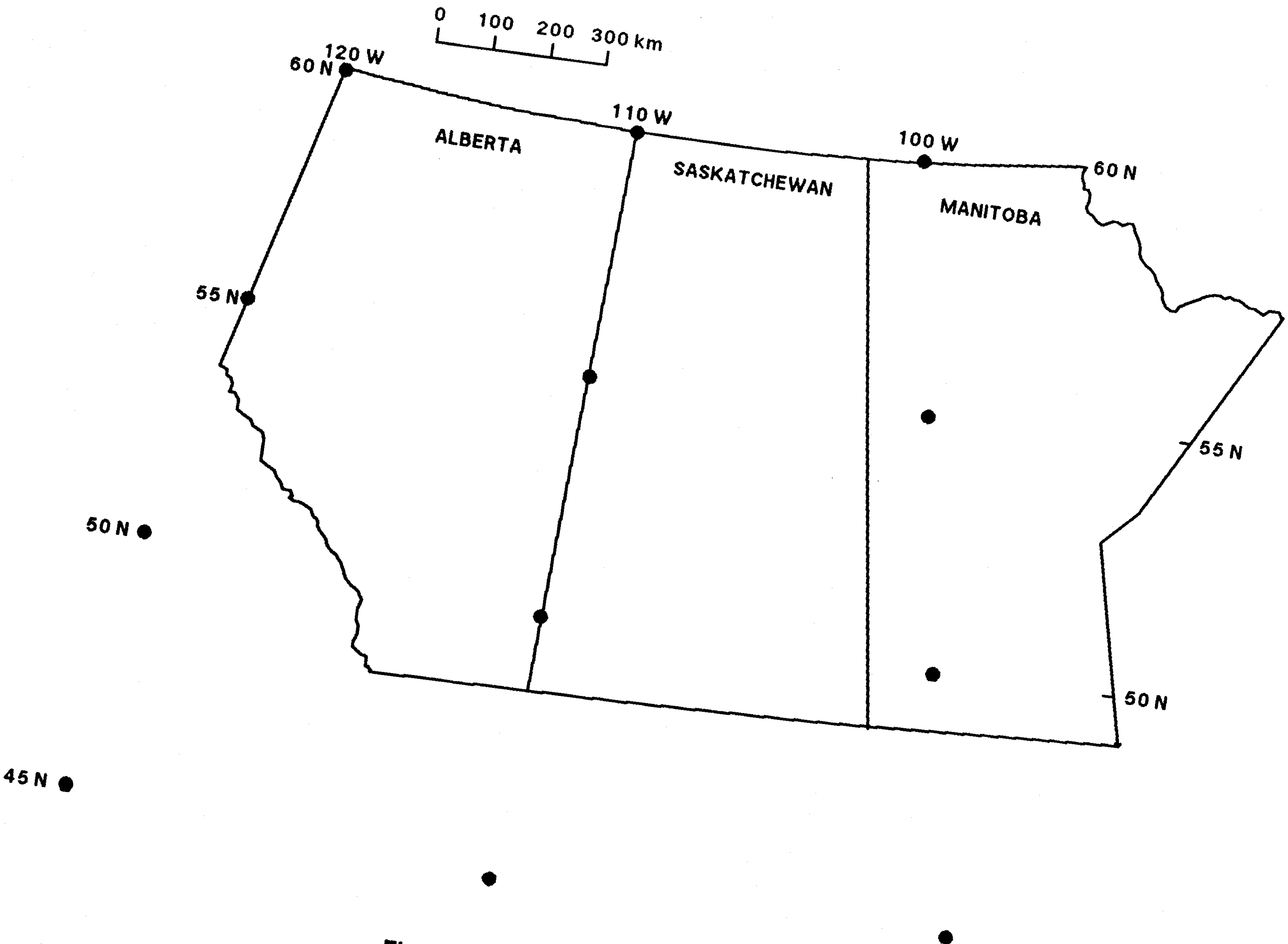

Figure 3.4: 50 kPa Grid Points Used in this Study.

3.2.2.2 ANOMALOUS 50 KPA CIRCULATION PATTERNS

One of the most efficient ways to determine upper-air circulation patterns is to examine their anomalies (e.g. Knox and Lawford, 1990). An anomalous circulation pattern is defined as the difference between the observed pattern and the long-term (in this case 41-year) average pattern during the same time period. Anomalous 50 kPa circulation patterns associated with each extended dry spell were determined in the following manner. First, daily averages for each grid point were calculated for the time period 1948-1988. Daily anomalous values were then determined by subtracting the 41-year average value from the actual value for any given day. The 50 kPa anomalous circulation pattern associated with each spell was then quantified in the following manner. The average 50 kPa anomalous value at each grid point was calculated for the entire dry spell period. Then, an anomalous 50 kPa map was generated through interpolation from the 12 grid points mentioned previously. An example of a 50 kPa anomaly map for the Canadian Prairie study area is given in Figure 3.5.

Using this map, an overall average 50 kPa height anomaly for the Canadian Prairie study area was then calculated. The following is an example of the computation for an average 50 kPa height anomaly using the map given in Figure 3.5:

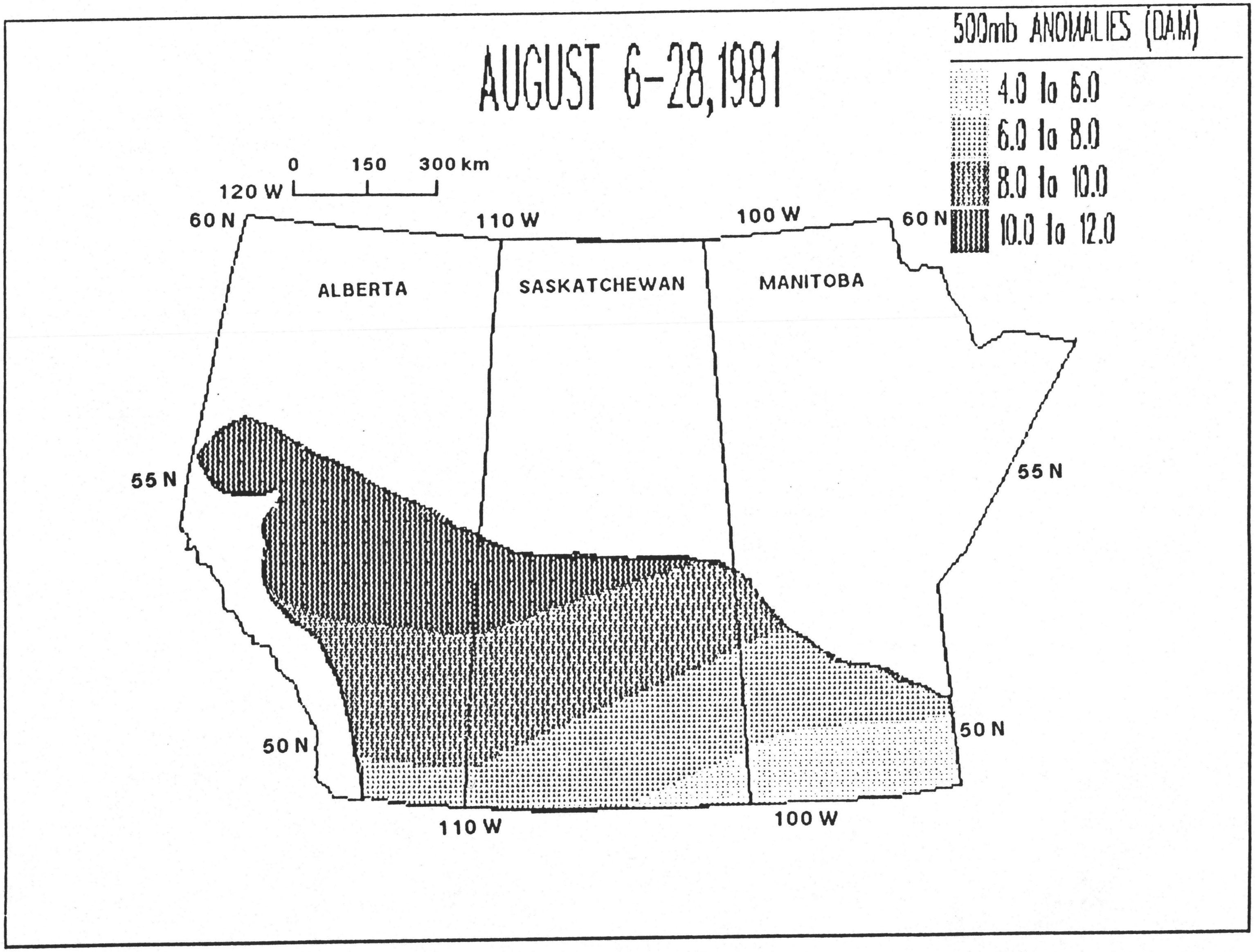

Figure 3.5: Example of a 50 kPa Anomaly Map, Aug 6-28, 1981.

50 kPa Anomaly (dam)	% Area Covered
4.0 to 6.0	11.85
6.0 to 8.0	27.63
8.0 to 10.0	32.56
10.0 to 12.0	27.96

Calculation of average 50 kPa height anomaly:

(5.0 x .1185) + (7.0 x .2763) + (9.0 x .3256) + (11.0 x .2796)

= 0.59 + 1.93 + 2.93 + 3.08

= 8.53 decameters

This final value was then considered to be the average 50 kPa height anomaly associated with this extended dry spell.

3.2.3 SEA SURFACE TEMPERATURES IN THE NORTH PACIFIC OCEAN

Once individual extended dry spells had been determined and 50 kPa anomalous circulation patterns identified, North Pacific sea surface temperature patterns associated with each extended dry spell were analyzed.

3.2.3.1 NATURE OF THE SEA SURFACE TEMPERATURE DATA

The sea surface temperature data set used in this study consisted of gridded monthly North Pacific sea surface temperatures for the period 1948-1988. The data were obtained from Scripps Institution of Oceanography in La Jolla, California. This is the same data set used by Namias and many others in all of their North Pacific sea surface temperature studies. The sea surface temperature data set is based on ship observations compiled by the Bureau of Commercial Fisheries, U.S. Weather Bureau reports, and the National Marine Fisheries Service and consists of temperature values on a 5° latitude-longitude grid (Namias, 1970; Davis, 1976). Therefore, the North Pacific study area consisted of a grid system of 181 points. A map showing the location of these grid points is given in Figure 3.6.

However, some of the values for certain grid points were still missing. The problem of missing data was handled in the following manner. If a grid point had more than half of its values missing during the 41-year study period, it was not used in the analysis. There were only 10 such grid points. A map showing these 10 points is given in Figure 3.7. As shown by this map, all of these grid points were located on the outside border of the study area. Therefore, their omission would not likely affect the overall North Pacific sea surface temperature anomaly pattern.

3.2.3.2 NORTH PACIFIC SEA SURFACE TEMPERATURE ANOMALY PATTERNS

As with upper-air circulation, the most efficient way to observe sea surface temperature patterns is to examine their anomalies. For this study, a sea surface temperature anomaly

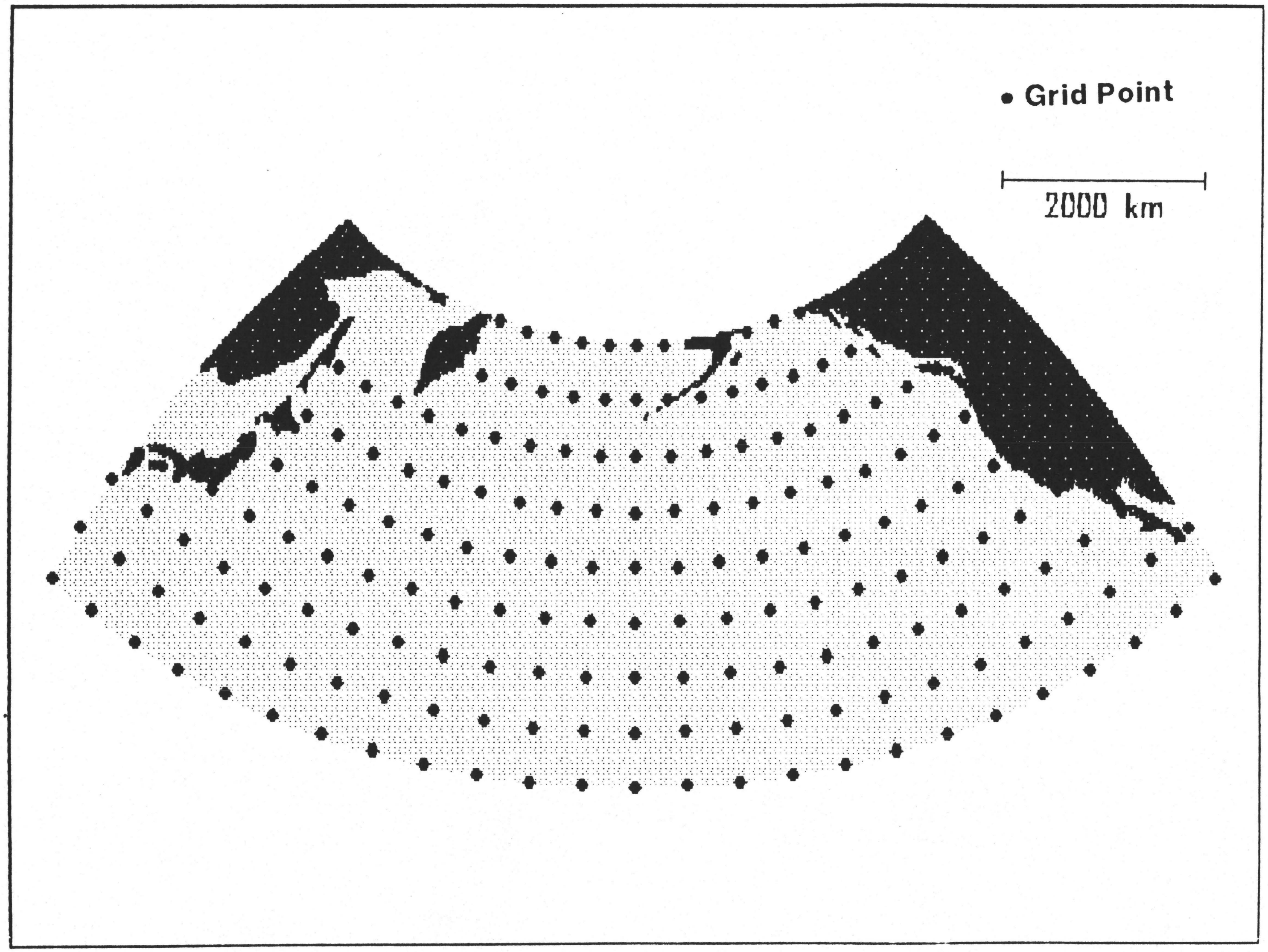

Figure 3.6: North Pacific Ocean Grid Points Used in this Study.

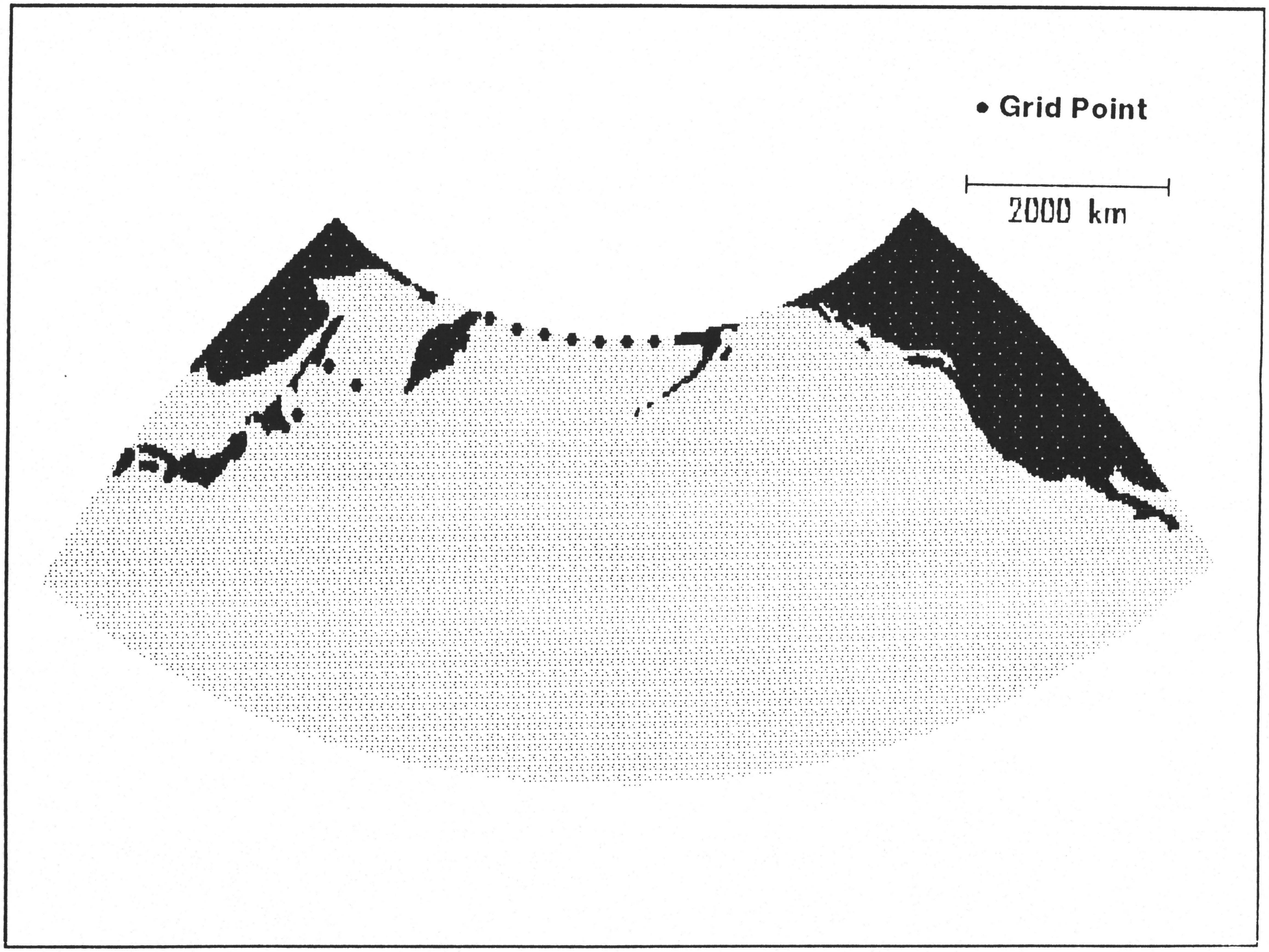

Figure 3.7: North Pacific Ocean Grid Points Not Used in this Study.

was defined as the difference between the observed sea surface temperature value for a particular month and the 41-year average value at the same location for the same month.

Sea surface temperature anomalies were calculated for each month and anomaly maps were then generated. These maps were produced using simple linear interpolation from each grid point. An example of a North Pacific sea surface temperature anomaly map is given in Figure 3.8. These monthly anomaly maps were then used in the analysis of sea surface temperature anomaly patterns as discussed in the next chapter.

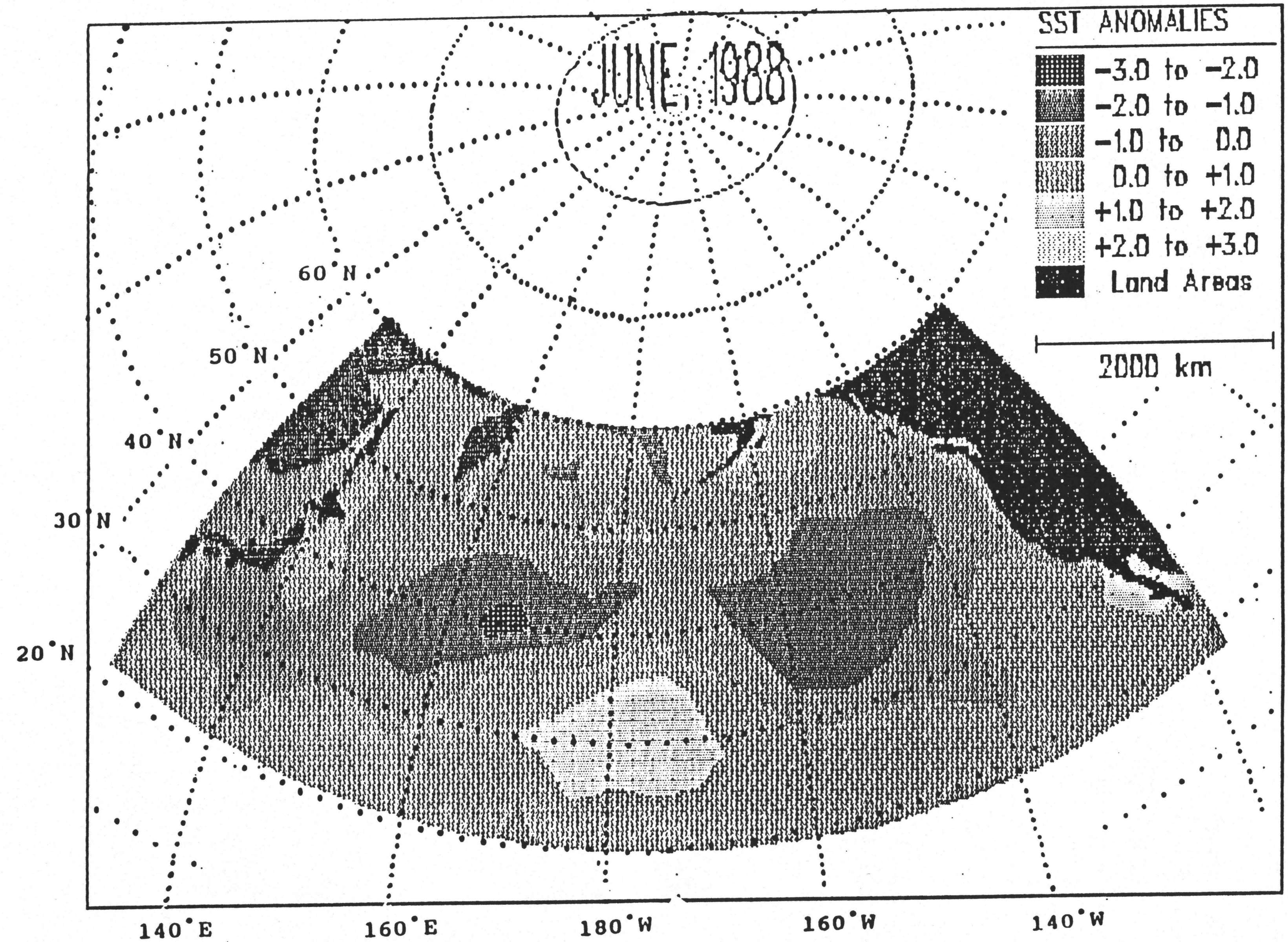

Figure 3.8: Example of a Sea Surface Temperature Anomaly Map, June, 1988.

CHAPTER 4

ANALYSIS OF EXTENDED DRY SPELLS OVER THE CANADIAN PRAIRIES AND SEA SURFACE TEMPERATURE ANOMALIES IN THE NORTH PACIFIC OCEAN

This chapter analyzes anomalous North Pacific sea surface temperatures and extended dry spells on the Canadian Prairies to determine if there is a significant relationship between them. This involves the examination of extended dry spells over the Canadian Prairies in terms of their definition, frequency, severity, and temporal characteristics. Sea surface temperature anomaly patterns in the North Pacific Ocean are also analyzed in order to determine their characteristic features.

4.1 EXTENDED DRY SPELLS

4.1.1 DEFINITION OF EXTENDED DRY SPELLS

There are several variables which might be examined when defining dry spells and droughts. These include temperature, precipitation, evapotranspiration, soil moisture, upper-air circulation, as well as their temporal and spatial characteristics. Different methods using some or all of these variables have been used to define dry spells and droughts. This investigation is interested in the causes of prolonged periods of no precipitation over the Canadian Prairies. As a result, this study considers the duration, spatial extent, and upper air-circulation (50 kPa) patterns associated with extended dry spells and droughts.

Dey (1973) defined a dry spell on the Canadian Prairies using duration and spatial extent. His definition was: a period of at least seven consecutive days during which 68% or more of the stations within the Prairies reported no measurable precipitation. However this definition does not take into account the upper-air circulation patterns associated with the dry spells. Therefore, for the purpose of this study, a more comprehensive version of Dey's definition will be used.

Definition of an Extended Dry Spell:

A period of at least 10 consecutive days during which 50% or more of the stations within the study area report no measurable precipitation and the entire period has a positive average 50 kPa anomalous height value within the study area.

The period was lengthened to 10 days because this study is looking for <u>extended</u> dry spells which lead to drought. The number of stations was reduced to 50% because the Canadian Prairies extend over a very large area. As a result, it is unlikely that an extended dry spell would encompass more than

68% of the study area. Finally, the entire period had to have a positive average 50 kPa anomaly or ridge associated with the spell. This is due to the fact that the study is examining the occurrence of synoptic climatological extended dry spells. Therefore, all the spells identified in this study are synoptic extended dry spells.

Using this definition, 35 individual extended dry spells were identified across the Canadian Prairies for the growing seasons of 1948-1988. A list of these extended spells is given in Table 4.1. An examination of this list indicated that some growing seasons had more than one extended dry spell associated with them. Since the growing season lasts for a period of four months, this is not an unusual phenomenon. However, it is observed that some spells occur very close to each other. The question is whether these spells are synoptically independent of each other or are they part of one longer spell?

It is known that once a large-scale upper-level ridge becomes quasi-stationary, it results in widespread dry conditions over the area (Dey, 1973; Dey and Chakravarti, 1976; Dey, 1982). However, some local convective cells can cause precipitation to fall in some areas. The ridge is not affected by these localized convections and thus remains quasi-stationary. This could be the case in some of the outlined extended dry spells in this study. The ridge was present during the entire time period but the spells were

Table 4.1: Extended Dry Spells During the Growing Season, 1948-1988

1. May 1-15, 1949.
2. May 3-12, 1951.
3. May 5-22, 1952.
4. Aug 16-25, 1952.
5. Aug 11-21, 1953.
6. Jul 13-23, 1955.
7. May 14-23, 1956.
8. Jun 4-13, 1956.
9. May 1-11, 1958.
10. May 13-25, 1958.
11. Jul 6-15, 1960.
12. Jul 18-27, 1960.
13. May 16-25, 1961.
14. May 30 - Jun 8, 1961.
15. Jun 19-28, 1961.
16. Jul 31 - Aug 9, 1961.
17. Aug 17-26, 1961.
18. May 1-12, 1966.
19. Aug 9-18, 1967.
20. Aug 22-31, 1967.
21. Aug 17-26, 1969.
22. May 29 - Jun 8, 1970.
23. May 6-15, 1971.
24. Aug 21-31, 1972.
25. May 10-19, 1973.
26. May 1-10, 1976.
27. May 1-24, 1980.
28. Aug 6-15, 1981.
29. Aug 19-28, 1981.
30. May 13-22, 1985.
31. Jun 30 - Jul 10, 1985.
32. May 23 - Jun 1, 1986.
33. May 3-12, 1987.
34. Jun 2-11, 1988.
35. Aug 22-31, 1988.

separated by the occurrence of localized convective events.

The main interest is to examine extended dry spells which lead to drought over the Canadian Prairies. Therefore, the spells that occurred relatively close to each other were further examined to determine if they were part of the same extended spell. The procedure used in the analysis of these cases was as follows. Firstly, those extended dry spells that occurred relatively close to each other (i.e. within two weeks) were selected. The break between spells was then examined to make sure that it had a positive average 50 kPa height value associated with it. This would ensure that an upper-level ridge was present during the entire time period (i.e the extended spells as well as the break between spells). After incorporating this procedure, it was found that seven "combined" extended dry spells had occurred. A list of these combined spells along with the individual spells from which they were taken is given in Table 4.2. Note that the percentage of stations encompassed by the combined extended dry spells were reduced but still remained above 25% (Table 4.3).

4.1.2 WEIGHTING AND RANKING OF EXTENDED DRY SPELLS

After combining some of the extended dry spells, the total number of extended spells over the Canadian Prairies was reduced from 35 to 27. In other words, there were 27 extended dry spells in the 41-year study period (Table 4.3). This suggests that 10-day dry spells are a frequent occurrence on the Canadian Prairies. However, for the purpose of this analysis, only the most severe extended dry spells are examined. Therefore, these spells were ranked in order to

Table 4.2: Combined Extended Dry Spells.

INDIVIDUAL SPELLS (Taken From Table 4.1)	COMBINED SPELL
1. May 16-23, 1956 (#7) Jun 4-13, 1956 (#8)	May 16 - Jun 13, 1956
2. May 1-11, 1958 (#9) May 13-25, 1958 (#10)	May 1-25, 1958
3. Jul 6-15, 1960 (#11) Jul 18-27, 1960 (#12)	Jul 6-27, 1960
4. May 16-25, 1961 (#13) May30 - Jun8, 1961 (#14) Jun 19-28, 1961 (#15)	May 16 - Jun 28, 1961
5. Jul31 - Aug9, 1961 (#16) Aug 17-26, 1961 (#17)	Jul 31 - Aug 26, 1961
6. Aug 9-18, 1967 (#19) Aug 22-31, 1967 (#20)	Aug 9-31, 1967
7. Aug 6-15, 1981 (#28) Aug 19-28, 1981 (#29)	Aug 6-28, 1981

determine the most severe ones that would most likely lead to drought on the Canadian Prairies.

In this investigation, three variables were used to assess the severity of the extended dry spells. These included duration in days, average 50 kPa anomalous height value (measured in decameters), and percentage of stations encompassed by the extended dry spell. A chronological list of extended dry spells along with the values of the variables associated with each spell is given in Table 4.3.

Table 4.3: Extended Dry Spells and Their Associated Variable Values.

EXTENDED DRY SPELL	DURATION (days)	AVE 50 KPA ANOMALOUS HEIGHT VALUE (dam)	% AREA COVERED
1. May 1-15, 1949	15	7.26	76.19
2. May 3-12, 1951	10	12.09	81.35
3. May 5-22, 1952	18	2.15	47.75
4. Aug 16-25, 1952	10	1.08	54.76
5. Aug 11-21, 1953	11	6.07	54.92
6. Jul 13-23, 1955	11	9.76	51.43
7. May14 - Jun13, 1956	31	4.97	27.37
8. May 1-25, 1958	25	3.50	44.86
9. Jul 6-27, 1960	22	5.05	33.17
10. May16 - Jun28, 1961	44	7.37	38.76
11. Jul31 - Aug26, 1961	27	5.58	54.73
12. May 1-12, 1966	12	5.17	62.17
13. Aug 9-31, 1967	23	5.71	56.79
14. Aug 17-26, 1969	10	4.31	67.86
15. May29 - Jun8, 1970	11	7.88	53.33
16. May 6-15, 1971	10	4.43	55.95
17. Aug 21-31, 1972	11	6.11	53.02
18. May 10-19, 1973	10	4.56	71.03
19. May 1-10, 1976	10	2.76	66.67
20. May 1-24, 1980	24	5.94	72.22
21. Aug 6-28,1981	23	8.53	32.77
22. May 13-22, 1985	10	6.22	63.10
23. Jun30 - Jul10, 1985	11	5.45	52.06
24. May23 - Jun1, 1986	10	14.62	70.63
25. May 3-12, 1987	10	9.48	61.51
26. Jun 2-11, 1988	10	11.70	72.86
27. Aug 22-31, 1988	10	0.20	50.62

Each of these aforementioned variables has an effect on the severity of an extended dry spell. The question is exactly how much effect does each variable have? Probably the best way to examine this situation is to try and weight each variable in terms of how they are actually weighted in the "real world" or how they actually affect extended dry spells and droughts on the Canadian Prairies.

In order to accomplish this, each variable is examined in greater detail. The first variable to be examined is the duration or length of the spell. In this investigation, the length of the spell is probably the most important variable. This is due to the fact that the study is examining <u>extended</u> dry spells that directly lead to drought on the Canadian Prairies. Also, it has been documented that sea surface temperature anomalies, once established, tend to persist for long periods of time (Namias and Cayan, 1981). Therefore, the extended dry spells associated with these sea surface temperature anomalies should also persist for a long period of time.

The next variable to be examined is the upper-air circulation anomalies associated with an extended dry spell. This variable is also very important because it is a major part of this paper's hypothesis which states that sea surface temperature anomalies over the North Pacific Ocean cause an upper-level ridge to become quasi-stationary over the Canadian Prairies. This ridge then leads directly to extended dry spells over the area. However, the ridge is not as important as the length of the spell because the formation of this ridge will not always be located over the same area. The study area used in this investigation has set boundaries and since the ridge is dynamic in nature, it is not confined to these boundaries. As a result, the ridge may be present, but not situated directly over the Canadian Prairie study area. Therefore, the magnitude of the 50 kPa anomaly may not be a definitive indicator of the strength of the ridge. As a result, the upper-air circulation anomalies associated with an extended dry spell are not given as much weight as its length.

The final variable to be examined is the spatial extent of the extended dry spell. In this study, this refers to the percentage of stations encompassed by the spell. This factor is not as important as the other two factors because the study area used in this investigation extends over a large area. As a result, it is unlikely that an extended dry spell would encompass the entire study area. Also, as was mentioned previously, certain stations over the Canadian Prairies can receive some precipitation even if a quasi-stationary ridge is present over the area. Therefore, spatial extent is not given as much weight as the other two variables but should still be considered when ranking extended spells because it is one of the factors that affect the severity of these spells.

In summary, this assessment suggests that the duration of an extended dry spell is the most important factor with the upper-air circulation patterns being second most important. The least important factor in this study is spatial extent. This information was taken into account with regards to the weighting of each variable and ultimately the ranking of individual extended dry spells. Each variable was weighted in the following manner. Duration of the spell is the most important factor and therefore is weighted twice as heavily as the upper-air circulation anomalies. The latter are more important than the spatial extent and thus are weighted twice as heavily as the spatial extent. In summary, this relationship can be written as:

Severity of an Extended Dry Spell = 4 x Length + 2 x 50 kPa Anomaly + 1 x Spatial Extent.

Note that this ranking procedure, even though somewhat arbitrary, is most likely the best method for this particular study because it was derived by scientifically assessing the effect of each variable as it pertains to actual extended dry spells and droughts on the Canadian Prairies. In other words, the extended dry spells were weighted in such a way as to identify actual droughts on the Prairies. The results of this weighting method are compared with actual droughts that occurred on the Prairies as discussed later on in this chapter (Section 4.1.3).

The variables associated with each spell are not measured in the same units. Therefore, they had to be normalized before they could be compared. This is done by subtracting the variable's mean from the actual value and then dividing by the variable's standard deviation (Ebdon, 1985). Table 4.4 shows the mean and standard deviation for each variable.

Table 4.4: Mean and Standard Deviation for each Extended Dry Spell Variable

VARIABLE	MEAN	STANDARD DEVIATION
1. Length (days)	15.89	8.66
2. 50 kPa Anomaly (dam)	6.22	3.30
3. Spatial Extent (%)	56.49	13.73

A list of each extended dry spell along with the normalized value of each variable is given in Table 4.5.

After normalization, the variables were combined using the weighting method described above. The following is an example of how the weighted dry spell value is calculated using the spell which occurred from May 1-15, 1949.

Variable	Normalized Value
Duration	-0.10
Ridge	0.32
Spatial Extent	1.44

Calculation:

$$(4 \times -0.10) + (2 \times 0.32) + (1 \times 1.44)$$

$$= -0.40 + 0.64 + 1.44$$

$$= 1.68$$

This number was considered to be the weighted value of the extended dry spell.

Table 4.5: Extended Dry Spells and Their Associated Normalized Variables.

EXTENDED DRY SPELL	DURATION	AVE 50 KPA ANOMALOUS HEIGHT VALUE	% AREA COVERED
1. May 1-15, 1949	-0.10	0.32	1.44
2. May 3-12, 1951	-0.68	1.78	1.81
3. May 5-22, 1952	0.24	-1.23	-0.64
4. Aug 16-25, 1952	-0.68	-1.55	-0.13
5. Aug 11-21, 1953	-0.56	-0.04	-0.12
6. Jul 13-23, 1955	-0.56	1.08	-0.37
7. May14 - Jun13, 1956	1.74	-0.37	-2.12
8. May 1-25, 1958	1.05	-0.82	-0.85
9. Jul 6-27, 1960	0.70	-0.35	-1.70
10. May16 - Jun28, 1961	3.23	0.35	-1.29
11. Jul31 - Aug26, 1961	1.28	-0.19	-0.13
12. May 1-12, 1966	-0.45	-0.31	0.41
13. Aug 9-31, 1967	0.82	-0.15	0.02
14. Aug 17-26, 1969	-0.68	-0.57	0.82
15. May29 - Jun8, 1970	-0.56	0.51	-0.23
16. May 6-15, 1971	-0.68	-0.54	-0.04
17. Aug 21-31, 1972	-0.56	-0.03	-0.25
18. May 10-19, 1973	-0.68	-0.50	1.06
19. May 1-10, 1976	-0.68	-1.04	0.74
20. May 1-24, 1980	0.93	-0.08	1.15
21. Aug 6-28,1981	0.82	0.71	-1.73
22. May 13-22, 1985	-0.68	0.00	0.48
23. Jun30 - Jul10, 1985	-0.56	-0.23	-0.32
24. May23 - Jun1, 1986	-0.68	2.55	1.03
25. May 3-12, 1987	-0.68	0.99	0.37
26. Jun 2-11, 1988	-0.68	1.67	1.19
27. Aug 22-31, 1988	-0.68	-1.82	-0.65

This procedure was carried out for all the identified spells. The extended dry spells were then ranked by using these weighted values. Table 4.6 shows the ranked extended dry spells along with their weighted values. The spells are presented in order of their severity starting with the most severe.

Table 4.6: Ranked Extended Dry Spells

EXTENDED DRY SPELL	WEIGHTED VALUE
1. May 16 - Jun 28, 1961	12.33
2. May 1-24, 1980	4.71
3. Jul 31 - Aug 26, 1961	4.61
4. May 14 - Jun 13, 1956	4.09
5. May 23 - Jun 1, 1986	3.41
6. Aug 9-31, 1967	3.00
7. Aug 6-28, 1981	2.97
8. May 3-12, 1951	2.65
9. Jun 2-11, 1988	1.81
10. May 1-25, 1958	1.71
11. May 1-15, 1949	1.68
12. Jul 6-27, 1960	0.40
13. May 3-12, 1987	-0.37
14. Jul 13-23, 1955	-0.45
15. May 29 - Jun 8, 1970	-1.45
16. May 1-12, 1966	-2.01
17. May 5-22, 1952	-2.14
18. May 13-22, 1985	-2.24
19. Aug 11-21, 1953	-2.44
20. Aug 21-31, 1972	-2.55
21. May 10-19, 1973	-2.66
22. Jun 30 - Jul 10, 1985	-3.02
23. Aug 17-26, 1969	-3.03
24. May 6-15, 1971	-3.84
25. May 1-10, 1976	-4.06
26. Aug 16-25, 1952	-5.95
27. Aug 22-31, 1988	-7.01

Once the extended dry spells were ranked in terms of their severity, they were further analyzed in order to determine the most severe or major spells. In order to determine this, the weighted values of each extended dry spell were plotted in frequency distribution format (Figure 4.1). From this graph, it can be seen that there is one extended dry spell that is very severe. This spell occurred from May 16 - Jun 28, 1961. The rest of the spells are distributed over a more compressed range. However, between the weighted dry spell values of 0.0 and 2.0, there appears to be a break in the frequency of occurrence of extended dry spells. This break may signify that there is a difference between the spells with values greater than 1.0 and those with values less than 1.0. The break can probably be assumed to be the difference between major extended dry spells leading to droughts and other normal extended spells. Therefore, for this study, a major extended dry spell is defined as an extended dry spell that has a weighted value of greater than 1.0. Based on this definition, there were 11 major extended dry spells in the 41-year study period (see Table 4.6). This works out to an average of approximately one major extended dry spell or drought every four growing seasons which is probably quite representative of conditions in the Canadian Prairie region. A list of the major extended dry spells in order of their severity is given in Table 4.7.

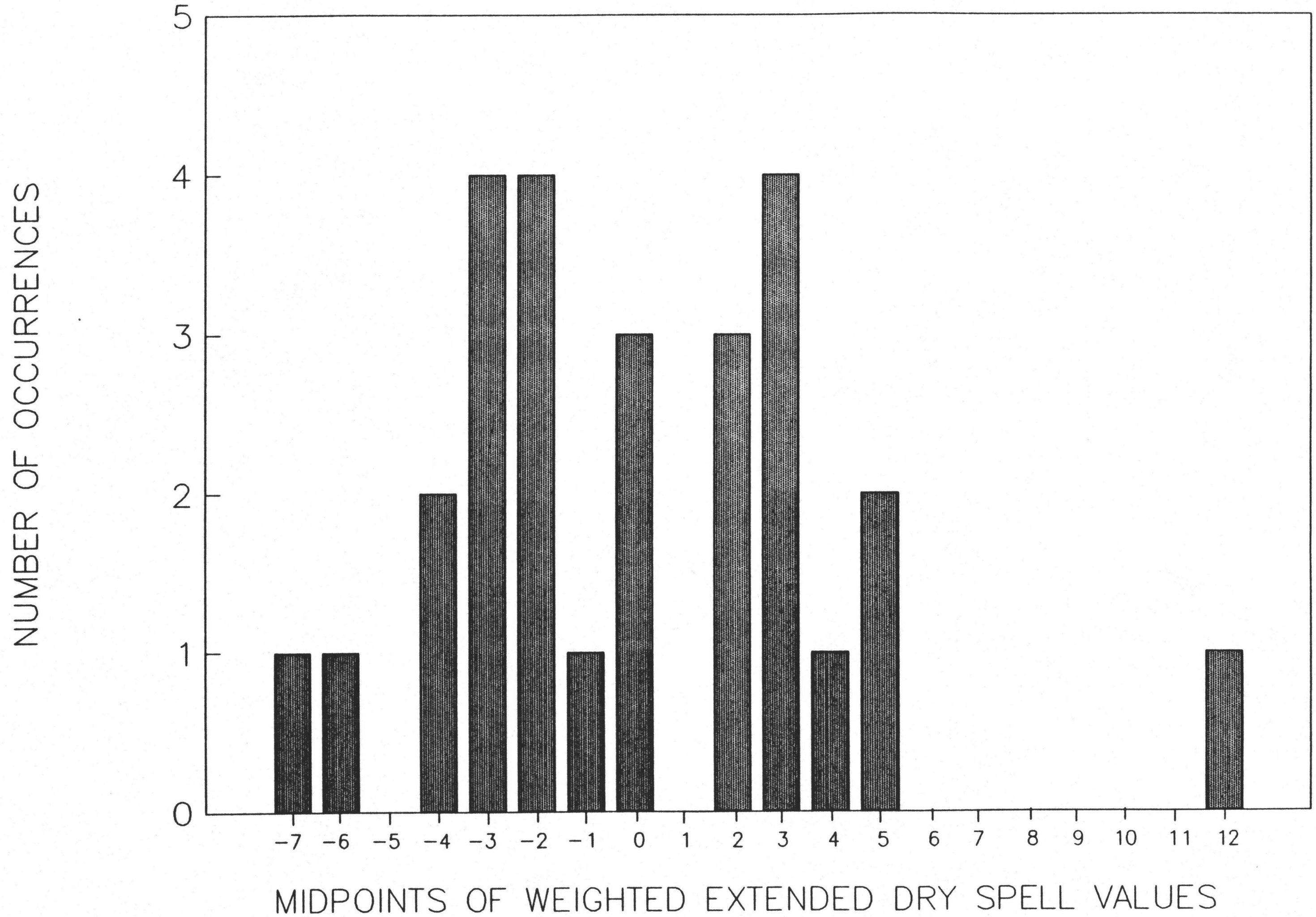

Figure 4.1: Bar Graph Showing the Frequency Distribution of Weighted Extended Dry Spell Values on the Canadian Prairies.

Table 4.7: Major Extended Dry Spells.

1. May 16 - Jun 28, 1961
2. May 1-24, 1980
3. Jul 31 - Aug 26, 1961
4. May 14 - Jun 13, 1956
5. May 23 - Jun 1, 1986
6. Aug 9-31, 1967
7. Aug 6-28, 1981
8. May 3-12, 1951
9. Jun 2-11, 1988
10. May 1-25, 1958
11. May 1-15, 1949

4.1.3 MAJOR EXTENDED DRY SPELLS VS WHEAT YIELDS

The major extended dry spells have been determined using the methods outlined earlier in this chapter. These spells were compared with reported droughts that occurred during the growing season on the Canadian Prairies for the years 1948-1988 in order to determine if the analyses carried out in defining these major spells were valid. One of the best methods of identifying droughts over the Prairies is in terms of agricultural crop yields. Extended dry periods or droughts usually bring about major agricultural crop reductions over large areas of the Canadian Prairies. The major agricultural product produced on the Canadian Prairies is wheat (Walker, 1989). As a result, annual wheat yields should provide a good indication of whether a major extended dry spell or drought has occurred during a particular growing season.

Annual wheat yields over the Canadian Prairies for the years 1948-1988 were obtained from the Canadian Wheat Board in Winnipeg, Man. (note that the yields were obtained in bushels per acre). These yields were graphically compared to their 5-year running mean (Figure 4.2). The 5-year running mean shows the average trend for wheat yields throughout the entire study period. Individual wheat yields can then be compared to this running mean to determine if yields were above or below average. The growing seasons during which major extended dry spell episodes occurred are also indicated on Figure 4.2. As shown by this graph, seven out of the eleven major extended dry spell or drought episodes were associated with wheat yields below the 5-year running mean. Also, the most severe extended dry spell (1961), had a wheat yield considerably below this average. Most of the major extended dry spells that were associated with wheat yields higher than the 5-year running mean were early growing season spells. In other words, they occurred in May and therefore probably did not have a great effect on wheat yields because the rest of the growing season had ample moisture for crop growth. Any major extended dry spell that occurred in June (eg. 1961 and 1988) did have a drastic effect on wheat yields because June has the highest monthly precipitation and also is the time period of maximum growth for crops (Chakravarti, 1972).

The graph also shows that there were some years that had wheat yields considerably below the 5-year running mean but

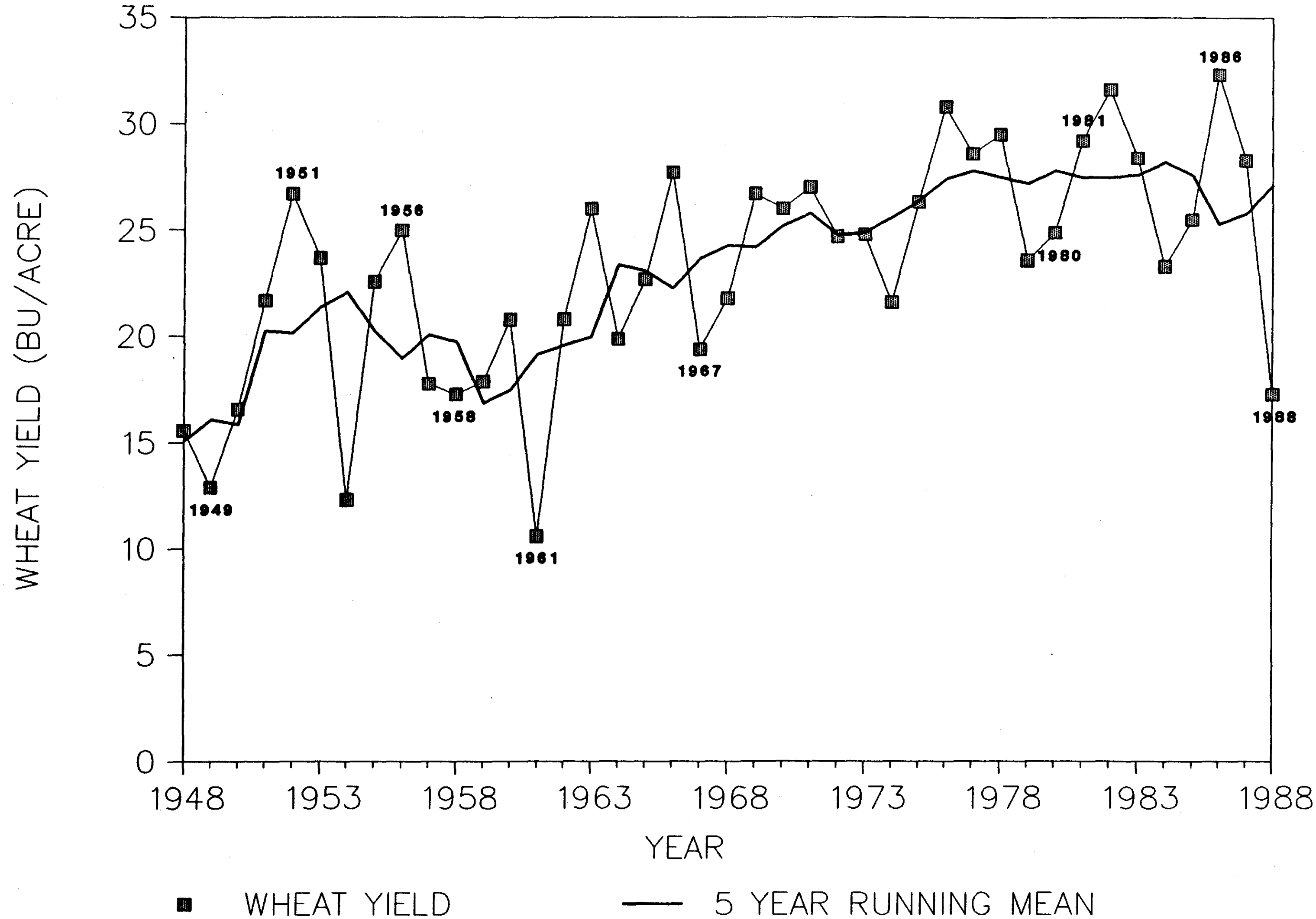

Figure 4.2: Comparative Line Graph Showing Actual Vs 5 Year Running Mean Wheat Yields During the Canadian Prairie Growing Season (1948-88). Growing Seasons Associated with Major Extended Dry Spells are also given.

did not experience a major extended dry spell. This is probably due to the fact that other factors besides dry spells and droughts can have an effect on Canadian Prairie wheat yields. These factors include pests, diseases, frost, and hail (Walker, 1989). In summary, it can be stated that reduced Canadian Prairie wheat yields do basically coincide with the major extended dry spell or drought episodes outlined in this study. In fact, when weighted extended dry spell values for the growing seasons that had extended spells associated with them were correlated with contemporaneous anomalous wheat yields (defined here as the difference between the annual wheat yield and the 5-year running mean wheat yield), a correlation coefficient of -0.44 was obtained. This value, which is significant at the 0.05 significance level, indicates that there is a significant association between the severity of extended dry spells and wheat yields on the Canadian Prairies. Therefore, it can be said that the extended dry spell ranking results obtained in this analysis do compare significantly well with real time droughts as reported by the Canadian Wheat Board.

4.1.4 TEMPORAL DISTRIBUTION OF EXTENDED DRY SPELLS

The temporal distribution of extended dry spells and droughts often provide some insight into the meteorological processes occurring in a particular region. The temporal distribution of extended dry spells is given in Figure 4.3.

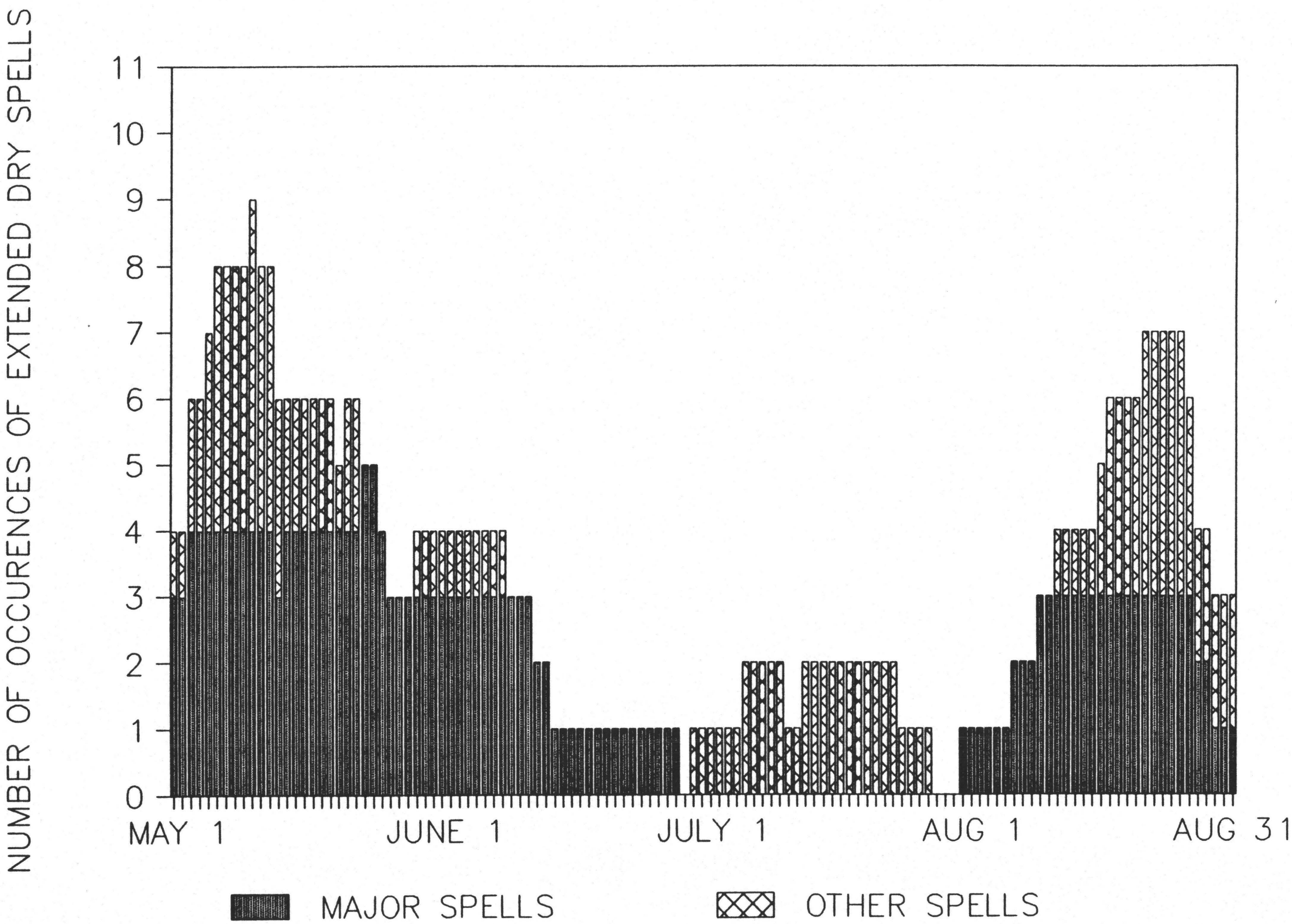

Figure 4.3: Stacked Bar Graph Showing the Temporal Distribution of Extended Dry Spells on the Canadian Prairies (1948-88).

As shown by this graph, the majority of the extended dry spells occur in May, early June, and August. Very few extended spells occurred during late June and July. This would indicate that there may be some meteorological process that occurs in late June and early July that changes the precipitation pattern over the Canadian Prairies. This process could involve an increase of convective activity associated with the higher air temperatures that occur during this time period. As a result, the extended dry spells that did occur during this time period were very unusual because this is also the period when the agricultural area of the Canadian Prairies receive the most precipitation (Chakravarti, 1972).

4.2 SEA SURFACE TEMPERATURE ANOMALIES IN THE NORTH PACIFIC OCEAN

The next step in the analysis was the identification of sea surface temperature anomaly patterns in the North Pacific Ocean. It has been documented that atmospheric flow patterns usually respond quickly to sea surface temperature anomaly patterns (Namias and Cayan, 1981). Therefore, the role of sea surface temperatures was studied by relating Canadian Prairie extended dry spells with contemporaneous sea surface temperature anomaly patterns. In other words, the month in which the extended dry spell occurred was the same month chosen for the sea surface temperature analysis. For example, the extended dry spell that occurred from May 1-15,1949 would be related to the sea surface temperature anomaly pattern that occurred during May 1949.

Since this investigation identified 27 individual extended dry spells, sea surface temperature anomaly maps for 27 individual months were required. However, some spells occurred over the course of two consecutive months and therefore, required two monthly sea surface temperature anomaly maps. Taking these spells into consideration, a total of 33 sea surface temperature anomaly maps were required. These maps were generated using the procedure outlined in Chapter 3. The maps associated with each extended dry spell are given in Appendix B - Table B.1. These maps are included for: 1) major extended dry spells and, 2) other extended dry spells.

4.2.1 CHARACTERISTICS OF SEA SURFACE TEMPERATURE ANOMALIES

Since this study's main focus includes the major extended dry spells that would most likely lead to drought, the sea surface temperature anomaly maps associated with these spells were examined in more detail. The majority of them were found to have regions of anomalously cold water located in the east-central North Pacific Ocean. The centre of this region of water did not occur consistently at one point, although it did usually appear within the area bounded by 30°N to 40°N latitude and 165°W to 135°W longitude. Table

4.8 gives a list of the major extended dry spells along with the approximate location of the centre of the cold anomaly in the east-central North Pacific. These locations were determined using the sea surface temperature anomaly maps given in Appendix B.

Table 4.8: Major Extended Dry Spells and Associated Locations of Cold SST Anomalies in the East-Central North Pacific

MAJOR DRY SPELLS (RANKED)	CENTRE OF THE SST ANOMALY
1. May 16 - Jun 28, 1961	40°N,150°W
2. May 1-24, 1980	35°N,163°W
3. Jul 31 - Aug 26, 1961	35°N,150°W
4. May 14 - Jun 13, 1956	30°N,145°W
5. May 23 - Jun 1, 1986	35°N,155°W
6. Aug 9-31, 1967	40°N,160°W
7. Aug 6-28, 1981	39°N,165°W
8. May 3-12, 1951	NO ANOMALY
9. Jun 2-11, 1988	40°N,150°W
10. May 1-25, 1958	30°N,165°W
11. May 1-15, 1949	NO ANOMALY

The sea surface temperature anomaly maps associated with the major extended dry spells also appear to have another noticeable characteristic. This includes the appearance of anomalously warm water along the central west coast of North America. In most cases, this anomalous water is substantially warmer than the anomalous cold region of water found in the east-central North Pacific. In other words, there is a sea surface temperature anomaly gradient located between the anomalously cooler east-central North Pacific and the anomalously warmer central west coast of North America. Note that even though an anomalously cold region of water was not present in the east-central North Pacific during every major extended dry spell, a sea surface temperature anomaly gradient was still present. This is due to the fact that there was still an anomalously warm region of water along the central west coast of North America. Therefore, it appears that the gradient, and not just the cold or warm region of water, is the important characteristic in these sea surface temperature anomaly patterns.

4.2.2 QUANTIFICATION OF SEA SURFACE TEMPERATURE ANOMALY PATTERNS

Based on this inspection, it appears that a sea surface temperature anomaly gradient exists over the eastern North Pacific Ocean during most major extended dry spell episodes. Since the main objective of this study was to relate extended dry spells over the Canadian Prairies with anomalous sea surface temperature patterns over the North Pacific Ocean, a means had to be found to quantify these sea surface temperature anomaly patterns.

Different methods were tried in order to accomplish this. The first of these was trend surface analysis. This method is used in the analysis of change over space and in this case, attempts to quantify the gradient associated with the sea surface temperature anomaly pattern (Unwin, 1975). However, when this procedure was carried out, the results did not show any significant gradient. This is probably due to the fact that the sea surface temperature anomaly patterns are very complex and as a result, any general trend or gradient is distorted by the complexity of the pattern. Therefore, a method other than trend surface analysis had to be used in order to quantify this gradient.

Next, it was decided to examine the core areas of the anomalies which produced the sea surface temperature anomaly gradient. These areas included the east-central North Pacific and the central west coast of North America. As was outlined previously, the anomalously cold region of water occurred mainly in the area bounded by 30°N to 40°N latitude and 165°W to 135°W longitude. Upon further examination, it appeared that the area of anomalously warmer water along the central west coast of North America occurred consistently near the grid point 50°N, 125°W. More generally, it appeared to occur in the region bounded by the coordinates 45°N to 55°N latitude and 130°W to 125°W longitude. Therefore, it was decided to use these two areas in the quantification of the sea surface temperature gradient. A map showing the location of these two areas is given in Figure 4.4.

The next step was to determine the maximum anomaly values within these two areas for each map. A computer program located the grid point with the largest absolute

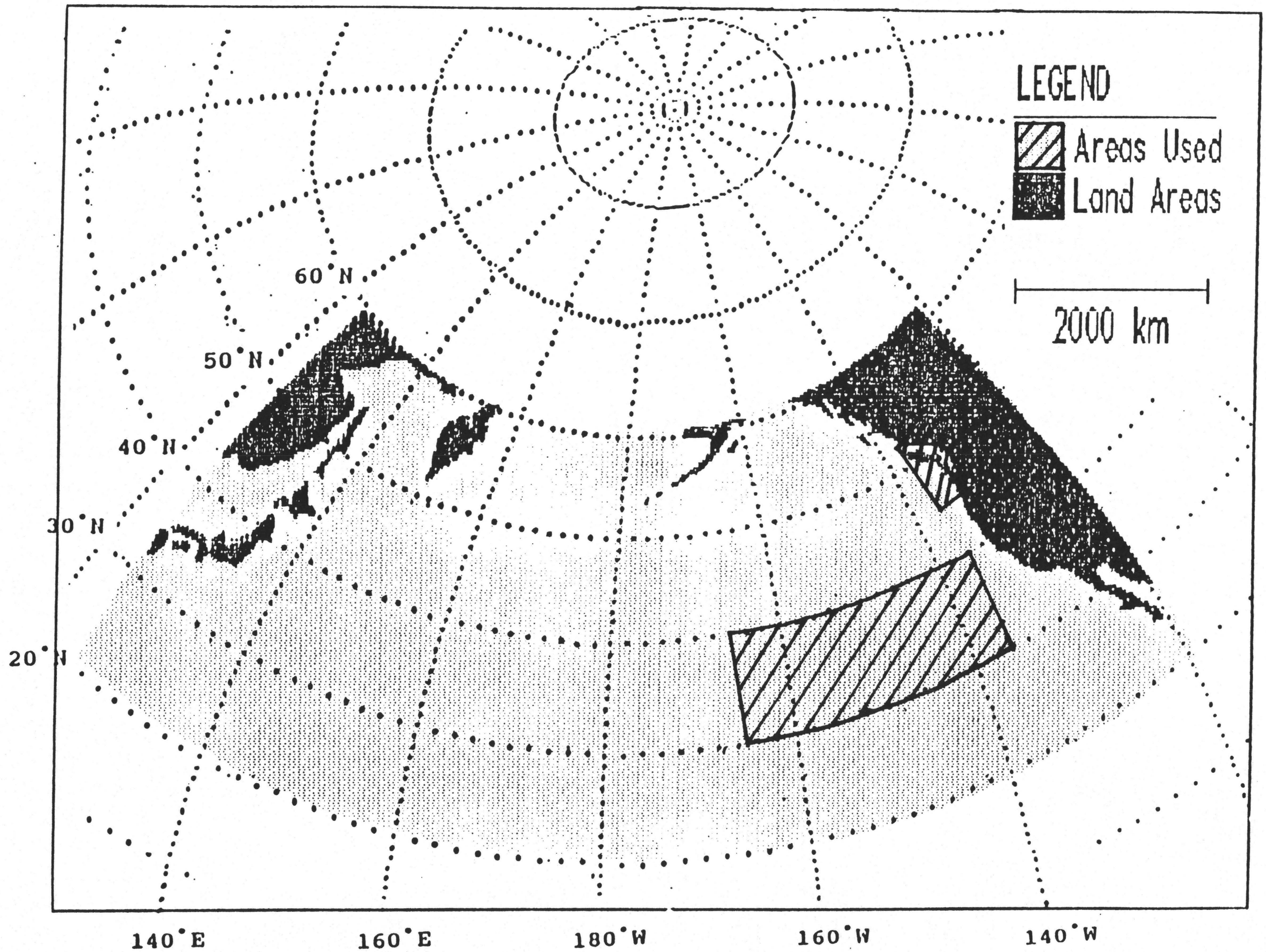

Figure 4.4: North Pacific Ocean Areas Used in the Sea Surface Temperature Anomaly Analysis.

anomaly value, warm or cold, for each area. The sea surface temperature anomaly gradient was then calculated by subtracting the largest absolute anomalous value found in the east-central North Pacific from the largest absolute anomalous value found along the central west coast of North America. Note that for this study, the sea surface temperature anomaly gradient is positive when the temperature anomaly along the west coast of North America is warmer than the temperature anomaly in the east-central North Pacific, and negative when the temperature anomaly along the west coast of North America is colder than the temperature anomaly in the east-central North Pacific.

This analysis was carried out for the sea surface temperature anomaly maps associated with all 27 extended dry spells. Note that if a dry spell occurred over two consecutive months, then the weighted average sea surface temperature anomaly gradient for the two months was used. For example, if an extended spell occurred during the last half of May and the first half of June, then the sea surface temperature anomaly gradient is calculated by taking the average gradient for May and June. A list of the extended dry spells along with their contemporaneous sea surface temperature anomaly gradients is given in Table 4.9.

From this table, it can be seen that 10 out of the 11 major extended dry spells had a positive sea surface temperature anomaly gradient associated with them. Also, it

Table 4.9: Extended Dry Spells and Associated Contemporaneous Sea Surface Temperature Anomaly Gradients

EXTENDED DRY SPELL	SST ANOMALY GRADIENT (°C)
1. May 16 - Jun 28, 1961*	+2.2
2. May 1-24, 1980*	+2.1
3. Jul 31 - Aug 26, 1961*	+2.1
4. May 14 - Jun 13, 1956*	+1.5
5. May 23 - Jun 1, 1986*	+1.3
6. Aug 9-31, 1967*	+2.6
7. Aug 6-28, 1981*	+2.1
8. May 3-12, 1951*	-1.3
9. Jun 2-11, 1988*	+2.4
10. May 1-25, 1958*	+4.0
11. May 1-15, 1949*	+2.2
12. Jul 6-27, 1960	-1.4
13. May 3-12, 1987	+3.4
14. Jul 13-23, 1955	-2.8
15. May 29 - Jun 8, 1970	-2.1
16. May 1-12, 1966	-1.2
17. May 5-22, 1952	-1.1
18. May 13-22, 1985	-1.3
19. Aug 11-21, 1953	-1.7
20. Aug 21-31, 1972	-1.6
21. May 10-19, 1973	-1.5
22. Jun 30 - Jul 10, 1985	+1.0
23. Aug 17-26, 1969	-1.2
24. May 6-15, 1971	-3.3
25. May 1-10, 1976	-2.4
26. Aug 16-25, 1952	-1.6
27. Aug 22-31, 1988	-2.8

* signifies a major extended dry spell

is observed that most of the other less severe extended spells were associated with negative gradients. This implies that major extended dry spells over the Canadian Prairies may in fact be related to sea surface temperature anomaly patterns over the North Pacific Ocean. This pattern includes a sea surface temperature anomaly gradient that consists of colder than normal temperatures in the east-central North Pacific and warmer than normal temperatures along the central west coast of North America. However, some statistical analysis is required to determine the significance of this relationship.

CHAPTER 5

RELATIONSHIPS BETWEEN NORTH PACIFIC SEA SURFACE TEMPERATURE ANOMALIES AND EXTENDED DRY SPELLS AND DROUGHTS ON THE CANADIAN PRAIRIES

This chapter examines the different relationships found between North Pacific sea surface temperature anomalies and synoptic extended dry spells on the Canadian Prairies. It begins with a simple linear regression between the aforementioned variables to determine if their relationship is significant. Also, a conceptual model is constructed showing the relationship between North Pacific sea surface temperature anomalies and the most severe or major extended dry spells. Next, the possibility of a lag relationship between the two variables is examined including the development of a probability model. The chapter concludes with a brief discussion of some of the different aspects found within the aforementioned relationships.

5.1 STATISTICAL CORRELATION

The two main variables in this investigation, synoptic extended dry spells over the Canadian Prairies and sea surface temperature anomalies over the North Pacific Ocean, have been quantified and statistically analyzed. The statistical procedure used was simple linear regression. This procedure regresses a dependent variable (severity of extended dry spells) against an independent variable (sea surface temperature anomaly gradients). The strength of the association between the two variables is measured by a correlation coefficient (R). This R value can be tested for significance using a critical value table found in most statistical books (Ebdon, 1985).

The results of the analysis are given in Figure 5.1. The graph shows that there is a positive relationship between the two variables. An R value of 0.68 was obtained which is significant at the 0.01 significance level. This significant positive relationship indicates that as the sea surface temperature anomaly gradient over the eastern North Pacific Ocean increases, extended dry spells over the Canadian Prairies become more severe.

5.2 CONCEPTUAL MODEL

Another objective of this study is to construct a conceptual model of North Pacific sea surface temperature anomaly patterns associated with the major extended dry spell or drought episodes on the Canadian Prairies. The model is used to summarize both the sea surface temperature anomaly patterns and 50 kPa anomalous height patterns associated with the occurrence of major extended dry spells. To produce this model, composite maps showing both patterns associated with

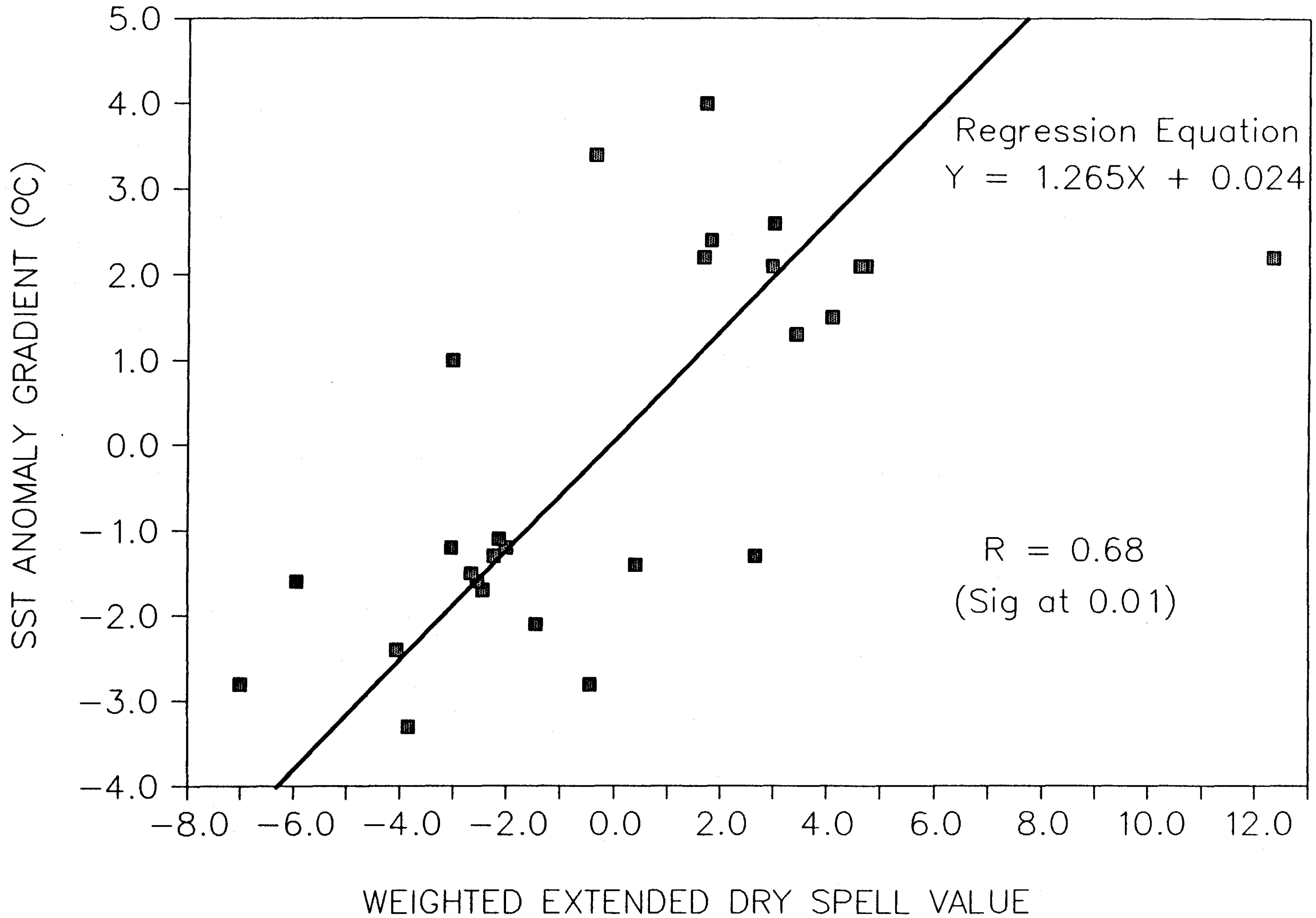

Figure 5.1: Simple Linear Regression Between Sea Surface Temperature Anomaly Gradients in the North Pacific Ocean and Weighted Extended Dry Spell Values on the Canadian Prairies.

the 11 major extended dry spell episodes were produced (Figures 5.2 and 5.3). Note that these maps were produced by determining the average patterns both in sea surface temperature anomalies, and 50 kPa anomalous heights, associated with the major extended dry spells.

As shown in Figures 5.2 and 5.3, a distinct sea surface temperature anomaly pattern and 50 kPa anomaly pattern are evident during these time periods. The composite sea surface temperature anomaly pattern distinctly shows the positive sea surface temperature anomaly gradient which includes the anomalously cold area of water centred in the region bounded by 30°N to 40°N latitude and 165°W to 135°W longitude and the anomalously warm area of water centred in the region bounded by 45°N to 55°N latitude and 130°W to 125°W longitude. This was the same gradient used in the simple linear regression analysis between North Pacific sea surface temperature anomalies and extended dry spells on the Canadian Prairies.

Another interesting feature is the well defined 50 kPa anomaly pattern associated with these sea surface temperature anomaly patterns. As shown in Figure 5.3, the 50 kPa anomaly is centred near the Alberta - Saskatchewan boundary and covers all of the Canadian Prairie study area. As a result, the subsidence associated with this anomaly pattern or ridge is most likely responsible for the occurrence of major extended dry spells on the Canadian Prairies.

To summarize these composite maps, a conceptual model

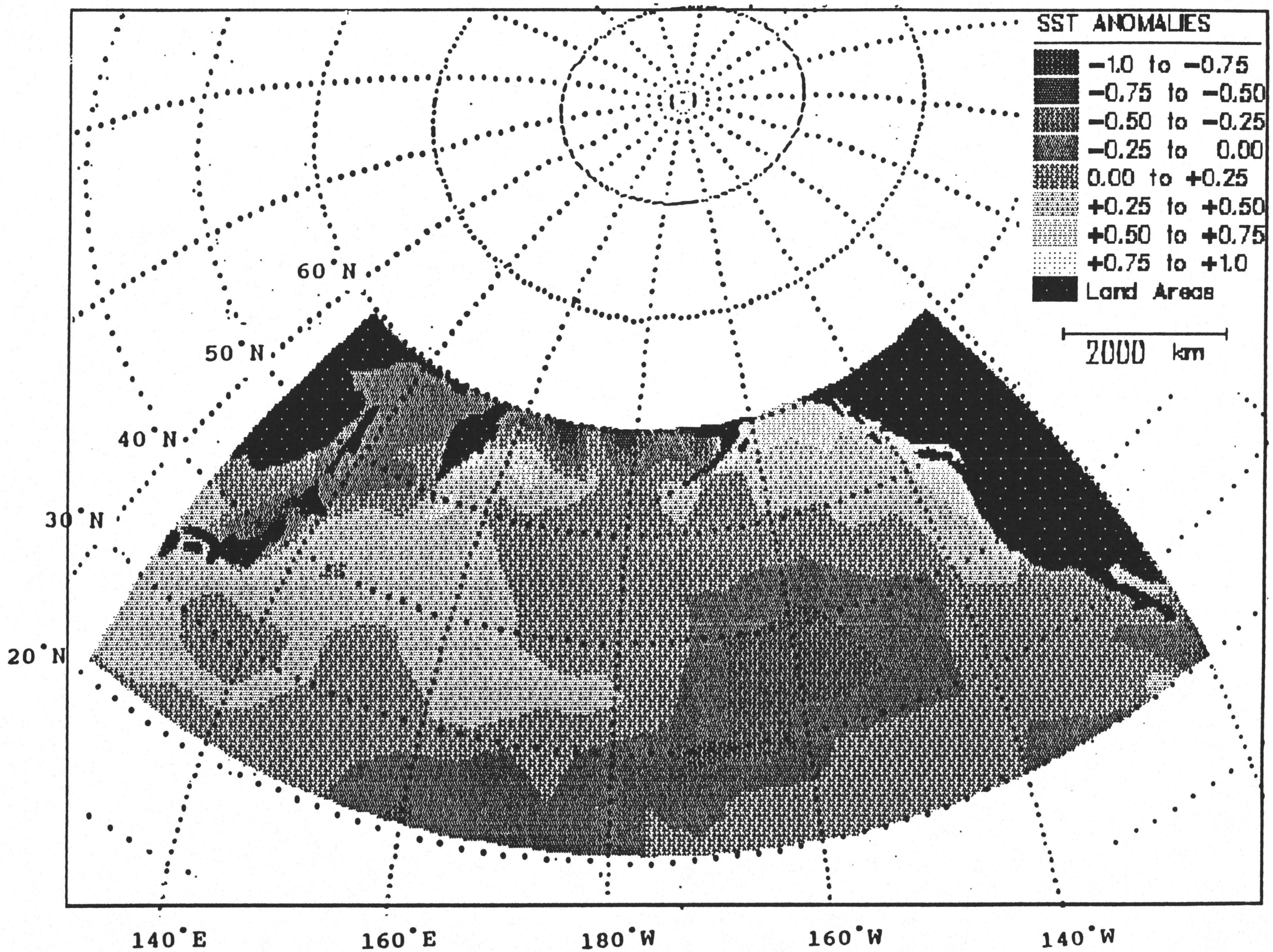

Figure 5.2: Composite Map Showing the Average Sea Surface Temperature Anomalies in the North Pacific Ocean Associated with Major Extended Dry Spells on the Canadian Prairies.

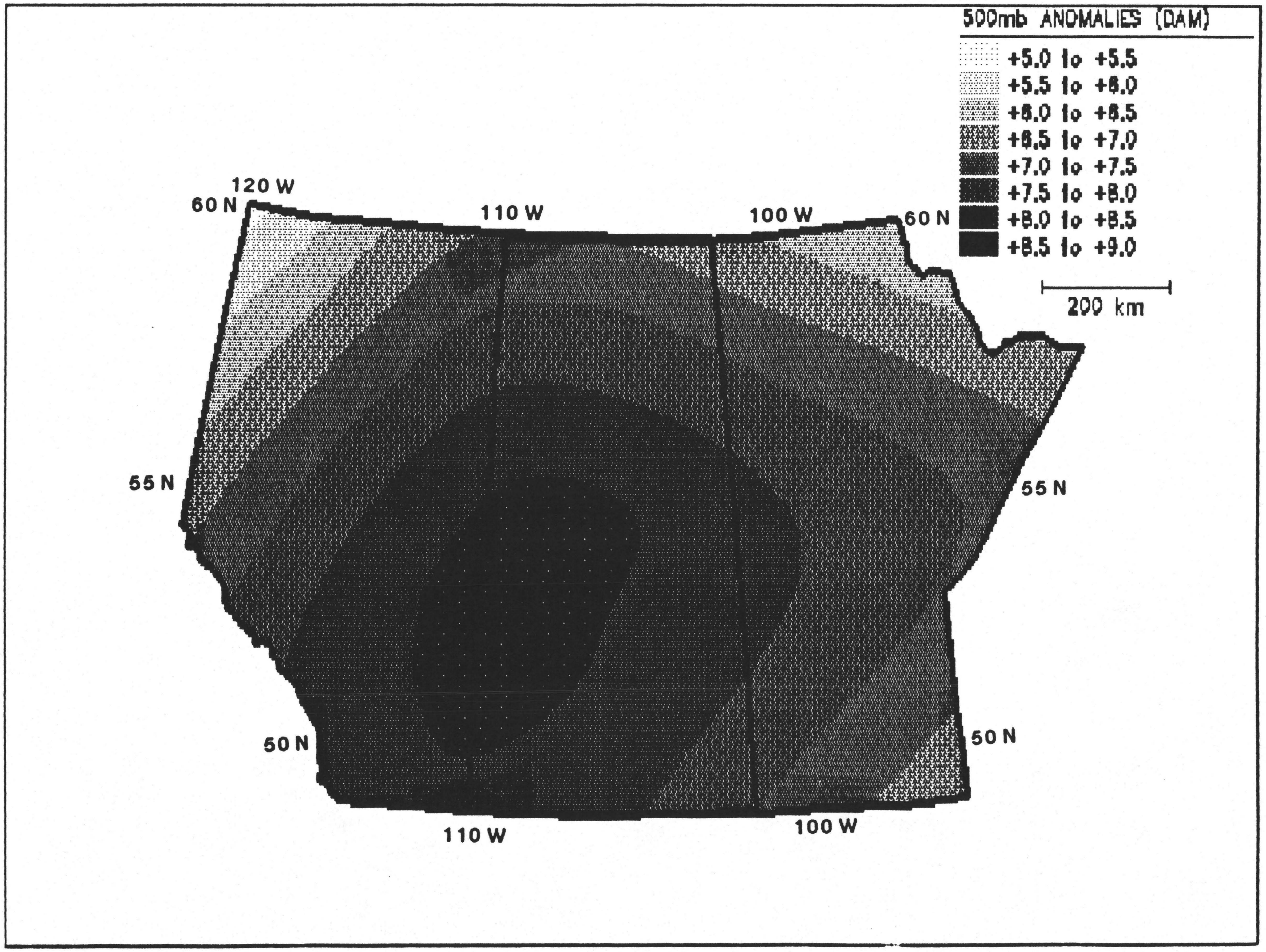

Figure 5.3: Composite Map Showing the Average 50 kPa Anomalies over the Canadian Prairies Associated with Major Extended Dry Spells on the Canadian Prairies.

showing the typical sea surface temperature anomaly pattern and 50 kPa anomaly pattern associated with major extended dry spells on the Canadian Prairies has been constructed (Figure 5.4).

The model indicates that the occurrence of major extended dry spells on the Canadian Prairies are associated with a distinctive sea surface temperature anomaly pattern in the North Pacific Ocean as well as a distinctive 50 kPa anomaly pattern over the Prairie region. The fact that these aforementioned patterns are so well defined indicates that there is indeed a relationship between North Pacific sea surface temperature anomalies and major extended dry spells on the Canadian Prairies. As a result, this model could form the basis of a predictive technique for major extended dry spells and droughts over the Canadian Prairie region.

5.3 LAG RELATIONSHIPS

It has already been determined that there is a significant positive contemporaneous relationship between North Pacific sea surface temperature anomaly gradients and extended dry spells on the Canadian Prairies. It has also been determined that a distinct North Pacific sea surface temperature anomaly pattern is contemporaneously associated with a distinct 50 kPa anomalous height pattern over the Prairies during these major extended dry spell episodes. However, both of these findings are based on contemporaneous

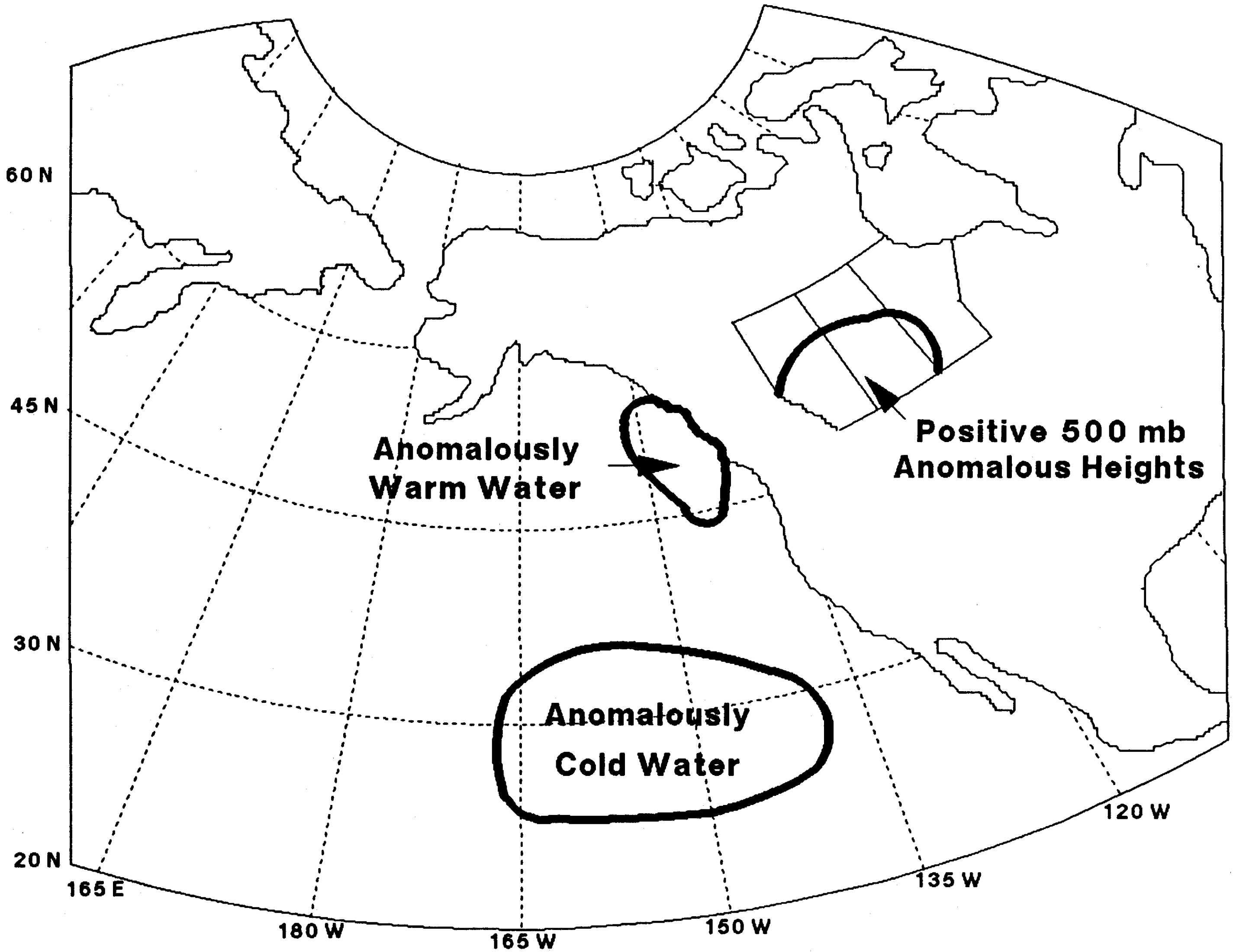

Figure 5.4: Conceptual Model Showing the Typical Sea Surface Temperature Anomaly Pattern in the North Pacific Ocean and the Typical 50 kPa Anomaly Pattern over the Canadian Prairies Associated with Major Extended Dry Spells on the Canadian Prairies.

relationships. Therefore, sea surface temperature anomaly gradients were examined only during those months which had extended dry spells associated with them.

It is a known fact that the huge heat capacity of the oceans means that sea surface temperature anomalies, once produced, tend to persist for several months (Namias and Cayan, 1981). Also, many studies that involve looking for possible teleconnections between sea surface temperature anomalies and anomalous weather conditions have used sea surface temperature lags in their analyses (e.g. Namias, 1976,1978,1982,1983; Harnack, 1979). As a result, it was decided to examine the other monthly sea surface temperature anomaly gradients that were not contemporaneously associated with extended dry spells over the Canadian Prairies to determine if a lag relationship existed.

This analysis was carried out by determining the sea surface temperature anomaly gradient for every growing season month during the years 1948-1988. A list of these gradients is given in Table 5.1. From this table, it is found that there are some months which have positive anomalous sea surface temperature gradients but were not contemporaneously associated with a major extended dry spell on the Canadian Prairies. However, when the data were examined more closely, it was discovered that most of these positive gradients occurred prior to major extended dry spell episodes. In other words, there appeared to be a persistence of positive sea

Table 5.1: Growing Season Monthly Sea Surface Temperature Anomaly Gradients (°C)

YEAR	MAY	JUN	JUL	AUG
1948	-1.3	+1.7	+2.5	-1.3
1949	+2.2*	-2.1	+3.0	+3.2
1950	-3.1	-2.8	-2.3	-1.4
1951	-1.3**	-2.3	+2.6	-2.6
1952	-1.1*	-2.0	+2.7	-1.6*
1953	+1.4	-3.1	+2.1	-1.7*
1954	-1.4	-1.1	+1.9	-1.1
1955	-3.3	-3.0	-2.8*	+1.8
1956	+1.5**	-1.5	+1.0	+2.3
1957	+1.6	+3.2	+1.0	+2.3
1958	+4.0**	+3.8	+3.1	+3.2
1959	+1.4	-2.5	+2.1	-2.6
1960	+2.2	+2.0	-1.4*	-1.4
1961	+1.5	+2.6**	+3.5	+2.0**
1962	-1.6	-2.7	-2.2	-1.5
1963	+1.5	+2.1	+1.7	+2.0
1964	-2.6	+1.3	-2.2	-1.8
1965	-1.8	-2.0	-2.4	-1.8
1966	-1.2*	-1.5	-1.2	+1.7
1967	-1.3	-1.8	-2.1	+2.6**
1968	-2.7	-2.7	+3.0	-1.6
1969	+1.8	+3.3	+0.9	-1.2*
1970	-1.6	-2.3*	-3.2	-3.1
1971	-3.3*	-3.6	-2.3	-1.9
1972	-2.6	+1.5	-1.5	-1.6*
1973	-1.5*	-1.4	-1.7	-1.8
1974	-1.1	-1.5	-1.8	-1.5
1975	-3.0	-2.8	-2.8	-3.1
1976	-2.4*	-2.9	-2.3	+2.0
1977	-1.8	-1.4	-1.8	+2.0
1978	+1.5	+3.3	+1.5	-1.1
1979	-1.9	-1.8	+1.6	+2.2
1980	+2.1**	+1.8	+1.9	-2.6
1981	+2.3	+2.2	+1.5	+2.1**
1982	-3.0	-2.6	-1.5	+1.9
1983	+4.1	+3.0	+2.8	+3.2
1984	+2.3	-2.7	-2.3	+2.0
1985	-1.3*	-2.2	+1.7*	-1.6
1986	+1.1**	+2.8	+1.6	-2.9
1987	+3.4*	+2.1	+2.4	-2.1
1988	+2.1	+2.4**	+2.1	-2.8*

** Denotes occurrence of a major extended dry spell during this month.

* Denotes occurrence of an extended dry spell during this month but it is not a major extended spell.

surface temperature anomaly gradients prior to the occurrence of major extended dry spells. Therefore, sea surface temperature anomaly gradients during months prior to the growing season were also examined in order to determine the length of persistence of these gradients. Table 5.2 shows the duration of positive sea surface temperature anomaly gradients that were greater than or equal to +1.5°C prior to each outlined extended dry spell. Note that a value of 0 indicates that there was no persistence of a positive sea surface temperature anomaly gradient prior to the extended dry spell.

In addition to the examination of gradients prior to the outlined extended dry spells, positive sea surface temperature anomaly gradients during growing seasons that were not associated with extended dry spells were also examined. This was carried out to determine if there were any persistent positive anomaly gradients prior to or during these seasons. Table 5.3 shows the duration of these positive gradients. Note that the duration for 1963 and 1983 extend to the end of the growing season (i.e. up to and including August) and that a value of 0 indicates that no positive sea surface temperature anomaly gradients occurred just prior to or during these growing seasons.

Both Tables 5.2 and 5.3 show that the majority of the more persistent positive sea surface temperature anomaly gradients were associated with major extended dry spell

Table 5.2: Duration of Positive Sea Surface Temperature Anomaly Gradients Prior to Extended Dry Spells

EXTENDED DRY SPELL (RANKED)	DURATION (MONTHS)
1. May 16 - Jun 28, 1961*	8
2. May 1-24, 1980*	10
3. Jul 31 - Aug 26, 1961*	10
4. May 14 - Jun 13, 1956*	0
5. May 23 - Jun 1, 1986*	4
6. Aug 9-31, 1967*	0
7. Aug 6-28, 1981*	10
8. May 3-12, 1951*	0
9. Jun 2-11, 1988*	9
10. May 1-25, 1958*	4
11. May 1-15, 1949*	1
12. Jul 6-27, 1960	7
13. May 3-12, 1987	5
14. Jul 13-23, 1955	0
15. May 29 - Jun 8, 1970	0
16. May 1-12, 1966	0
17. May 5-22, 1952	0
18. May 13-22, 1985	0
19. Aug 11-21, 1953	0
20. Aug 21-31, 1972	0
21. May 10-19, 1973	0
22. Jun 30 - Jul 10, 1985	1
23. Aug 17-26, 1969	0
24. May 6-15, 1971	0
25. May 1-10, 1976	0
26. Aug 16-25, 1952	0
27. Aug 22-31, 1988	0

* signifies a major extended dry spell

episodes on the Canadian Prairies. On the other hand, most of the other years were associated with very brief or no positive sea surface temperature anomaly gradients. Taking all of these situations into consideration (i.e. the 27 outlined extended dry spells and the other 18 growing seasons

Table 5.3: Duration of Positive Sea Surface Temperature Anomaly Gradients Not Associated with Extended Dry Spells

GROWING SEASON	DURATION (MONTHS)
1948	2
1950	0
1954	1
1957	2
1959	1
1962	0
1963	7
1964	0
1965	0
1968	1
1974	0
1975	0
1977	1
1978	7
1979	2
1982	1
1983	8
1984	1

without extended dry spells), there were a total of 45 individual cases. Table 5.4 shows the probability of a major extended dry spell given the duration of the positive sea surface temperature anomaly prior to the dry spell. These probabilities were calculated by dividing the number of occurrences of major extended dry spells by the total number of cases for each duration (0 through 10 months) of a positive sea surface temperature anomaly gradient. For example, a probability of a major extended dry spell given a positive sea surface temperature anomaly gradient of 10 months is: 3/3 = 1.00.

Table 5.4: Probability of Major Extended Dry Spells Given the Duration of Positive Sea Surface Temperature Anomaly Gradients

DURATION OF POS SST ANOMALY GRADIENT (MONTHS)	NO. OF MAJOR EXTENDED DRY SPELLS	TOTAL NO. OF CASES	PROBABILITY OF MAJOR EXTENDED DRY SPELLS
0	11	45	0.2444
1	8	24	0.3333
2	7	15	0.4667
3	7	12	0.5833
4	7	12	0.5833
5	5	10	0.5000
6	5	9	0.5556
7	5	9	0.5556
8	5	6	0.8333
9	4	4	1.0000
10	3	3	1.0000

5.3.1 PROBABILITY MODEL

A probability model summarizing the results given in Table 5.4 is shown in Figure 5.5. This model suggests that as the duration of positive gradients gets longer, the probability of a major extended dry spell increases. Also, if the duration of this positive gradient is 9 months or longer, there is a 100% probability that a major extended dry spell occurs on the Canadian Prairies. This was the case in the spells that occurred in 1961, 1980, 1981, and 1988. In fact, when the duration of positive sea surface temperature anomaly

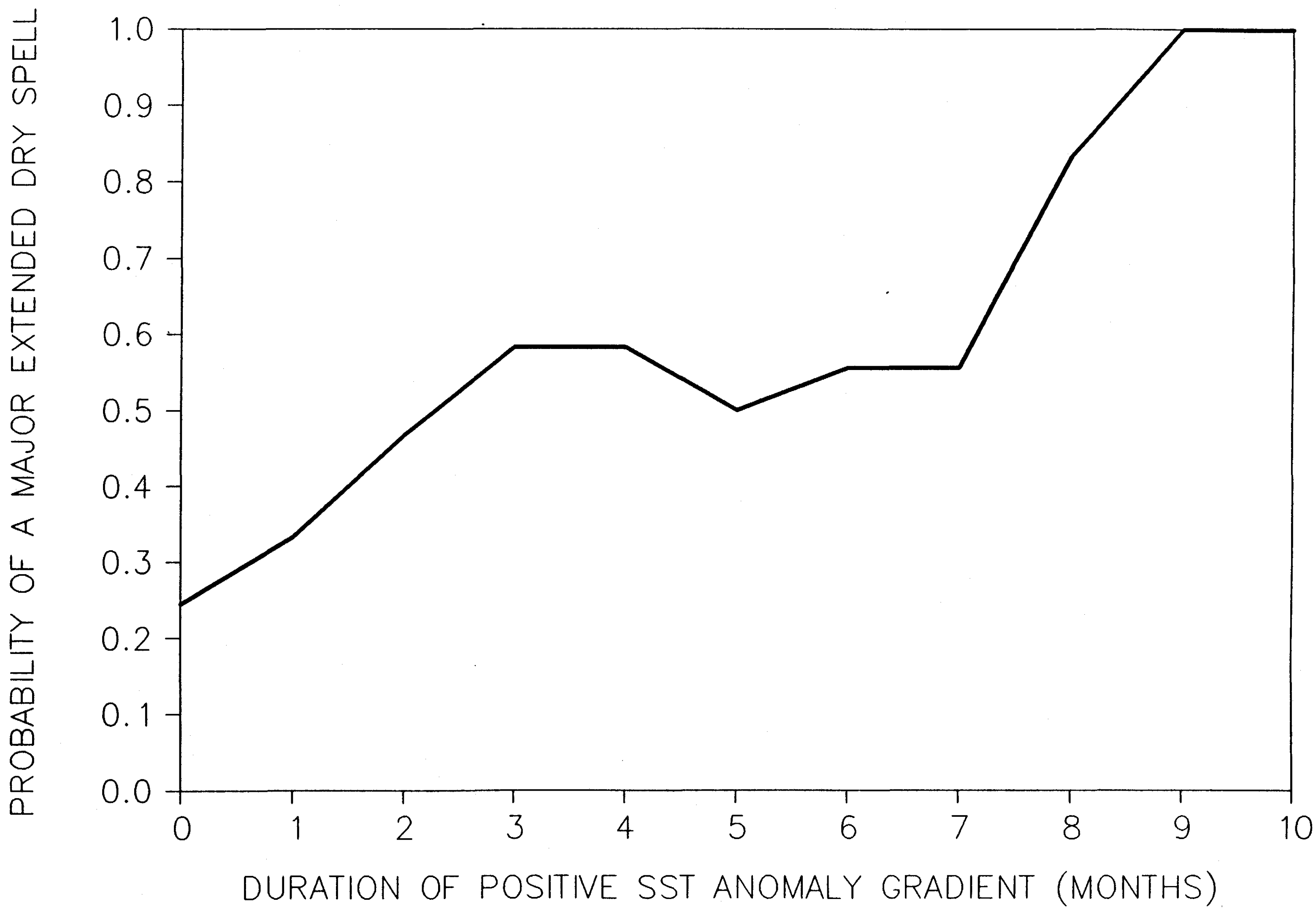

Figure 5.5: Probability Model Showing the Probability of a Major Extended Dry Spell given the Duration of a Positive Sea Surface Temperature Anomaly Gradient in the North Pacific Ocean.

gradients were correlated with the probability of occurrence of a major extended dry spell on the Canadian Prairies, a correlation coefficient of 0.91 was calculated which is statistically significant at the 0.01 significance level. This would indicate that major extended dry spell episodes are not only significantly associated to contemporaneous sea surface temperature anomaly gradients, but also to the persistence of these gradients. As a result, this model could also form the basis of a predictive technique for major extended dry spells on the Canadian Prairies.

5.3.2 THRESHOLD SEA SURFACE TEMPERATURE ANOMALY GRADIENTS

It is also interesting to note that all of the persistent sea surface temperature anomaly gradients found in Tables 5.2 and 5.3 were at least +1.5°C. In other words, it appears that this temperature may be a threshold sea surface temperature anomaly gradient that is associated with major extended dry spell episodes on the Canadian Prairies. It is also noticed that once this threshold temperature is reached, there is no relationship between the strength of the gradient and the severity of the major extended dry spells. The gradient has to be positive and at least +1.5°C. However, as is shown by the probability model, the duration of this positive gradient does influence the probability of occurrence of a major extended dry spell episode.

5.4 DISCUSSION

This section analyzes the different relationships between North Pacific sea surface temperature anomaly patterns and extended dry spells on the Canadian Prairies to get a better understanding of some of the physical processes involved within these relationships. This includes the examination the following different scenarios: i) the occurrence of positive sea surface temperature anomaly gradients associated with major extended dry spells, ii) the occurrence of positive sea surface temperature anomaly gradients not associated with a major extended dry spells, and iii) the occurrence of major extended dry spells not associated with sea surface temperature anomaly gradients.

5.4.1 POSITIVE SEA SURFACE TEMPERATURE ANOMALY GRADIENTS AND EXTENDED DRY SPELLS

The significant relationships between North Pacific sea surface temperature anomalies and extended dry spells over the Canadian Prairies were described earlier in this chapter. There are several possibilities as to why these relationships exist. The hypothesis of this thesis is that the sea surface temperature anomaly pattern somehow affects the upper-atmospheric (Rossby) long-wave pattern causing a 50 kPa ridge to form over the Canadian Prairies. This ridge then leads to the occurrence of major extended dry spells over the area. Several studies have been carried out in attempts to explain the relationship between sea surface temperatures and overlying upper-atmospheric circulation patterns. The main consensus is that the planetary or Rossby wave behaviour can be modulated or forced by large areas of persistent heat sources (Namias and Cayan, 1981). Simple models have indicated that certain wavelengths in the atmosphere may be 'excited' by large areas of heating or cooling which can then produce perturbations in the atmospheric flow in areas remote from the sea surface temperature anomaly pattern (Namias and Cayan, 1981). Also, sea surface temperature anomalies can have an effect on the overlying atmospheric circulation because they usually cover very large areas (e.g. hundreds of thousands of square kilometres), and persist for several months as is the case with those in this study. As a result, these anomalies can be responsible for large anomalous sensible and latent heat fluxes between the sea and the atmosphere (Harnack and Broccoli, 1979).

It has also been suggested that anomalous sea surface temperature gradients can have an effect on upper-atmospheric wave patterns. Namias (1978) proposed that these gradients produce and maintain enhanced atmospheric baroclinity (through differential sensible and latent heat fluxes) which leads to anomalous cyclonic activity and anomalous mean sea level pressures both locally and downstream. Also, Harnack and Broccoli (1979) used monthly sea surface temperature and 70 kPa height data for the years 1947-1977 for the North

Pacific Ocean and found that anomalous meridional flows in the mid-troposphere were often associated with anomalous east-west sea surface temperature gradients in the North Pacific both on a monthly and seasonal time scale. This also included an apparent strong relationship during the summer season.

In the present study, most of the Canadian Prairie major extended dry spells were found to be associated with a very persistent southwest-northeast sea surface temperature anomaly gradient in the North Pacific Ocean. The question is whether this gradient was the main factor producing ridging over the Prairies, a minor factor, or not a factor at all. The answer to this question is not known. The physical relationships between ocean and atmosphere are not well understood and as a result, it is difficult to pinpoint the exact causal relationships. However, since 7 out of the 11 major extended dry spell episodes in this study had persistent anomalous sea surface temperature gradients associated with them, and there was a significant positive relationship between the duration of these anomalous patterns prior to the spells and the probability of occurrence of a major extended spell, it can be proposed that these persistent anomalous gradients do have some effect on the occurrence of major extended dry spells over the Canadian Prairies. It is unlikely that they are the sole cause of these events since some major extended dry spells occur without them. Perhaps the gradient does not necessarily form the ridge but helps reinforce it. In other words, it acts as a positive feedback mechanism. Some other factor such as anomalous soil moisture conditions, anomalous snow cover in the Arctic, or tropical Pacific Ocean events such as El Nino or La Nina may initiate the ridge. The sea surface temperature anomaly gradient located in the North Pacific could then allow the ridge to persist thereby causing a major extended dry spell. However, these are only hypotheses. The actual physical processes involved in this relationship are not the main focus of this study.

5.4.2 POSITIVE SEA SURFACE TEMPERATURE ANOMALY GRADIENTS AND NO EXTENDED DRY SPELLS

As indicated earlier, some individual cases were found in which long durations of positive sea surface temperature anomaly gradients were not associated with major extended dry spells. From Tables 5.2 and 5.3, it can be seen that this situation occurred in the years 1960, 1963, 1978, 1983 and 1987. All of these years had at least five consecutive months of positive sea surface temperature anomaly gradients, but no associated occurrences of major extended dry spells. However, two of these years (1960 and 1987) were associated with the occurrence of an extended dry spell. Also, these spells were ranked just below the criteria set for major extended dry spells (i.e. 12th and 13th respectively; Table 4.6). As a result, it can be stated that these two cases were still associated with somewhat severe extended dry spells on the Canadian Prairies.

The other three years (1963, 1978, and 1983) had a very long duration of positive sea surface temperature anomaly gradients (7, 7, and 8 months respectively; Table 5.3) but were not associated with an extended dry spell of any kind. The question is why was there not a major extended dry spell during these growing seasons? One possible answer is that the persistent sea surface temperature anomaly gradient was associated with the formation of a ridge over the Canadian Prairies, but for some reason this ridge did not lead to a major extended dry spell over the area. This could be due to the ridge not being very strong. As a result, some local convectional cells may have formed thereby interrupting the extended dry spell and thus, it was not detected. Or perhaps, there was a high moisture content in the atmosphere. Another possible explanation is that the ridge was present but not situated directly over the Canadian Prairies. Therefore, its effects did not show up as an extended dry spell in this area.

In order to determine if upper-atmospheric circulation anomalies or ridges occurred during these time periods, Northern Hemisphere monthly 50 kPa height anomaly maps for the growing seasons of 1963, 1978, and 1983 were analyzed. These maps were obtained from the AES Archives in Downsview, Ont. and are found in Appendix C Table C - C.1. During the growing season of 1963, it is seen that there was a positive 50 kPa height anomaly centred near Hudson Bay during June and July. This anomaly is less than 5 dam above average and is situated east of the Canadian Prairies. As a result, it would not have caused an extended dry spell to occur over the Canadian Prairie region.

During the growing season of 1978, it was observed that a larger positive 50 kPa height anomaly (greater than 5 dam) is centred over the Great Lakes region during the month of May. This positive anomaly extended westward and occupied the eastern portion of the Canadian Prairies. However, it was very weak in this region and therefore did not cause an extended dry spell over the Prairies. Note that the months of June, July, and August did not have any positive 50 kPa height anomalies situated near the Canadian Prairie area.

The growing season of 1983 also had a positive 50 kPa height anomaly associated with it. The anomaly was present during July and August and during August, it was centred just south of the Canadian Prairies. The anomaly was greater than 5 dam above average and during the month of August, extended well into the Canadian Prairie region. However, no extended dry spell was detected. As was indicated earlier, this could be due to several factors such as local convectional cells or a high atmospheric moisture content.

In all of the three outlined cases, a positive 50 kPa anomaly occurred near the Canadian Prairies at some time during the growing season. However, this ridge did not produce an extended dry spell on the Canadian Prairies probably due to the reasons mentioned previously. Also, it should be remembered that monthly 50 kPa anomaly maps were used in this analysis. This study used daily data to identify individual extended dry spells and as a result, the monthly maps are not as accurate as a daily analysis. However, positive 50 kPa anomalies were still detected suggesting that the positive sea surface temperature anomaly gradients that occurred during these time periods were associated with ridge formations near the Canadian Prairie study area.

5.2.3 EXTENDED DRY SPELLS AND NO POSITIVE SEA SURFACE TEMPERATURE ANOMALY GRADIENTS

The final scenario to be examined are situations when there was the occurrence of a major extended dry spell on the Canadian Prairies but it was not associated with a persistent positive sea surface temperature anomaly gradient over the North Pacific Ocean. From Table 5.2, it is seen that this occurred during four major extended dry spells. These included: i) May 1-15,1949, ii) May 3-12,1951, iii) May 14 - Jun 13,1956, and iv) Aug 9-31,1967. The question is why were these spells not associated with persistent anomalous sea surface temperature gradients?

The fact is that there are several factors other than

North Pacific sea surface temperature anomalies that can initiate ridging and thus cause major extended dry spells over the Canadian Prairies. These include factors such as soil moisture conditions (Ookouchi et al., 1984), anomalous snow cover over Northern Canada (Namias, 1962; Roads, 1981; Kukla, 1981; Walsh et al., 1982), solar activities (Currie and Venkatarangan, 1978), and events in the tropical Pacific Ocean such as El Nino (Horel and Wallace, 1981; Chen, 1983; Yarnal, 1985; Ropelewski and Halpert, 1986; Hamilton, 1988; Pitcher et al., 1988) and La Nina (Trenberth et al., 1988).

It is possible that one or more of these factors could have initiated an anomalous ridge over the Canadian Prairies thus causing the occurrence of a major extended dry spell. However, it is not the purpose of this study to determine if these factors were indeed responsible for the occurrence of major extended dry spells on the Prairies. Also, if one examines Table 4.4, it is seen that three out of the four spells in question did have contemporaneous positive sea surface temperature anomaly gradients associated with them. The only one that did not was May 3-12,1951. Therefore, these three spells were associated with positive anomalous sea surface temperature gradients, but these gradients were not persistent. As a result, it still may be generally concluded that the sea surface temperature anomaly gradient in the North Pacific had an effect on causing these major extended dry spell episodes.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The main objective of this thesis was to determine if there was a significant statistical relationship between North Pacific sea surface temperature anomalies and extended dry spells on the Canadian Prairies during the growing season (May - August) for the period 1948-1988. This was achieved by first identifying individual extended dry spells on the Canadian Prairies and then ranking them in terms of their severity. From this list, the major extended dry spells were determined. All of the extended spells were then correlated with contemporaneous sea surface temperature anomaly gradients located in the east-central North Pacific Ocean.

The simple linear correlation results indicated that there was a significant positive relationship (at the 0.01 significance level) between these two variables. In other words, as the sea surface temperature anomaly gradient over the North Pacific Ocean became more positive (i.e. colder sea surface temperature anomalies in the east-central North Pacific and warmer sea surface temperature anomalies along the west coast of North America), extended dry spells over the Canadian Prairies became more severe. From the aforementioned relationship, a conceptual model showing the typical sea surface temperature anomaly pattern over the North Pacific and the typical 50 kPa anomalous height pattern over the Canadian Prairies associated with the major extended dry spell episodes on the Prairies was constructed. The model showed a distinctive pattern in sea surface temperature anomalies and 50 kPa anomalous heights suggesting that major extended dry spells are related to particular sea surface temperature anomaly patterns and therefore could perhaps be predicted from the model.

Since the relationships were based only on contemporaneous situations, it was decided to further examine the data to determine if the persistence of these sea surface temperature anomaly gradients had any association with the occurrence of major extended dry spells. A probability model, derived using the data from this analysis, showed the longer the positive anomalous gradients persisted, the greater the probability of a major extended dry spell on the Canadian Prairies. When the positive anomaly persisted at least nine months, the probability of a major extended dry spell was 100%. As a result, this model could also perhaps be used as a predictive technique for major extended dry spells and droughts.

The study concluded with a brief discussion of different aspects associated within the relationships. It was found that a positive relationship did not exist in some cases.

This was due to the fact that there are many different factors that have an effect on Canadian Prairie major extended dry spells and droughts. It was, however, presumed that since a significant relationship was found between the two variables, North Pacific sea surface temperature anomalies do have some effect on major extended dry spells over the Canadian Prairies. However, the precise physical processes involved were not determined.

6.2 CONCLUSIONS

This study has focused on the association between sea surface temperature anomalies in the North Pacific Ocean and extended dry spells and droughts on the Canadian Prairies. The results indicate a significant relationship between the two variables. The relationship is also unique because it involves a distinct sea surface temperature anomaly gradient in the North Pacific. The core areas of anomalously cold and warm water that produced the gradient consistently appear in very small geographical areas. This is quite remarkable when these areas are compared to that of the entire North Pacific Ocean.

However, it should be realized that this is only an association between the two variables. This study did not provide any explanation of the possible physical links between sea surface temperature anomalies and extended dry spells on the Prairies. In order to fully understand the relationship, the actual physical processes involved between the ocean and the atmosphere need to be investigated. Also, as was outlined previously, there are many other factors that can affect the upper-atmospheric long-wave pattern over the Prairies and thus cause major extended dry spells to occur in this area. As a result, further research is required in order to get a better understanding of the aforementioned relationship. This should include:

1) An analysis of the upper-air or jet stream pattern over the North Pacific Ocean and the Canadian Prairies associated with major extended dry spell episodes.

2) An examination of other factors such as anomalous soil moisture conditions, anomalous snow cover in the Arctic, solar variability, and El Nino and La Nina events to determine if there is a significant relationship between any of these factors and the occurrence of major extended dry spells on the Canadian Prairies.

3) An examination of anomalous wet periods during the growing season on the Prairies to determine if there is a negative sea surface temperature anomaly gradient over the North Pacific during these time periods.

In conclusion, it can be stated that there is a statistically significant relationship between North Pacific sea surface temperature anomalies and extended dry spells and droughts on the Canadian Prairies. However, more research is required in order to understand the physical processes involved in this relationship. The preceding study can be considered as the first step in determining the causes of growing season major extended dry spells on the Canadian Prairies. Hopefully, it can aid in the prediction of these events which would be very beneficial to the Canadian Prairie economy.

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APPENDIX A

DRY SPELLS

TABLE A - A.1: Stations Used in This Study.

ALBERTA:

	Station	Number	Time Period
1.	Elk Point *	3012280	1948-1988
2.	Edmonton	3012208	1948-1988
3.	Ranfurly	3015400	1948-1988
4.	Camrose	3011240	1948-1988
		3011241	July 1979
5.	Rocky Mtn House	3015520	1948-1977
		3015522	1978-1988
6.	Lacombe	3023720	1948-1988
7.	Olds *	3024920	1948-1988
8.	Drumheller	3022120	1948-1968
		3022136	1969-1988
9.	Empress *	3022400	1948-1988
10.	Calgary	3031093	1948-1988
11.	Gleichen *	3032800	1948-1988
12.	Brooks	3030840	1948-1954
		3030856	1955-1988
13.	Medicine Hat	3034480	1948-1988
14.	Lethbridge	3033880	1948-1988
15.	Foremost *	3032640	1948-1988
16.	Fort Macleod	3032680	1948-1988
17.	Manyberries	3044200	1948-1988
18.	Goose Mountain *	3062880	1948-1988
19.	Campsie	3061200	1948-1988
20.	Lovett *	3064040	1948-1988
21.	Carrot Creek *	3061360	1948-1988
22.	Fairview *	3072520	1948-1988
23.	Beaver Lodge	3070560	1948-1988

* denotes station had some missing data.

TABLE A - A.1 (Continued)

SASKATCHEWAN:

Station	Number	Time Period
1. Humboldt *	4013400	1948-1973
	4013401	1974-1988
2. Yorkton	4019080	1948-1988
3. Tugaske	4018160	1948-1988
4. Dilke *	4012200	1948-1988
5. Indian Head	4013480	1948-1988
6. Regina	4016560	1948-1988
7. Moose Jaw *	4015320	1948-1988
8. Moosomin	4015360	1948-1988
9. Willmar *	4018960	1948-1988
10. Estevan	4012400	1948-1988
11. Semans *	4017320	1948-1988
12. Midale	4015160	1948-1988
13. Leader *	4024160	1948-1969
	4024161	1970-1988
14. Swift Current	4028040	1948-1988
15. Maple Creek *	4024920	1948-1957
	4024936	1958-1988
16. Shaunavon *	4027480	1948-1978
	4027485	1979-1988
17. Aneroid *	4020160	1948-1988
18. Gravelbourg	4022960	1948-1988
19. Consul *	4031760	1948-1969
	4031776	1970-1988
20. North Battleford	4045600	1948-1988
21. Scott	4047240	1948-1988
22. Kindersley	4043888	1948-1971
	4043920	1972-1988
23. Prince Albert	4056240	1948-1988
24. Melfort	4055080	1948-1961
	4055085	1962-1988
25. Saskatoon	4057120	1948-1988
26. Outlook *	4055720	1948-1971
	4055736	1972-1988
27. Lost River	4074640	1948-1988

TABLE A - A.1 (Continued)

MANITOBA:

	Station	Number	Time Period
1.	Russell *	5012520	1948-1988
2.	Birtle *	5010240	1948-1988
3.	Virden *	5012960	1948-1988
4.	Brandon	5010480	1948-1988
5.	Pierson	5012080	1948-1988
6.	Cypress River *	5010640	1948-1988
7.	Portage La Prairie	5012280	1948-1971
		5012320	1972-1988
8.	Morden	5021848	1948-1988
9.	Winnipeg	5023222	1948-1988
10.	Emerson *	5020880	1948-1988
11.	Indian Bay	5031320	1948-1988
12.	Swan River *	5042800	1948-1988
13.	Dauphin	5040680	1948-1988

TABLE A - A.2: Example of Precipitation Data File (1986).

```
3012280 000000101000111010001100000000000001000101110000011010110100109011110100111101111000001111111100111011000000000001000100000000
3012208 000010011110110000001000000100000000001101100110111000111100009011110011111111111100001100010100010100100000000000000000001000000
3015400 000010000010110010001100001000000001001000110010111000010000009011110111011100111000010011101000101110000000000000000001000000
3011241 000010111110110000001100000100000000000100101110011000011000019011011111001110111100111001111000111010000000000000000011000000
3015522 001111101110110000001000000000000000001100100010001000011110119001111111111001111101111111111100011101100111000000000011000010
3023720 001110000110110000001100000000000000001100101110011000001110119011111111110011111000111111111100011111100000000000000001000010
3024920 001111011110110000011100000000000000011100100110111000011101119011111101111111111100011111111100011110100011100010000011000110
3022136 001111001100011000000000000000000000010000000001000110000000001090001100111000011110001100101100000000000000100000000000001000111
3022400 000110011110001000001100000000000000100010000010001000001000010900011000101010010000011001000000000010000000100000000000001000010
3031093 001111000110111000000100000000000000111000000011001000000001111900001011111110111000011010111000011100100001000000000000001000010
3032800 001111001100110000011000000000000000110000001111100000010111090001100100110101101001101110100000000001000110100000001100000110
3030856 011111101000111100011110000000000001011100000110000000011111119000110011111111110000000111110000011101011101100000000001000110
3034480 000110001110111000011110000000000111010100000110111000010000119000010001111101110010100111000000000100100001000000000000000011
3033880 011110001000011000011110001000000001110100000100010000000000119000110001000000100000100010000000000100100001000000000000000011
3032640 000111000000100100000111100000000000111011100001010100000000001191001000100100001000000100100000000101001000110000000000000000011
3032680 011111101100011000011110000100001111111100000110010100000000111900011001100000010000001100000000001010010001100000000000000000010
3044200 001110011110011000011110000000000001111100000100111000000001111901011001101000010000011010000000000000000000001000000000000000110
3062880 000000010100100011101000000000000000010011101111110011011100090111100011111111111000111111111100010101000010010011000010001101
3061200 000010010110100000001000000000000000000001000110011000100000009010100111011101111000010000101000111001000000000000000000100000100
3064040 000000000000000000000000000000000000011110110011011100010101111901111111111111111110001111101110111110110011000001000001100010
3061360 000010011010110010001000000000000000011001000110111000111000109011101011111111111100110111111000110000001000000100000111000000
3072520 011000000000100000001000000000000000010011000100101010000100091001000110011101100001101011100000000100000001000000100000001
3070560 010011101001100000000000001000000000000001100111000011001000109101111111010111111010011010001000010000000000000000100000000000001
4013401 000000011111111000000100000000001001100100010001111001011000109010111101111110001011011101111111101110100000100000000100000000010
4019080 100010001111011100000000000000000100100010001100011011001100019101111010111101010110010101011100011100100000000000000001000000001
4012200 000110011011111100000001000000000100100001000000100000000000000119010111101111000100000101001001100001100000100000000000011000000
4013480 000110011011111010000110000000001100100110100110111100000000011900111010101110011000010010101110001011100000000000000011000000
4016560 100110001101111000100100000000001000001100001101010000000010119001110011011100010100010101011000010100100010000000000000001000000
4015320 000110001111011100000110000000000100001000000101011000010001191011100010010000001001100010010000111001001100000000000001000000
4012400 000011011111010000100110000000000100101100000100010100001001191011100110110011100001101010001000001010000100100000111000000
4015360 100111011100001100000000000000000100110110000010001101001000119001110111111100110100100101001110110101100000000000000011000000
4018960 000111011100010000000110000000001001001000000100111000000000190011100100111111000000100101000000000101000010000000010111000000
4018160 001110011111111000010110000000001001000100000001001100001000011901011000111101011010011101100110000110011001000000000011000000
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4022960 000110011110001000001100000000010100000000000000001110000100111900111000111011000000000011100000000010010000100000000000001000000
4031776 000110011110111000001110000000001001101000000010011000000000111901011000101110010000011000100000000011000000010000000000000000000
4045600 000000101110001001011110000000001001100110010111110000110000190010110001111010110000001001011100000000100000100000000000000000000
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5010240 000110001100110100000000000000010011001011111000111110110011910111110111111110111111101111110111111100110100100011110000000
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5012080 000011001010010000000010000000001100101100000110011000011001191001100111111101100011001110001000001111000000100001010100000000
5010640 100110011000000000000110000000000001001000011000100101110001900119001111110001011010011101011011110010000000010110000000000
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5021948 000111100100000000000100000000000100100100000110001100100000090011001001011000101100001110101101111111000000000000101100001
5023222 000110010110110000000000000000000100100100101100011100110001100010100101110100101100100101111100001101000000000001010110000
5020380 100110011001000000001000000000100100100000010001001000000000911001111111100010110100111010010010111100010000000001010000011
5031320 000110010100100000000000000000000100100100101011100011101111000110011100001110100101001100101001100111101000011000100101000000001
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```

TABLE A - A.3: Replacement Stations.

ALBERTA:

STATION	REPLACEMENT STATION	TIME PERIOD	DISTANCE (km)
Elk Point	Marwayne	Jun,Jul 1963 Jul 1964	60
	Tulliby Lake	May 1978 Aug 1981	53
	Cold Lake	Jun 1961	80
Empress	Pollockville	Jul 1961	113
Olds	Bowden	May,Jun 1963	16
	Madden	Jul 1963	42
Gleichen	Queenstown	Jun 1962 May,Jul,1963	27
Goose Mountain	High Prairie	May 1948,1951	64
	Sweathouse	May,Jun 1955 Aug 1961	77
Fairview	Berwyn	Aug 1956	50
Lovett	Entrance	Jun 1950 Jun,Jul 1953	115
Carrot Creek	Edson	Jun,Jul 1954 May 1956 Aug 1965	39
Foremost	Taber	Aug 1955	61

SASKATCHEWAN:

STATION	REPLACEMENT STATION	TIME PERIOD	DISTANCE (km)
Dilke	Lumsden	May,Jun,Jul,Aug 1949, Aug 1950	36
Moose Jaw	Caron	Jul 1953	22
Humboldt	Muenster	May 1977	9
Maple Creek	Klintonel	Jul 1951 May 1987	65
Aneroid	Hazenmore	May,Jun,Jul 1962	12

Shaunavon	Instow	Jun 1956	14

TABLE A - A.3 (Continued)

Consul	Claydon	Jun,Jul,Aug 1983, Aug 1984 May,Jul 1985 May,Jun,Jul 1986	43
Outlook	Glenside	Jun 1986	16
Semans	Nokomis	Aug 1961 Jul 1962 May,Jun,Jul 1964	24
	Duval	May,Aug 1963 Aug 1964	31
Leader	Abbey	Jul 1962	58
Willmar	Arcola	Jun 1961	16

MANITOBA:

Birtle	Hamiota	May 1952	45
Virden	Reston	Jun 1956	35
Cypress River	St. Alphonse	May 1964	15
Emerson	Morden	May 1979	68
Russell	Birtle	May 1953	40
Swan River	Durban	Jul 1964	24

APPENDIX B

SEA SURFACE TEMPERATURES

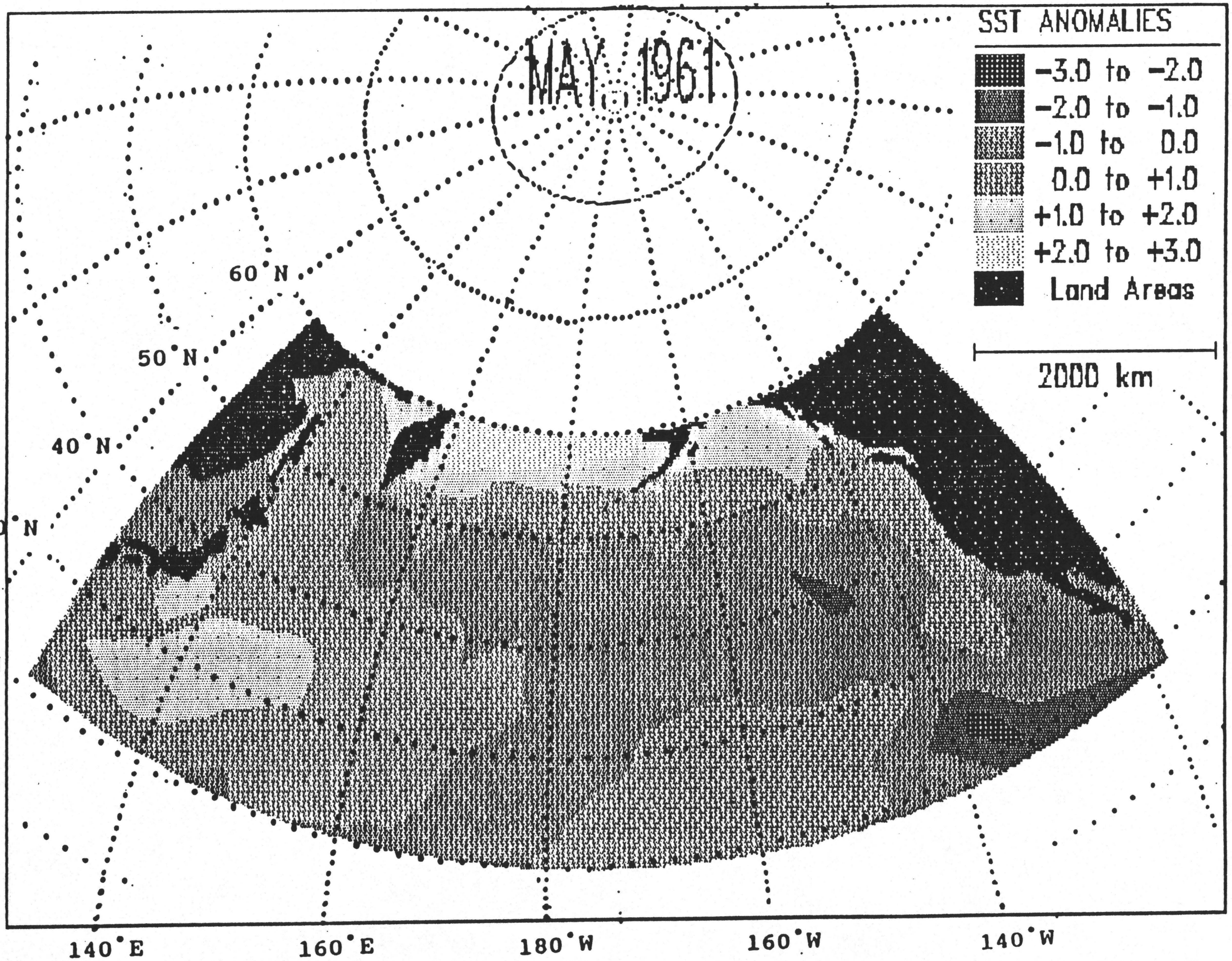
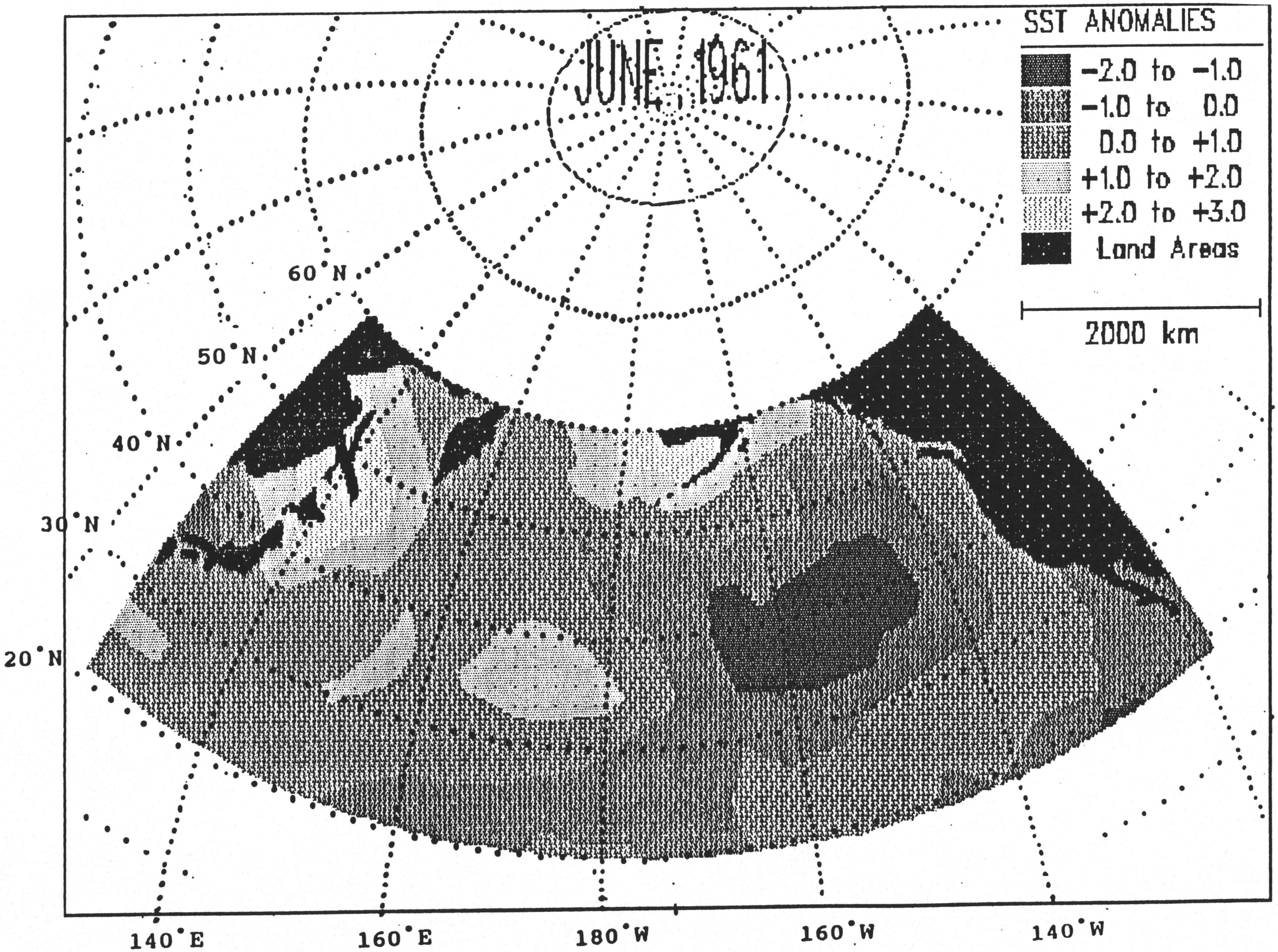
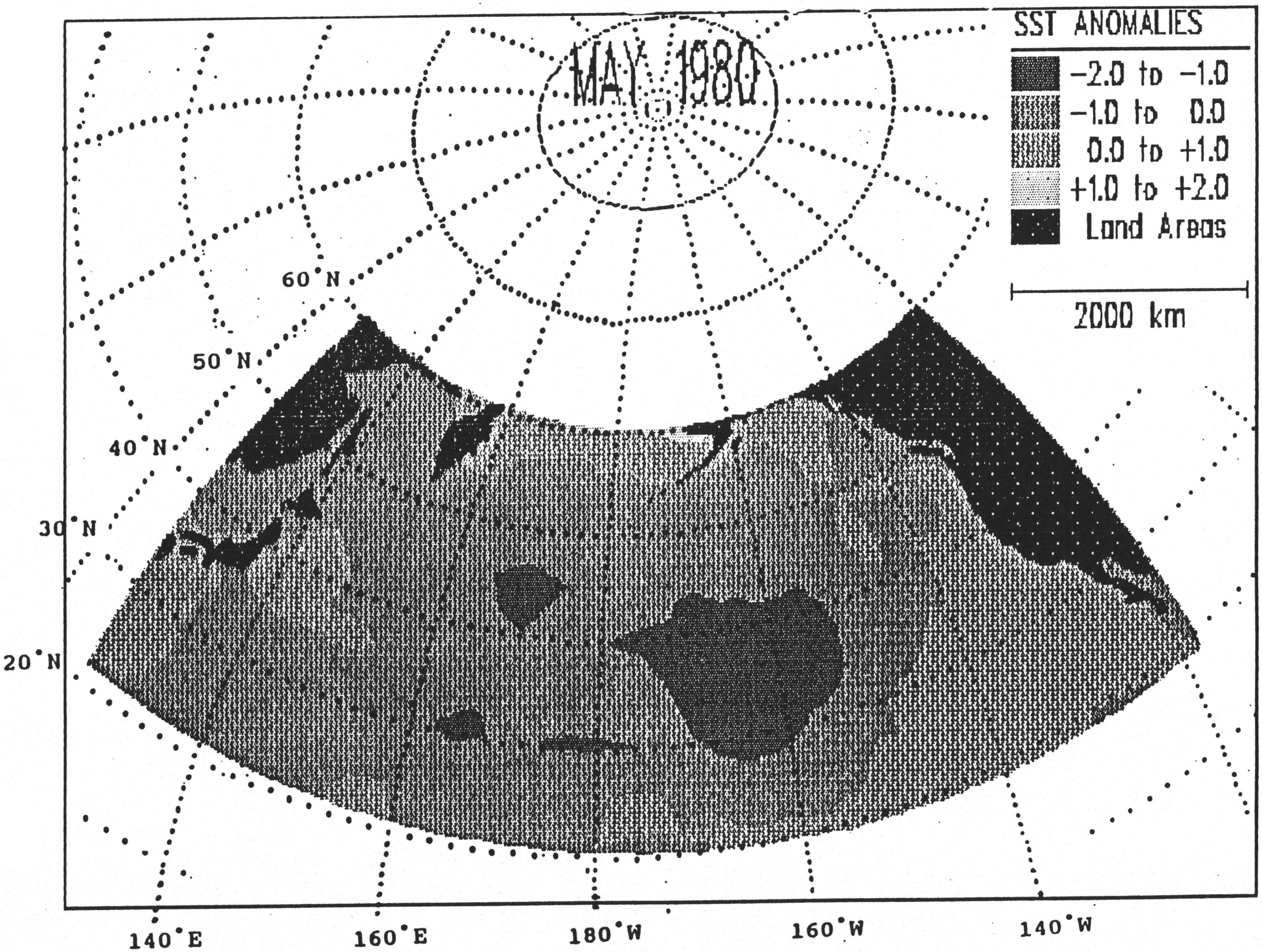
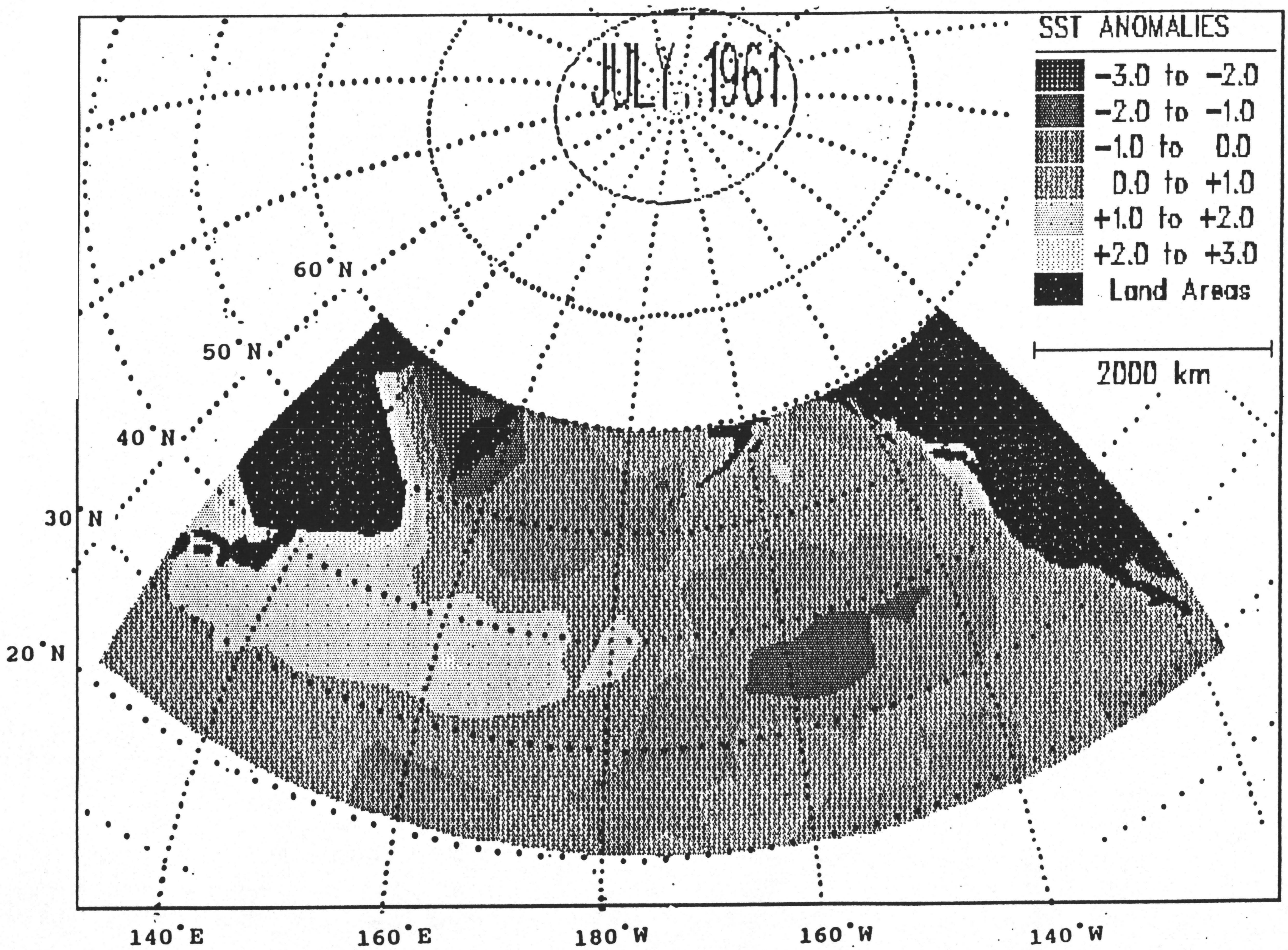


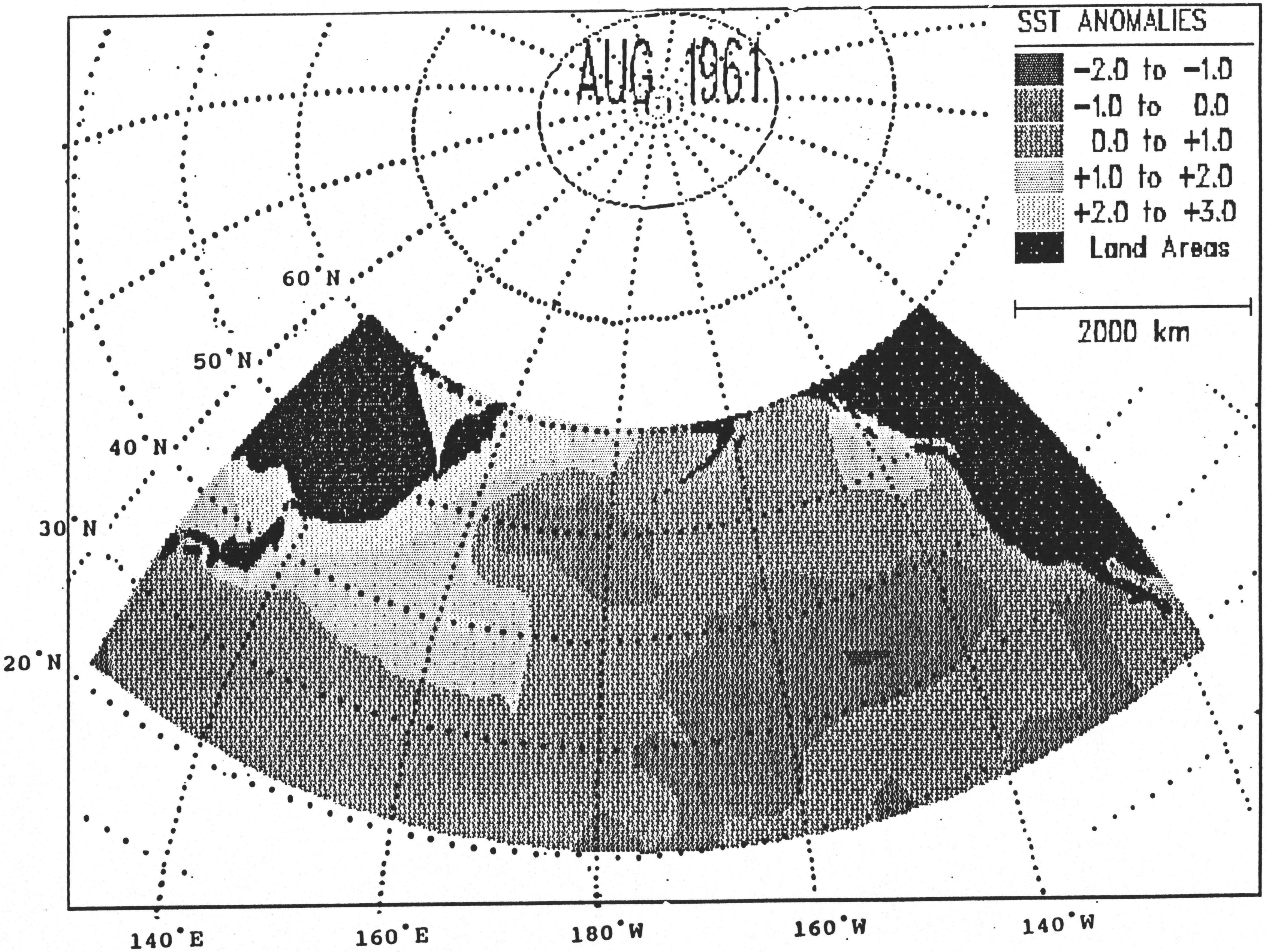
Table B - B.1: Sea Surface Temperature Anomaly Maps
A: Major Extended Dry Spells

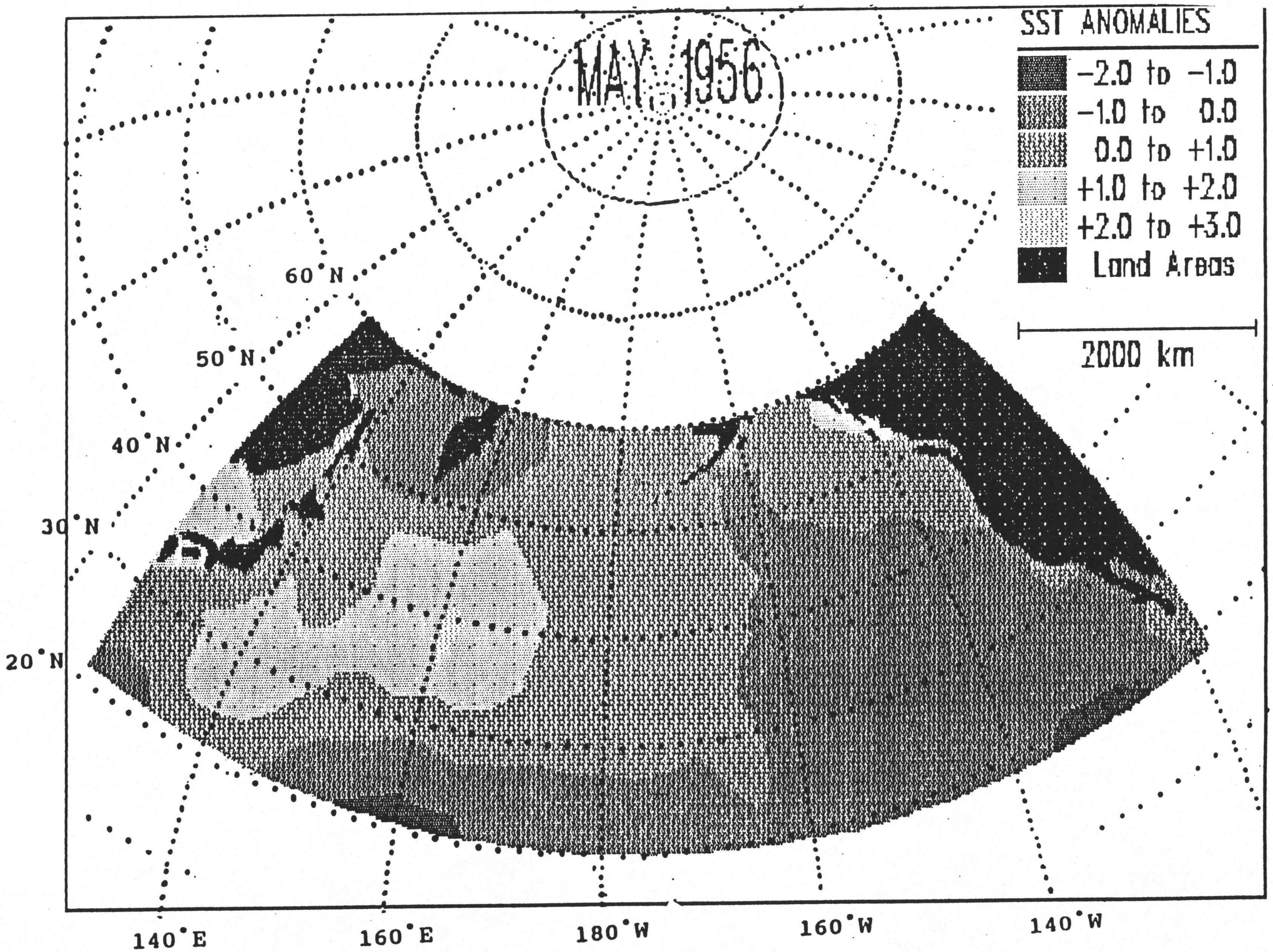

JUNE, 1961
SST ANOMALIES
−2.0 to −1.0
−1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

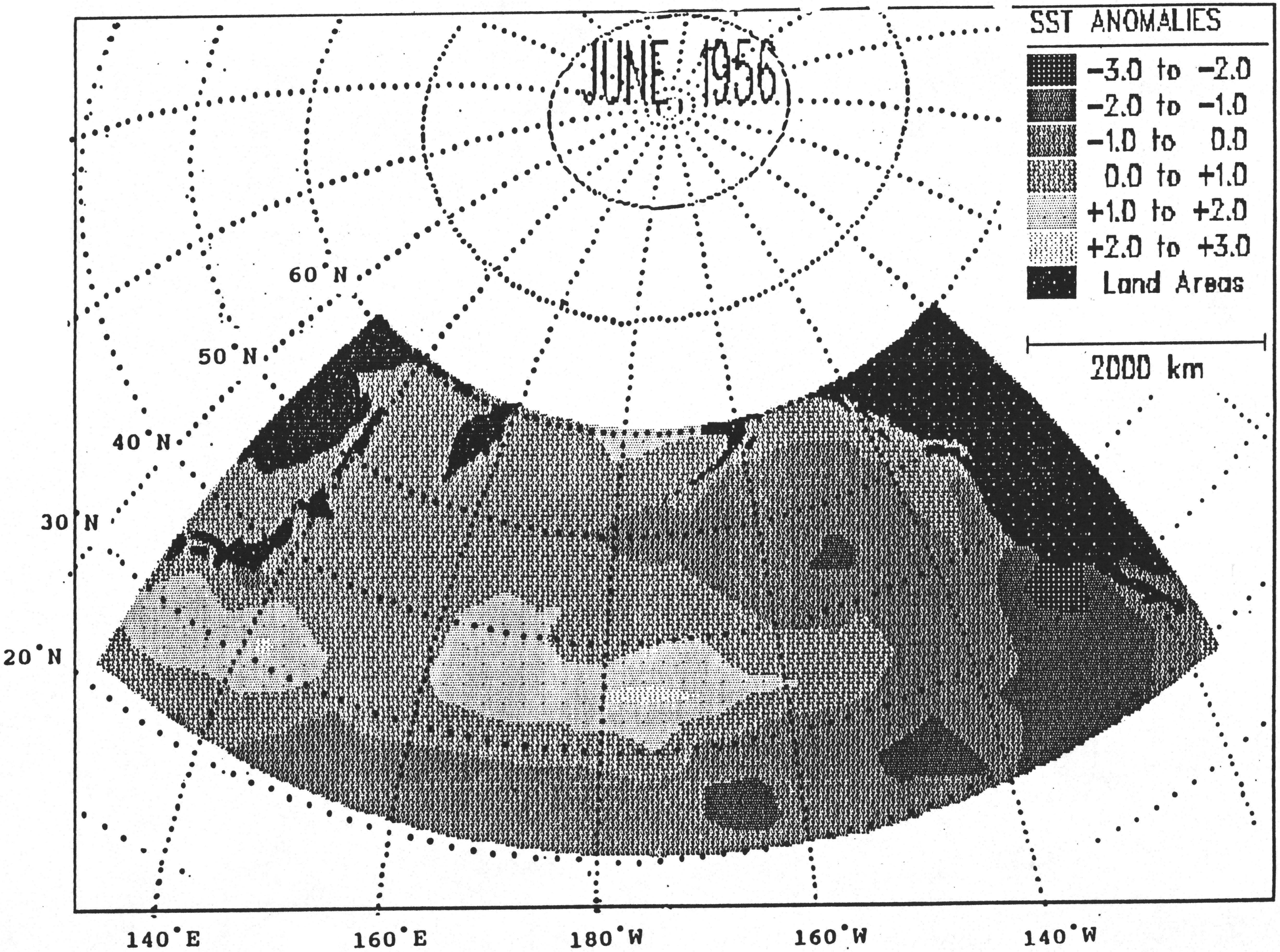

MAY, 1980
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

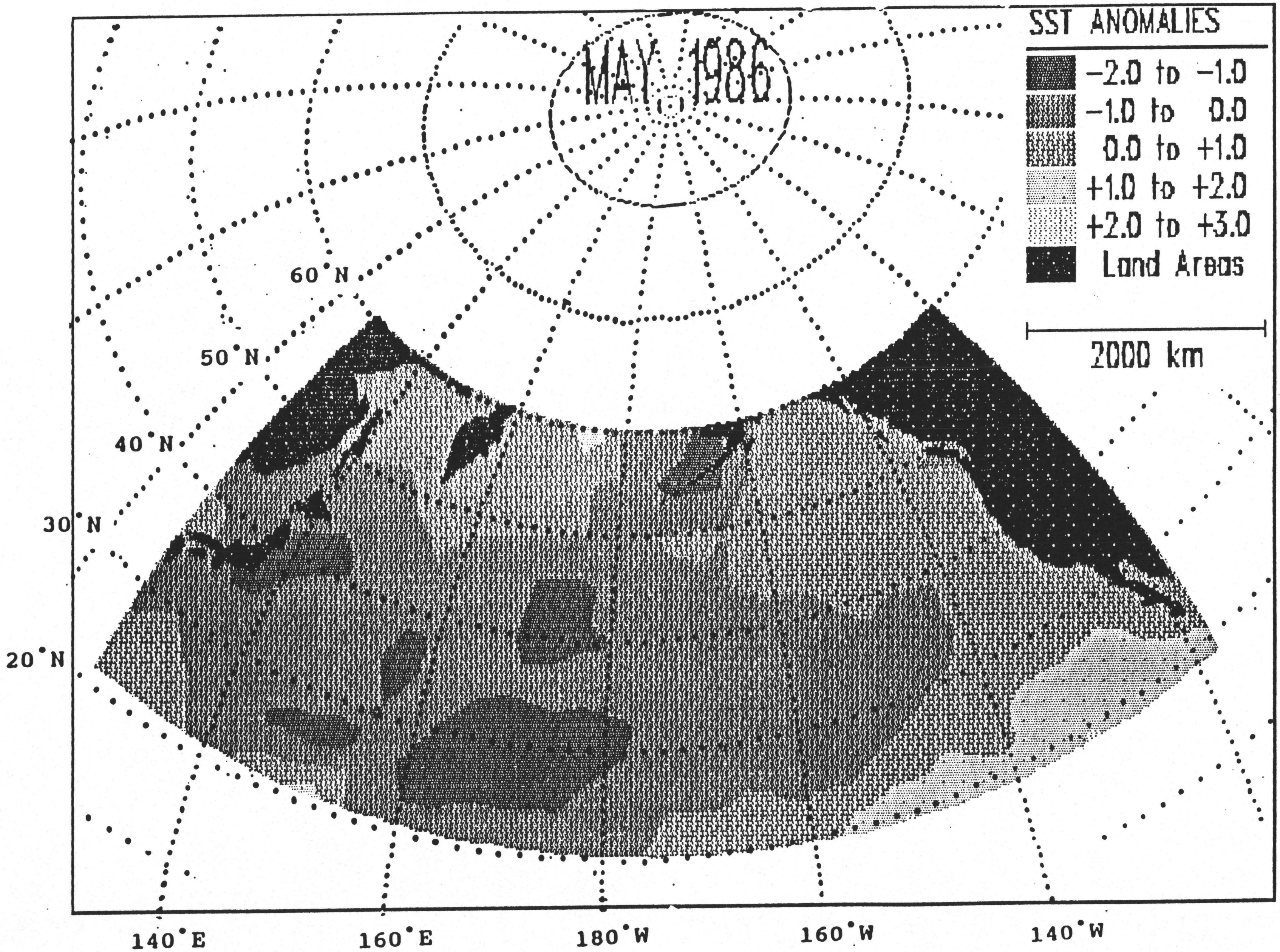


JULY, 1961
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60 N
50 N
40 N
30 N
20 N
140 E
160 E
180 W
160 W
140 W

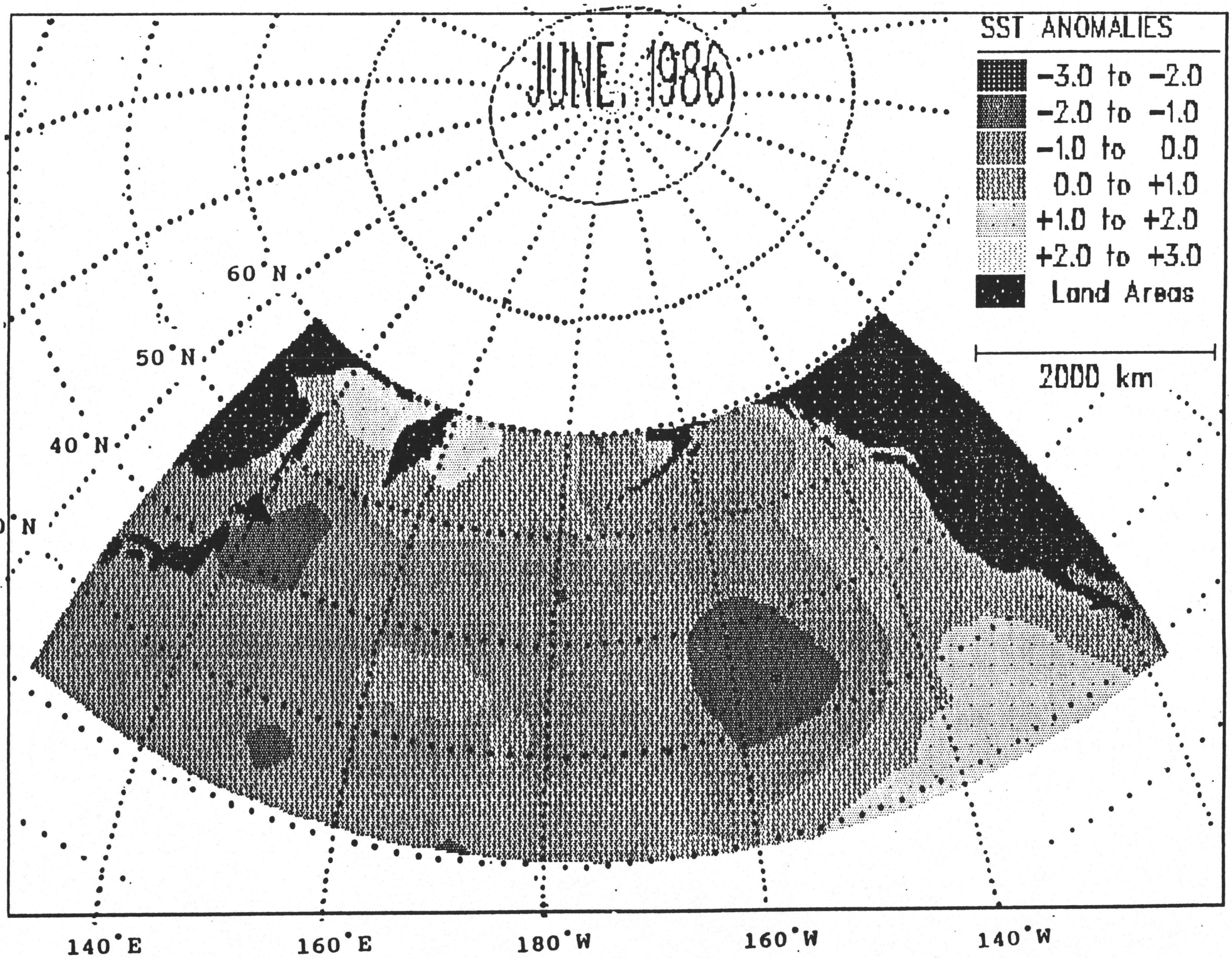

AUG. 1961
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60 N
50 N
40 N
30 N
20 N
140 E
160 E
180 W
160 W
140 W

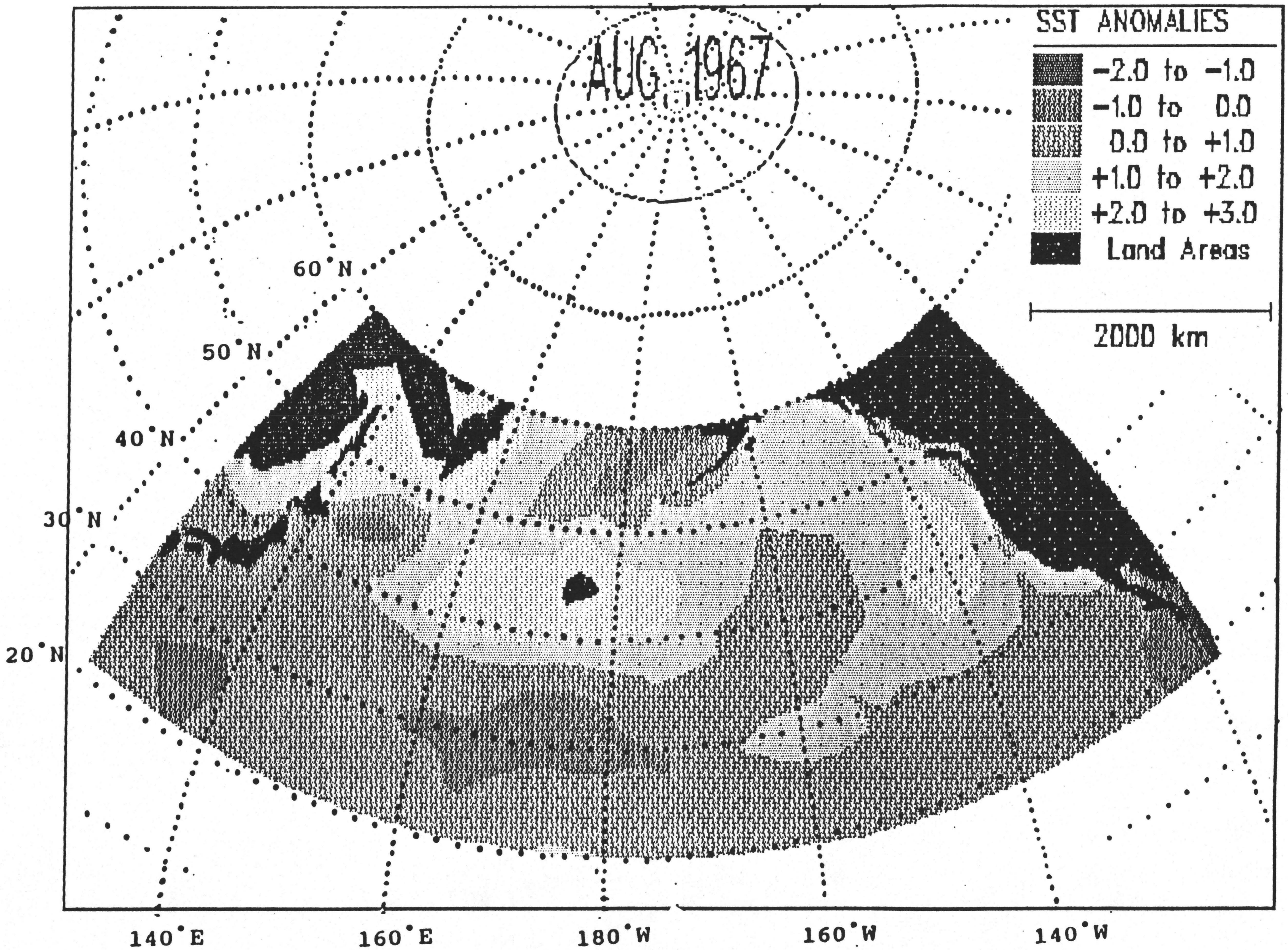

MAY 1956
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

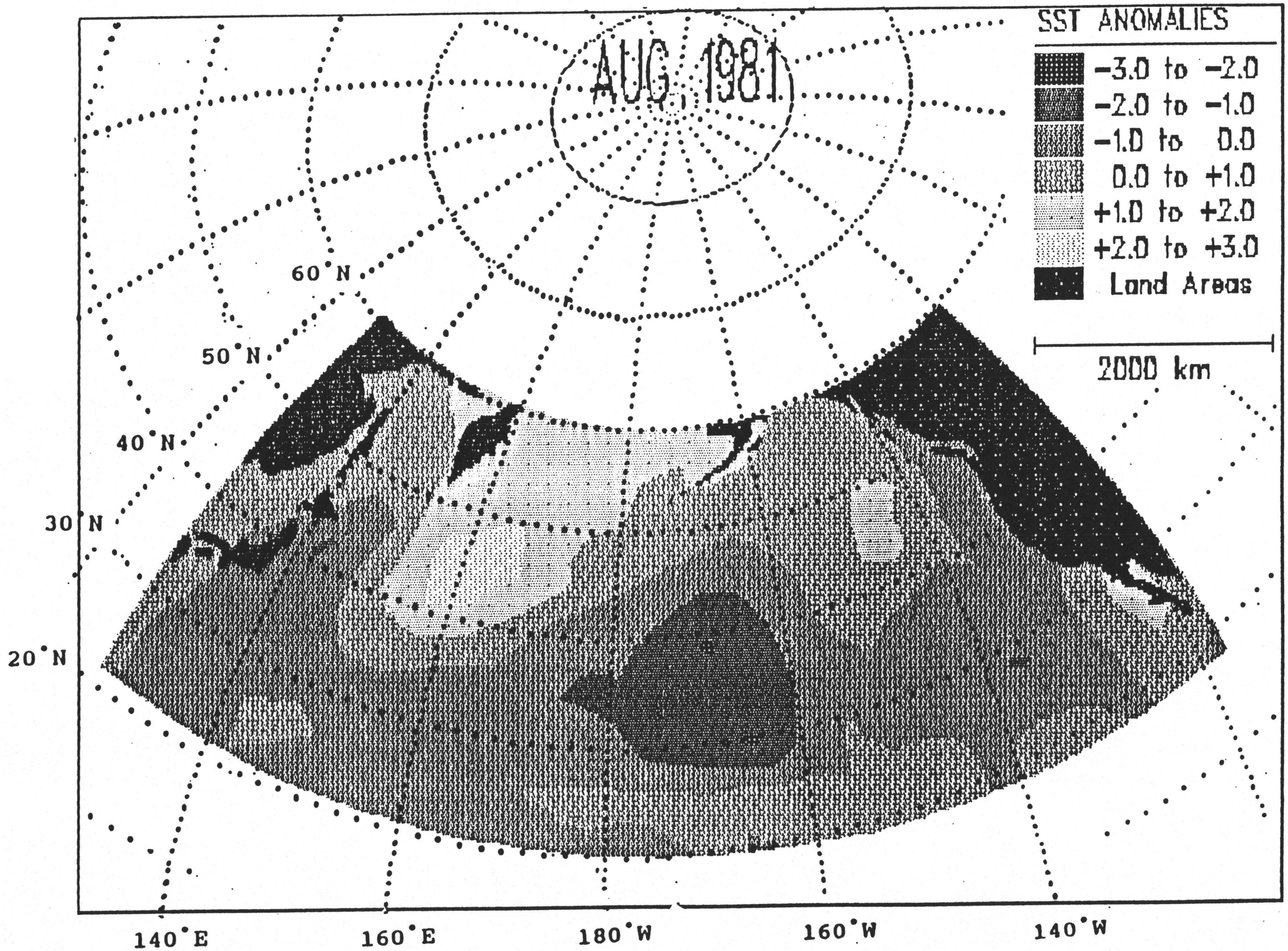

JUNE, 1956
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

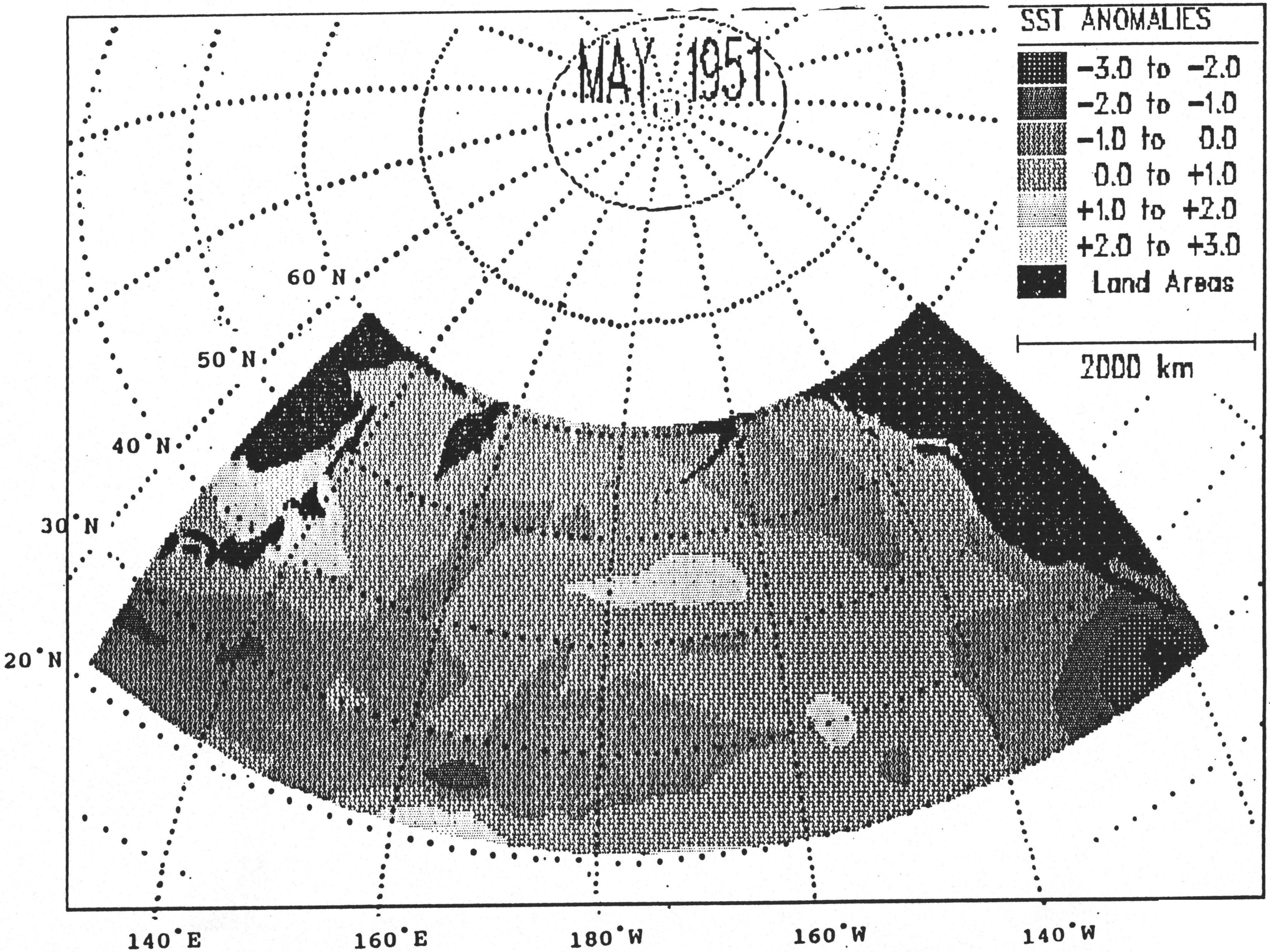


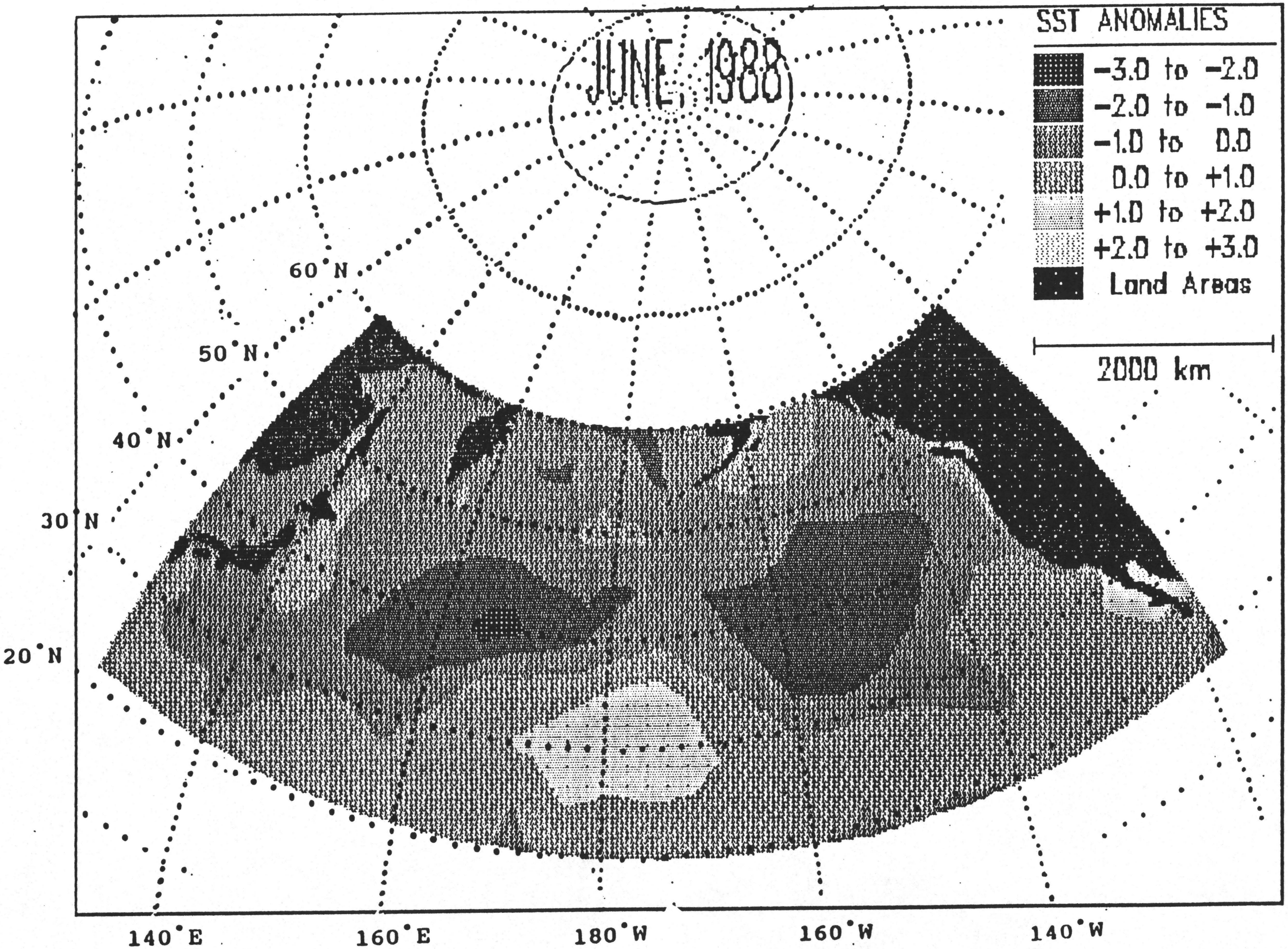
MAY 1986
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

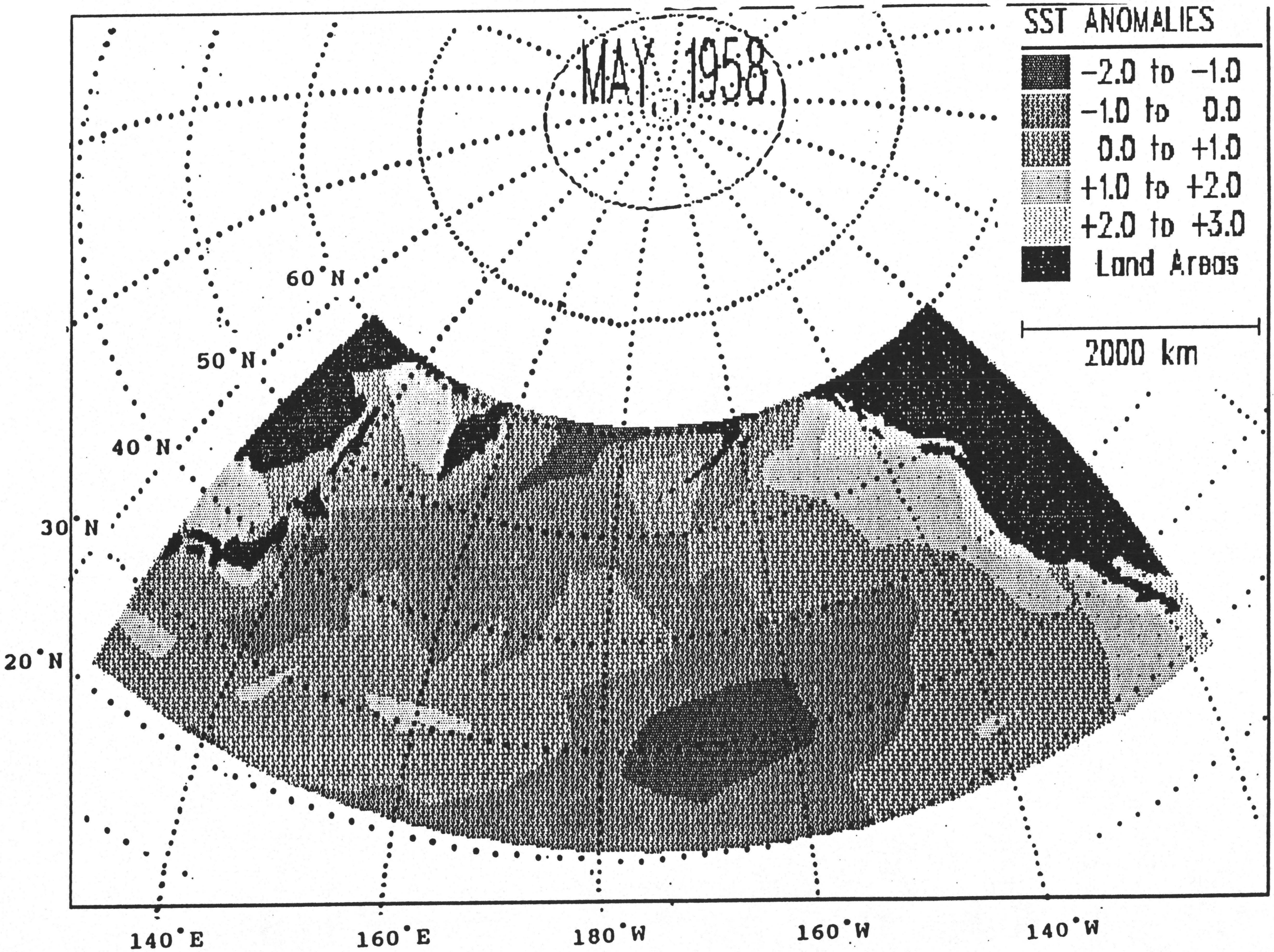

JUNE, 1986
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

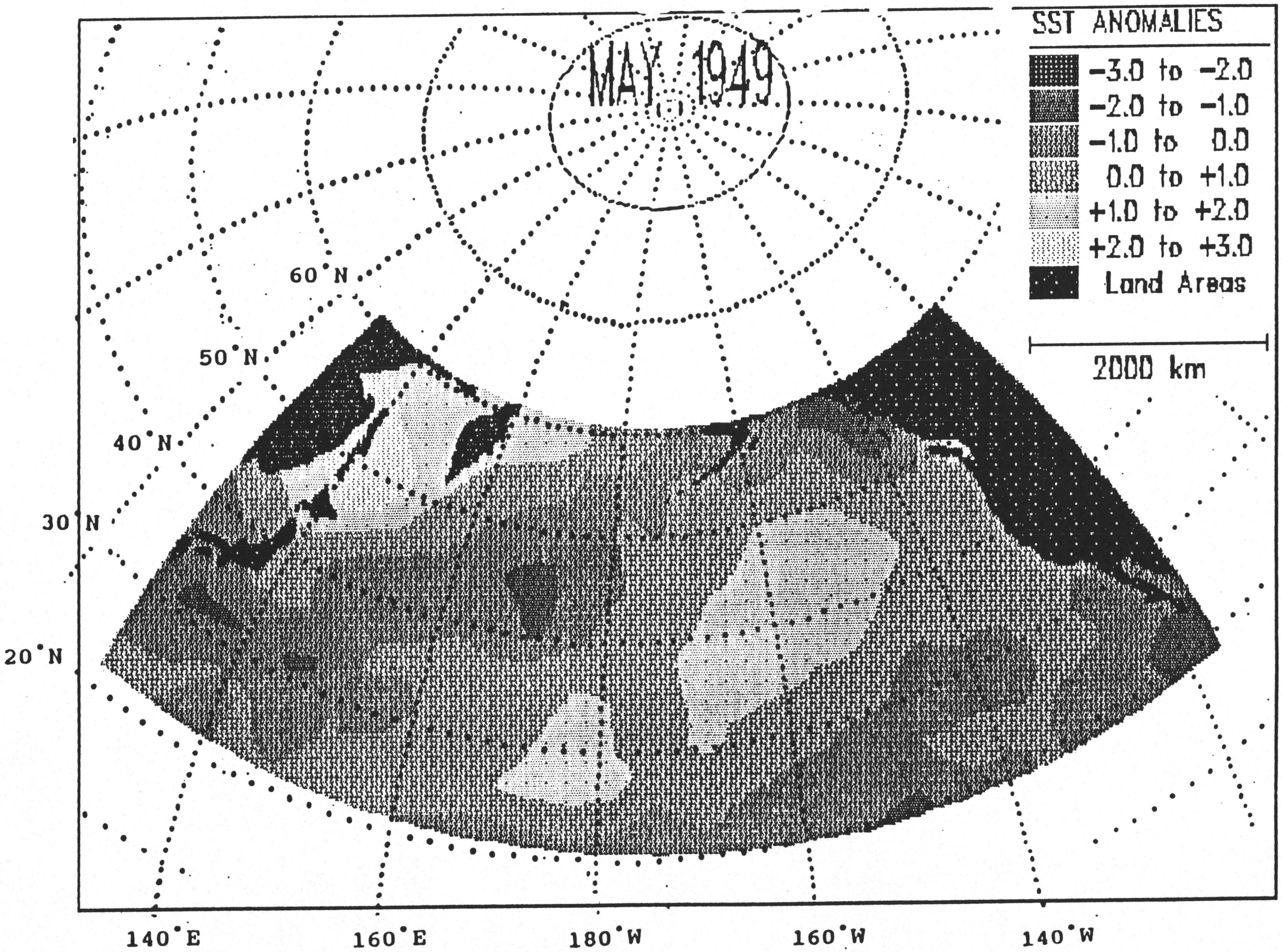

AUG. 1967
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


AUG. 1981
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


MAY 1951
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


JUNE, 1988
SST ANOMALIES
−3.0 to −2.0
−2.0 to −1.0
−1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


MAY 1958
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


MAY 1949
SST ANOMALIES
−3.0 to −2.0
−2.0 to −1.0
−1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

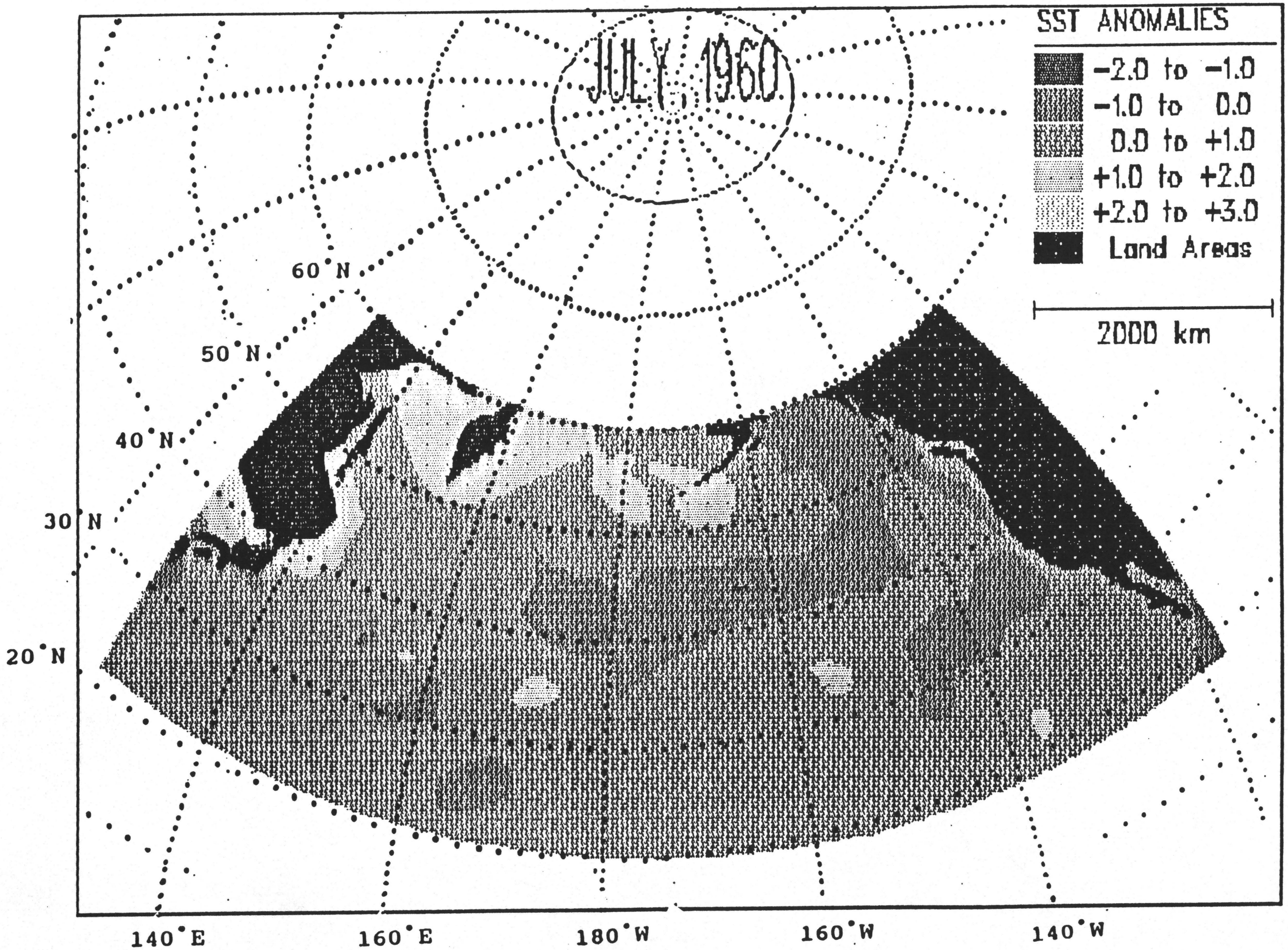
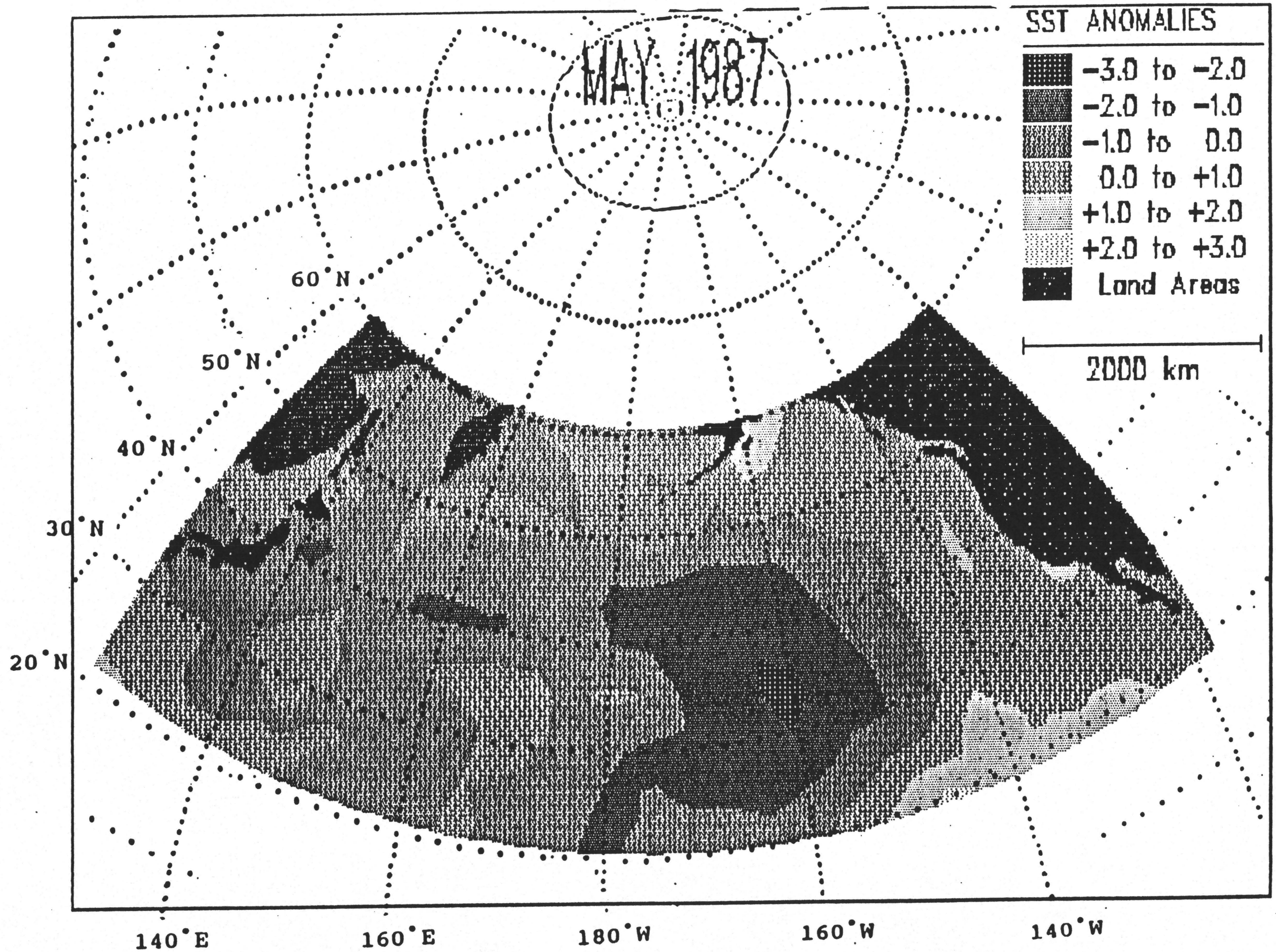
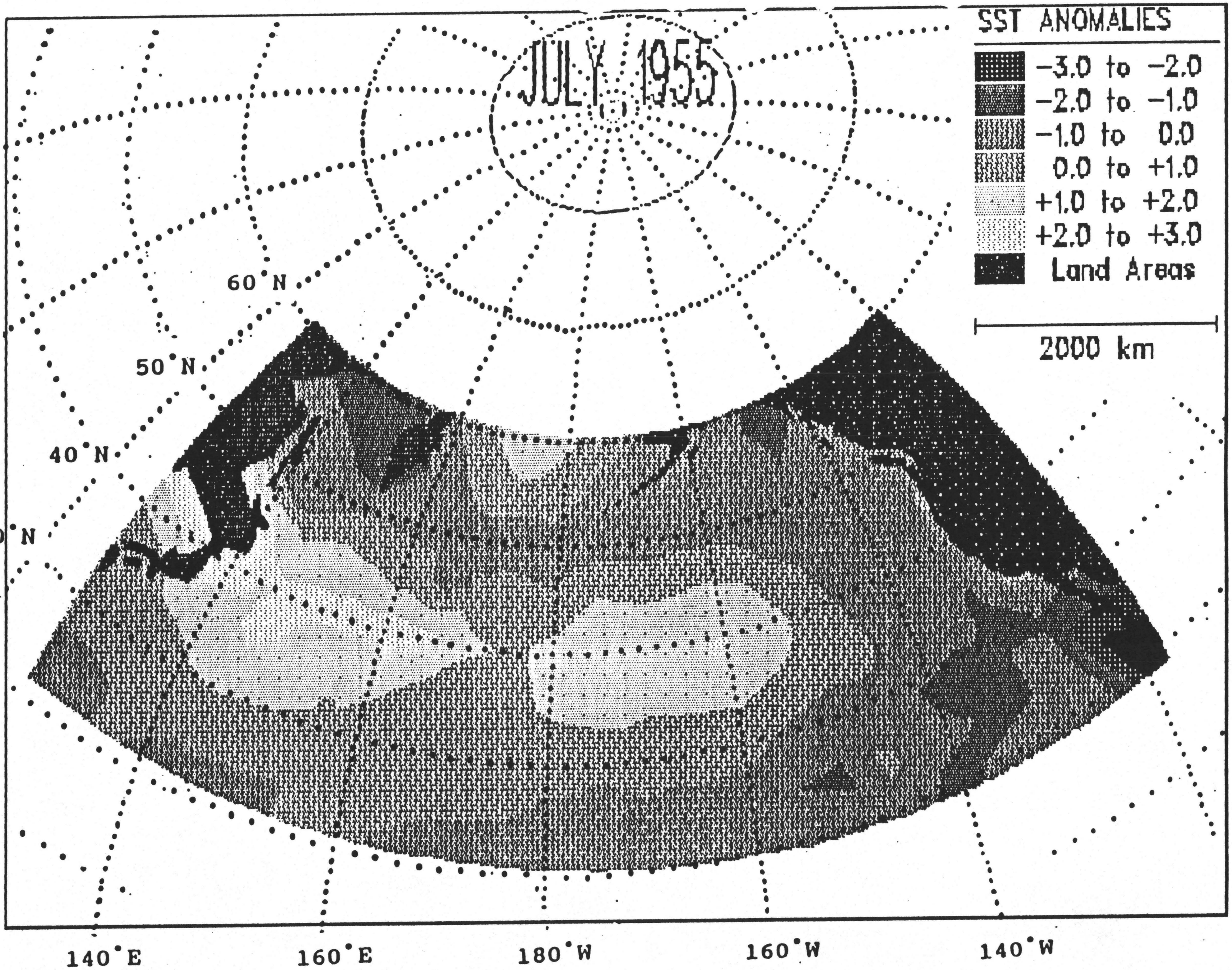
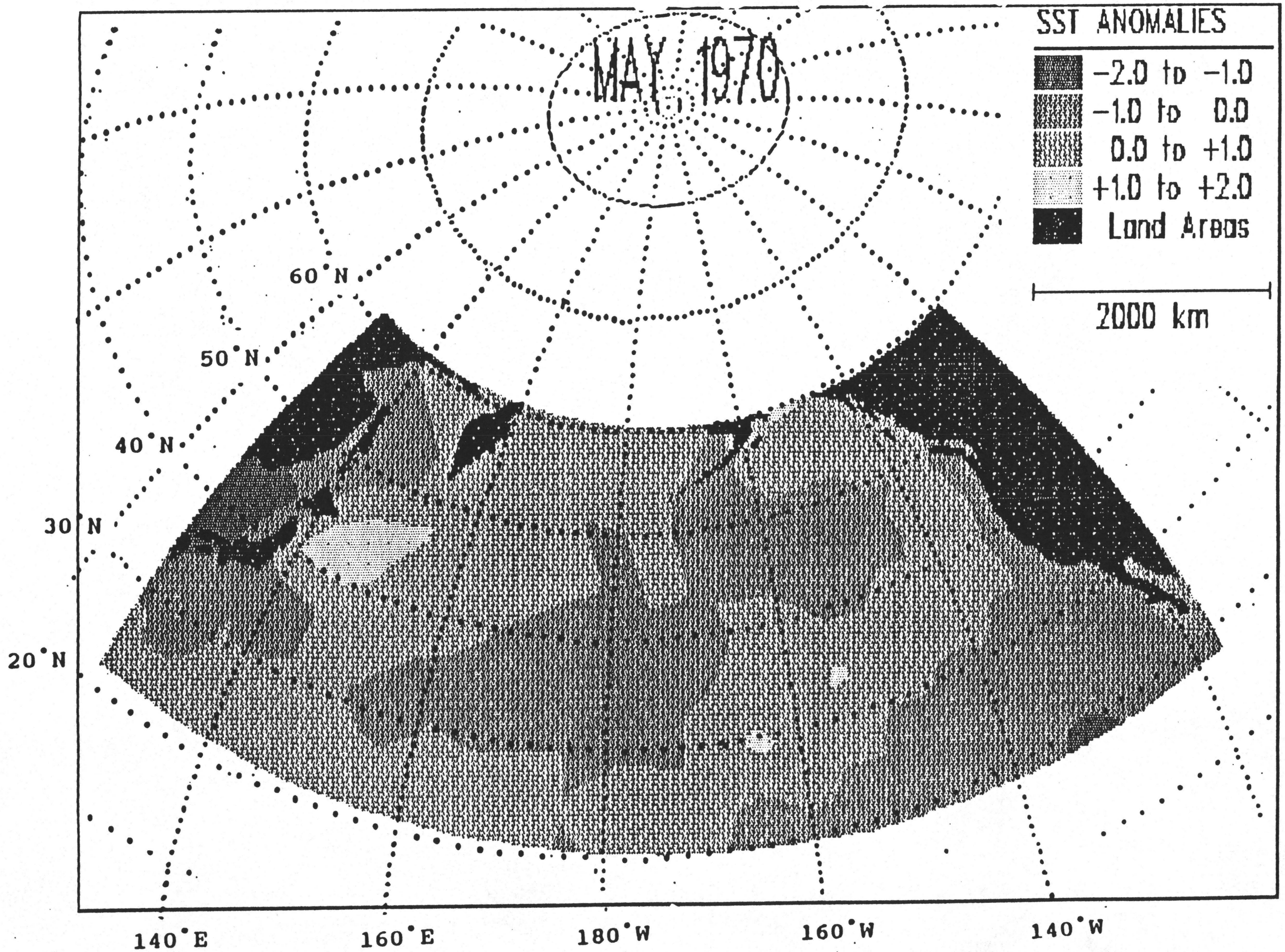
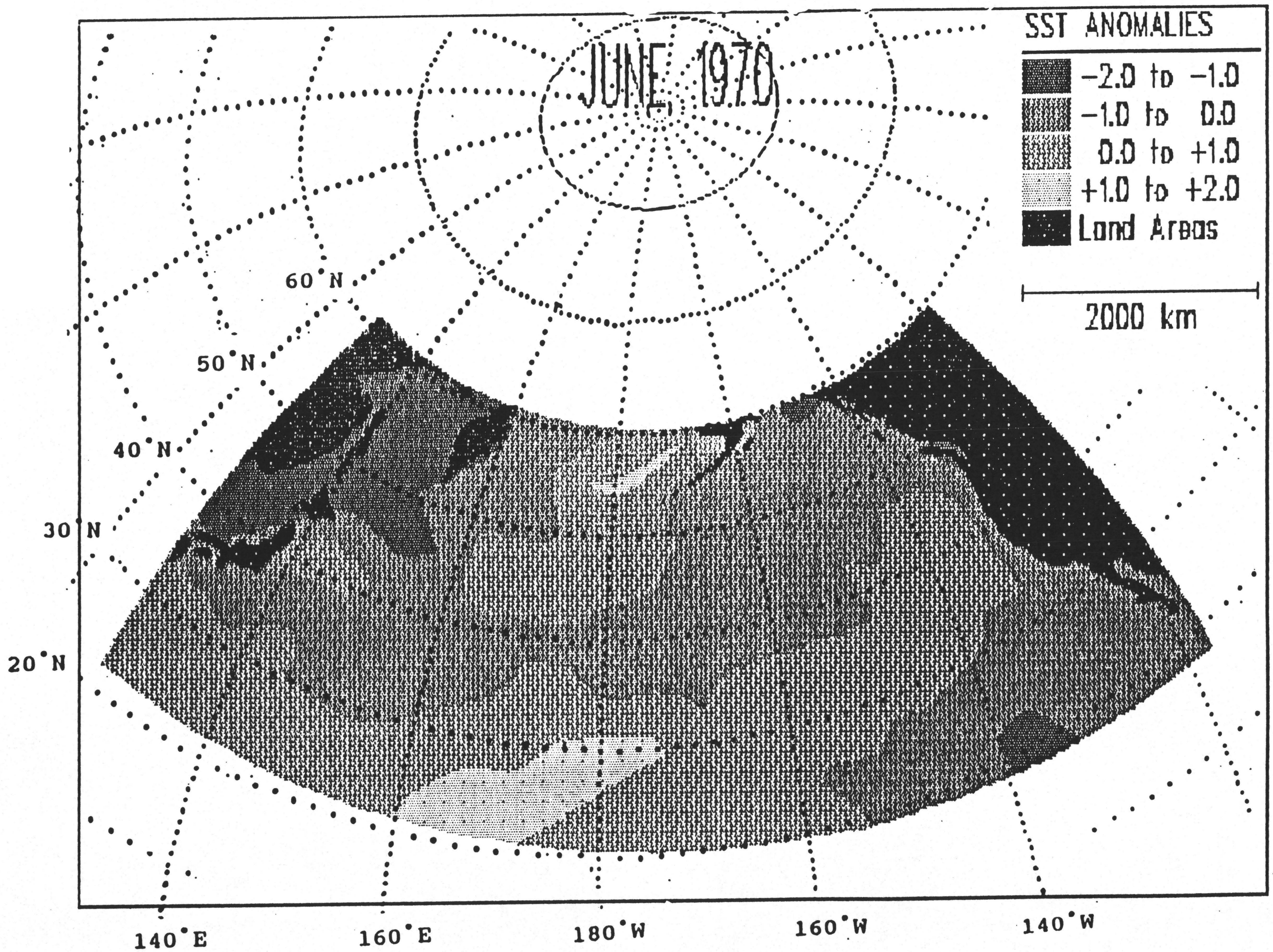


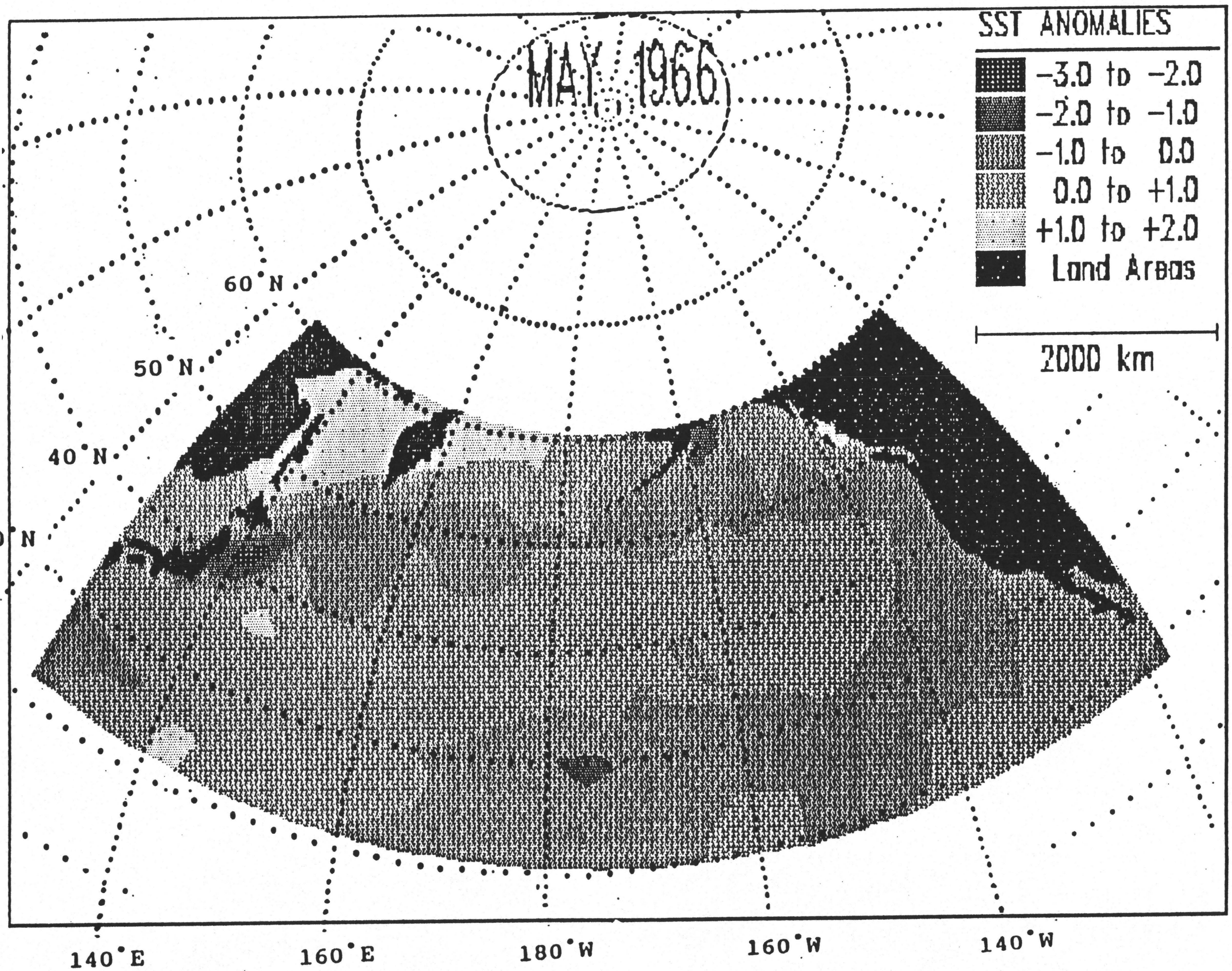
Table B - B.1 Sea Surface Temperature Anomaly Maps
B: Other Extended Dry Spells


MAY 1987
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

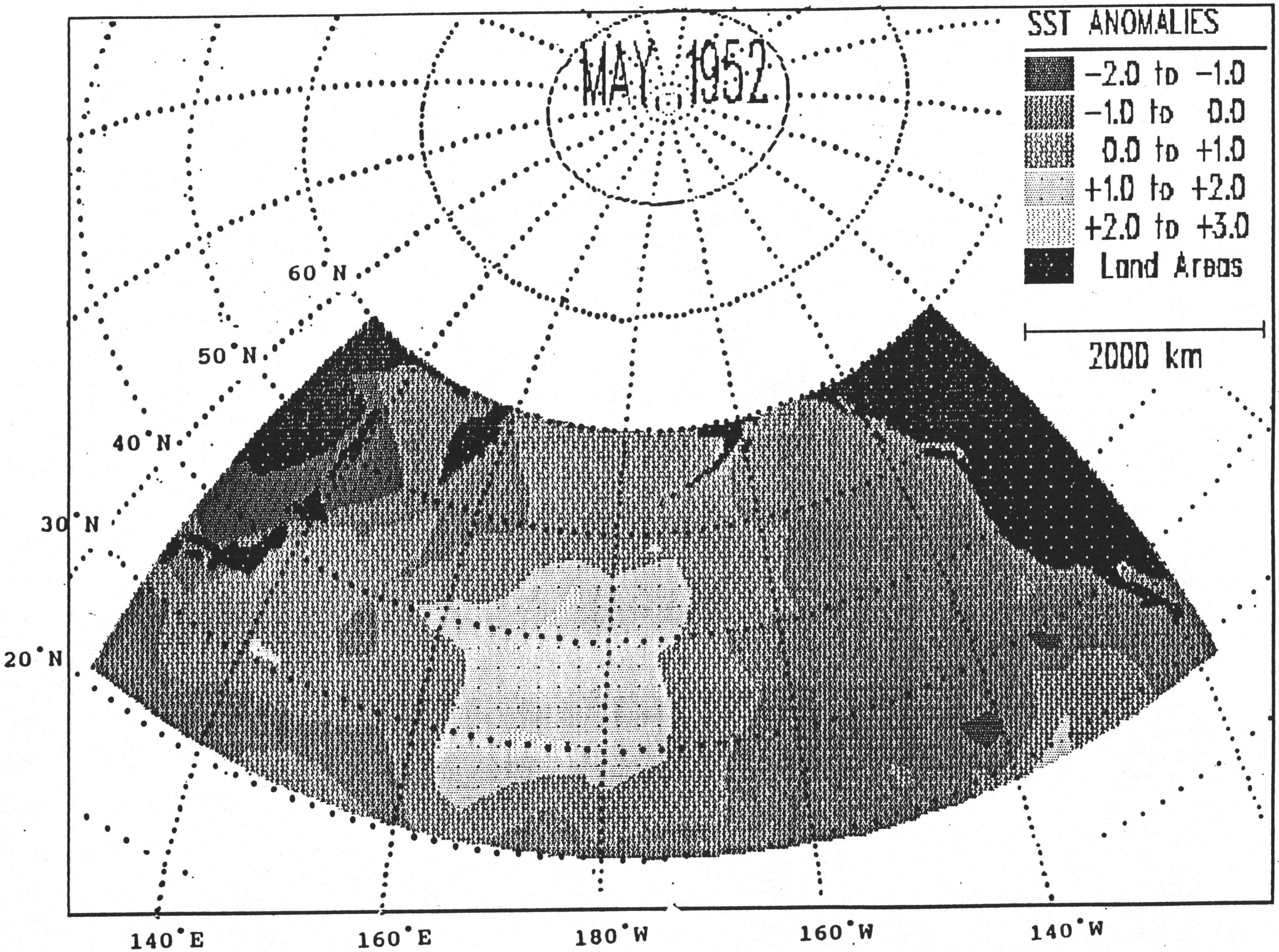

JULY, 1955
SST ANOMALIES
−3.0 to −2.0
−2.0 to −1.0
−1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

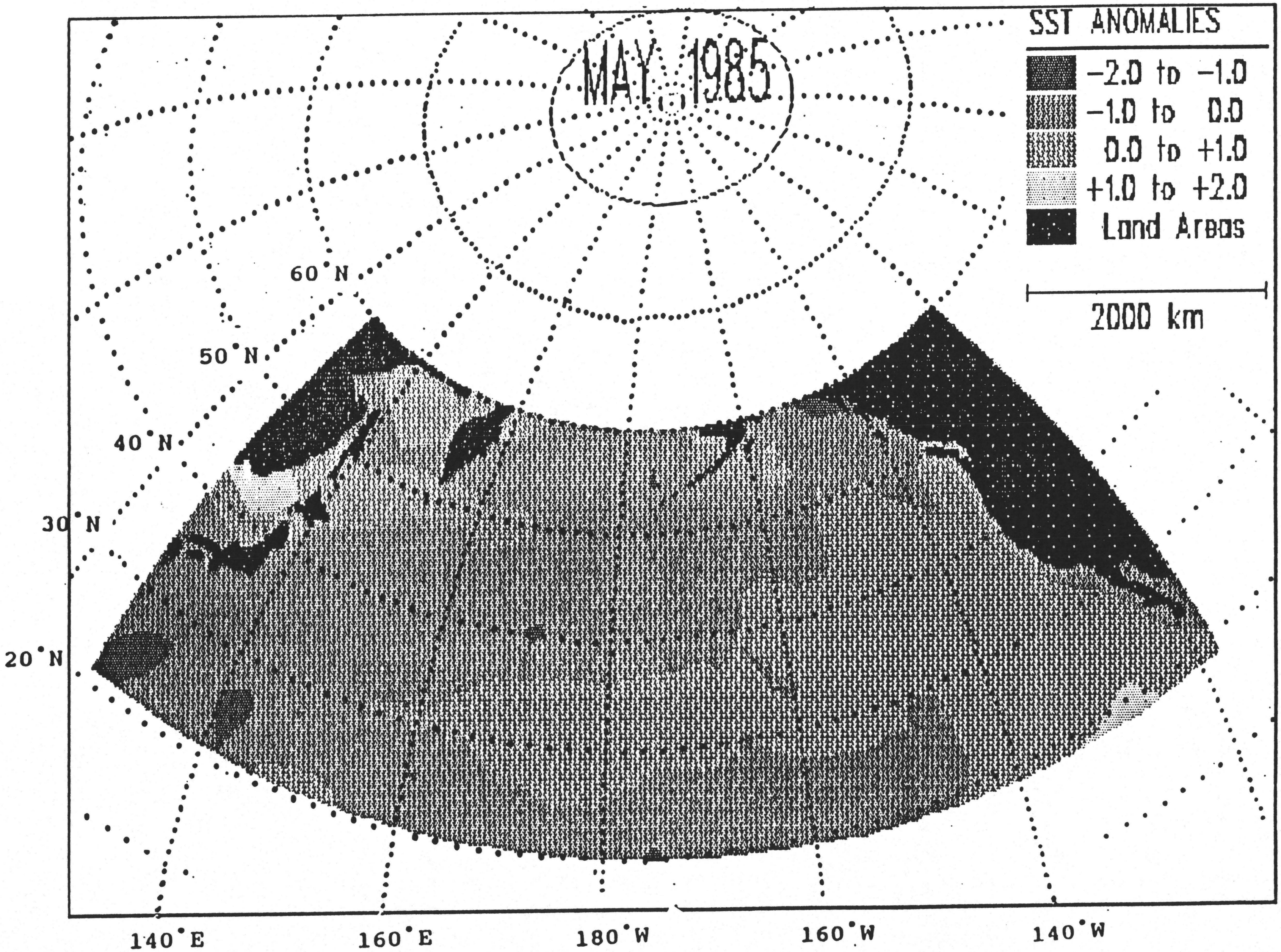

MAY, 1970
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

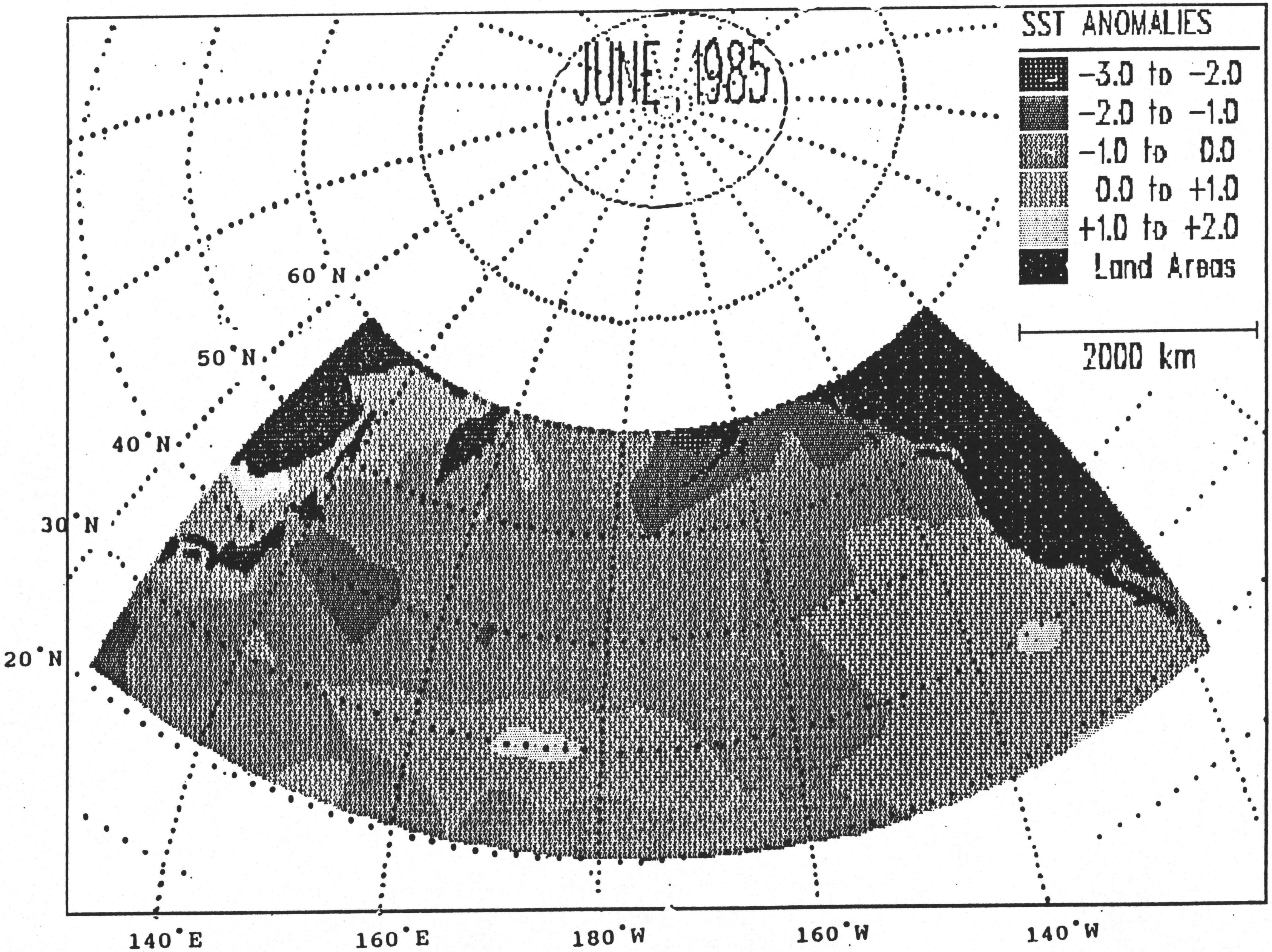

JUNE 1970
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W



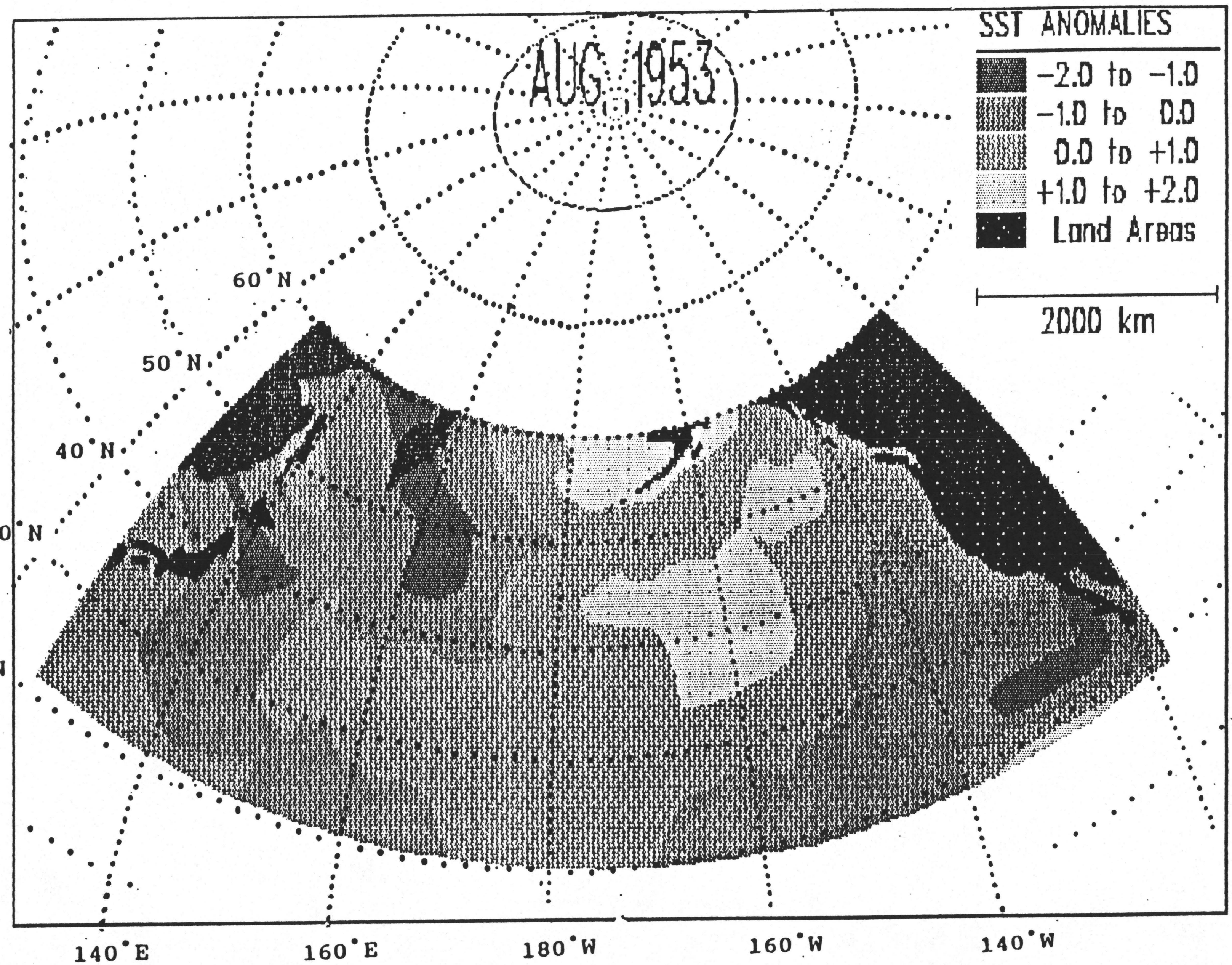
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
MAY, 1966
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

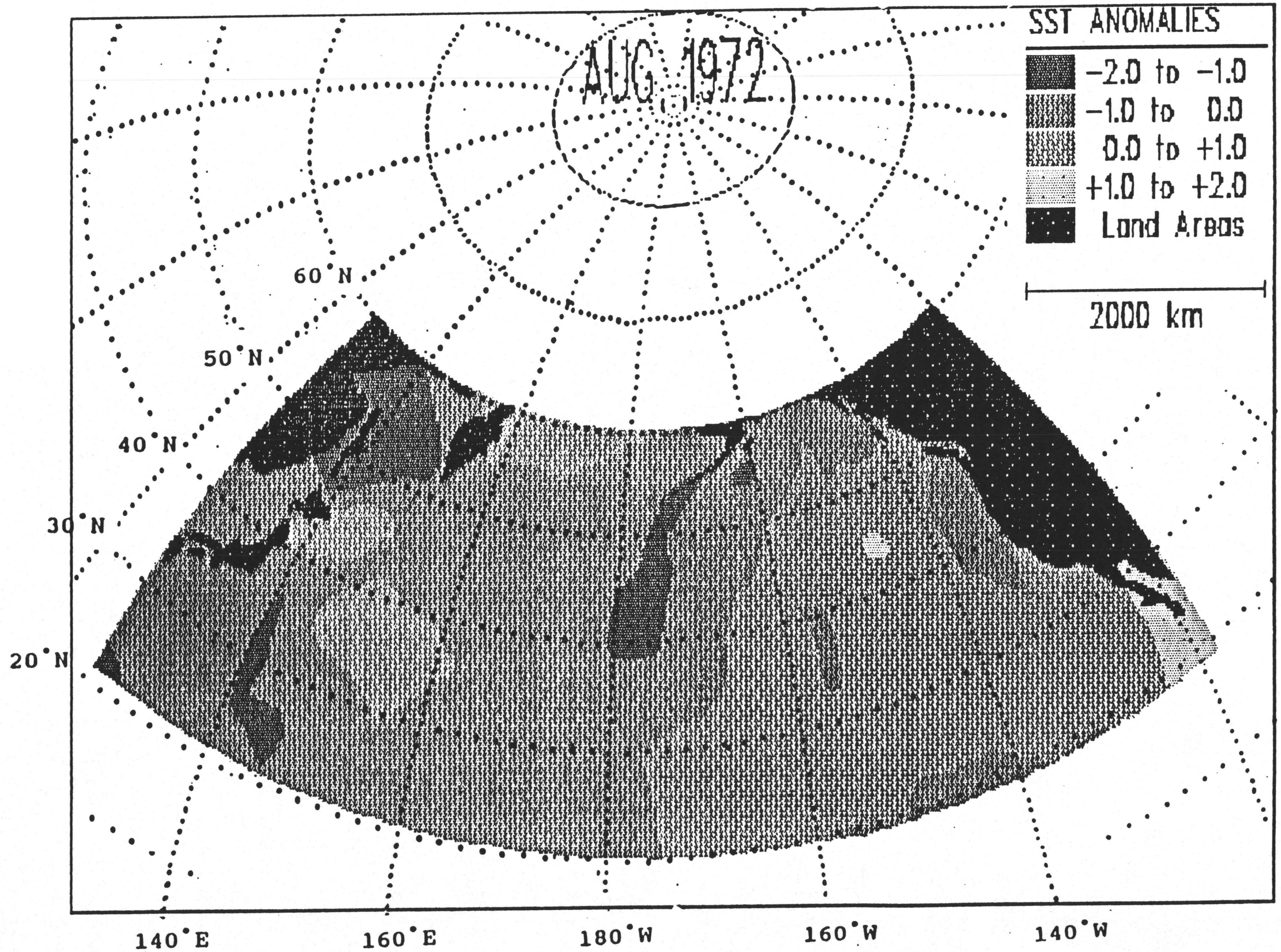

MAY, 1952
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

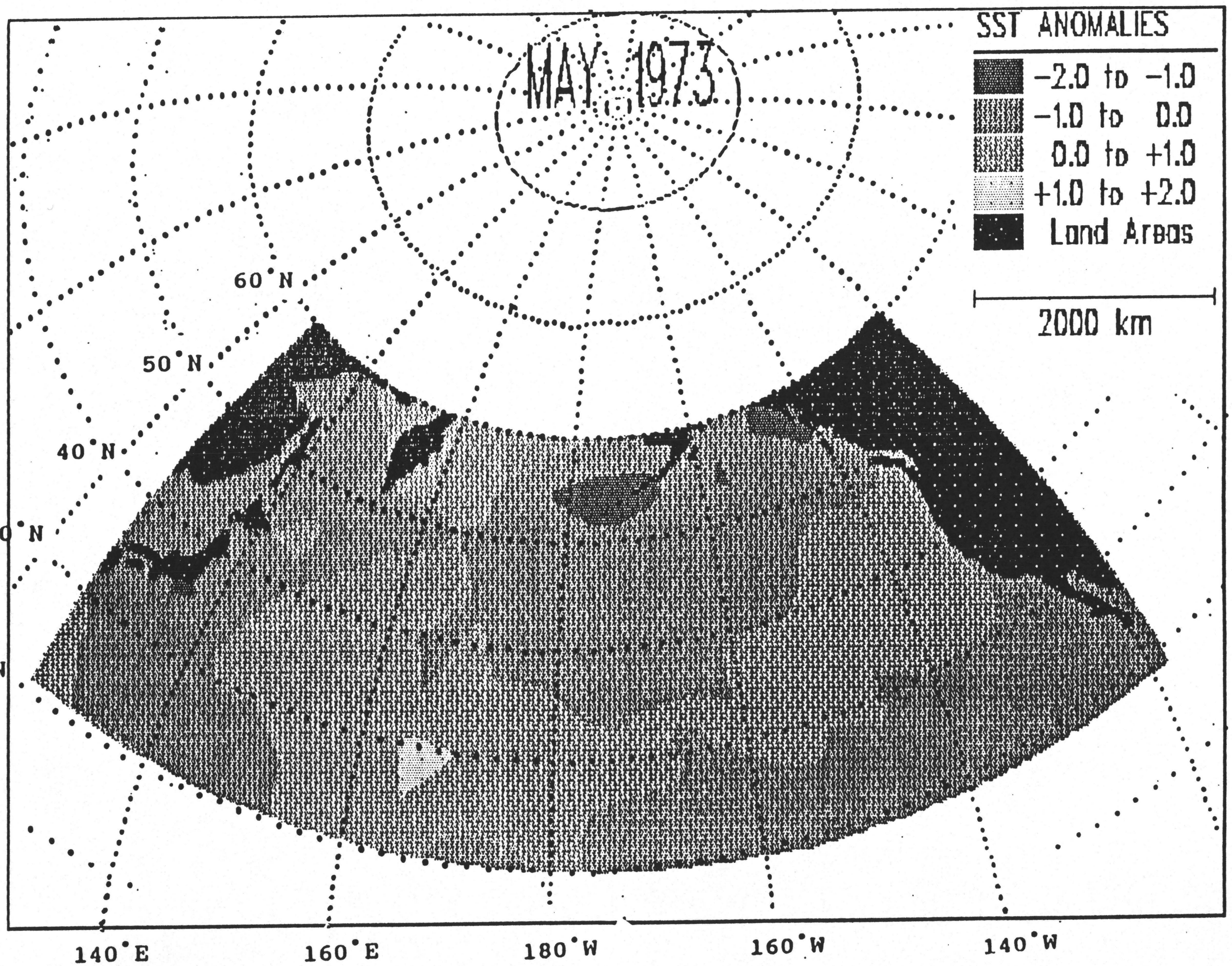

MAY 1985
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W



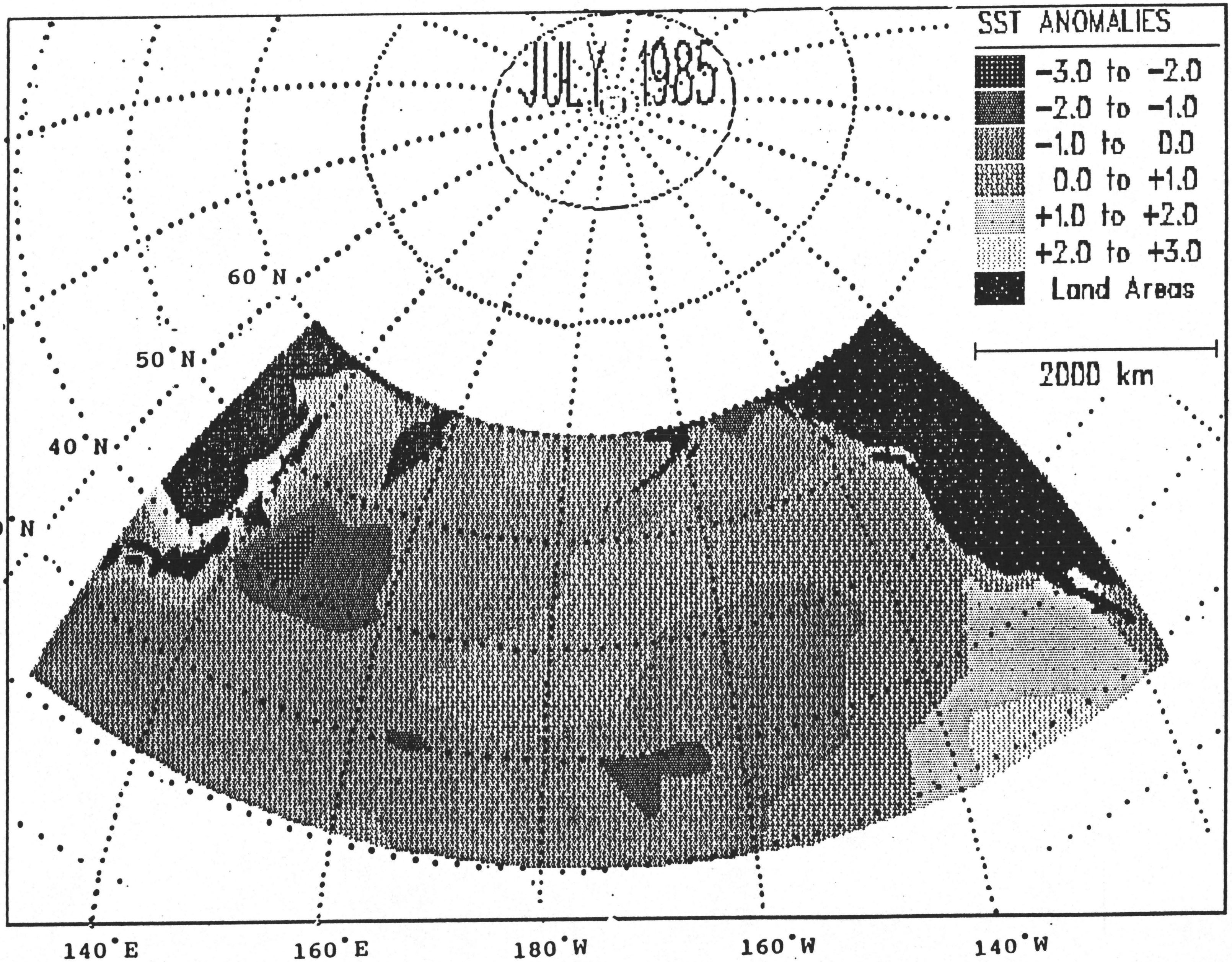
JUNE 1985
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

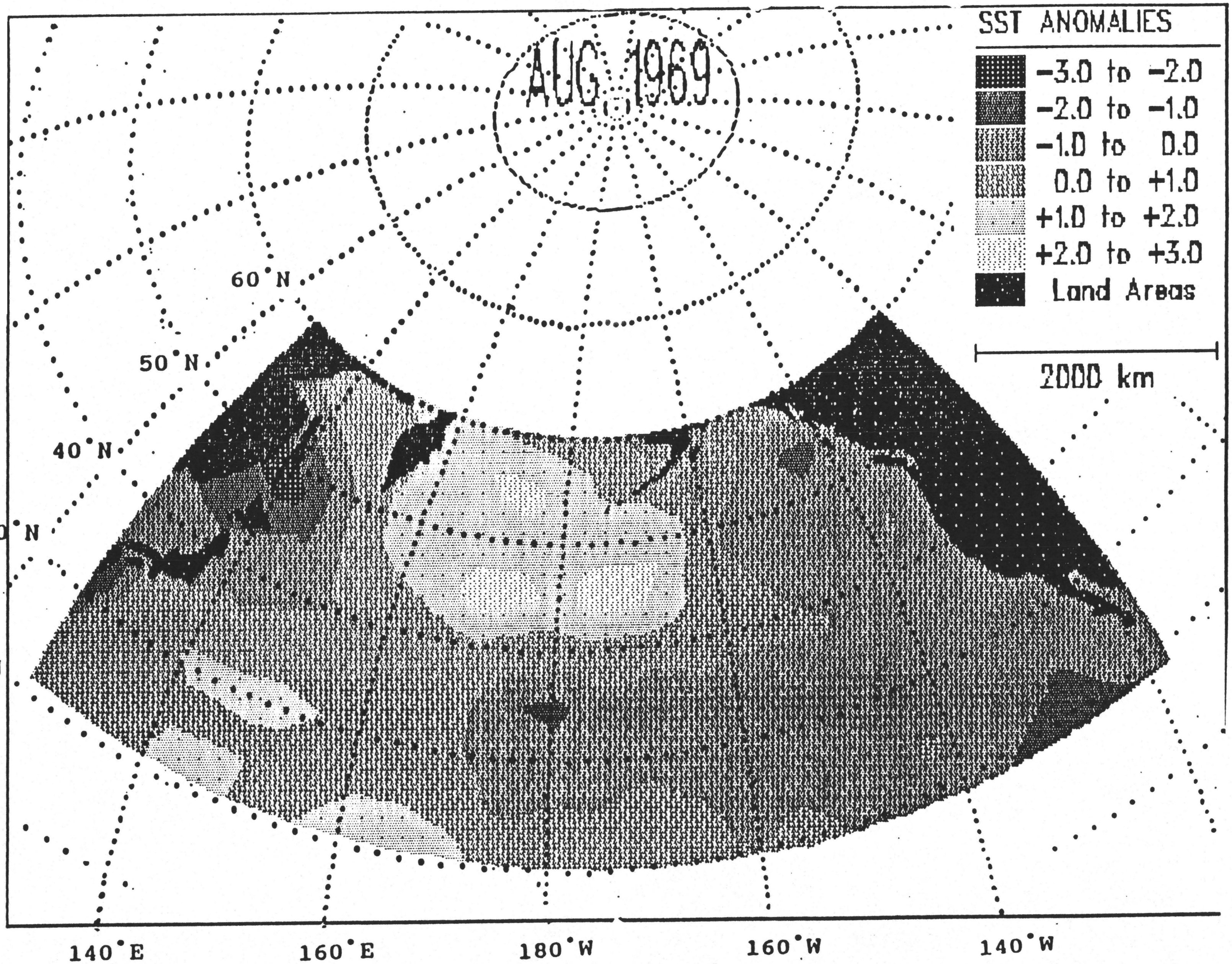

AUG. 1953
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


AUG 1972
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

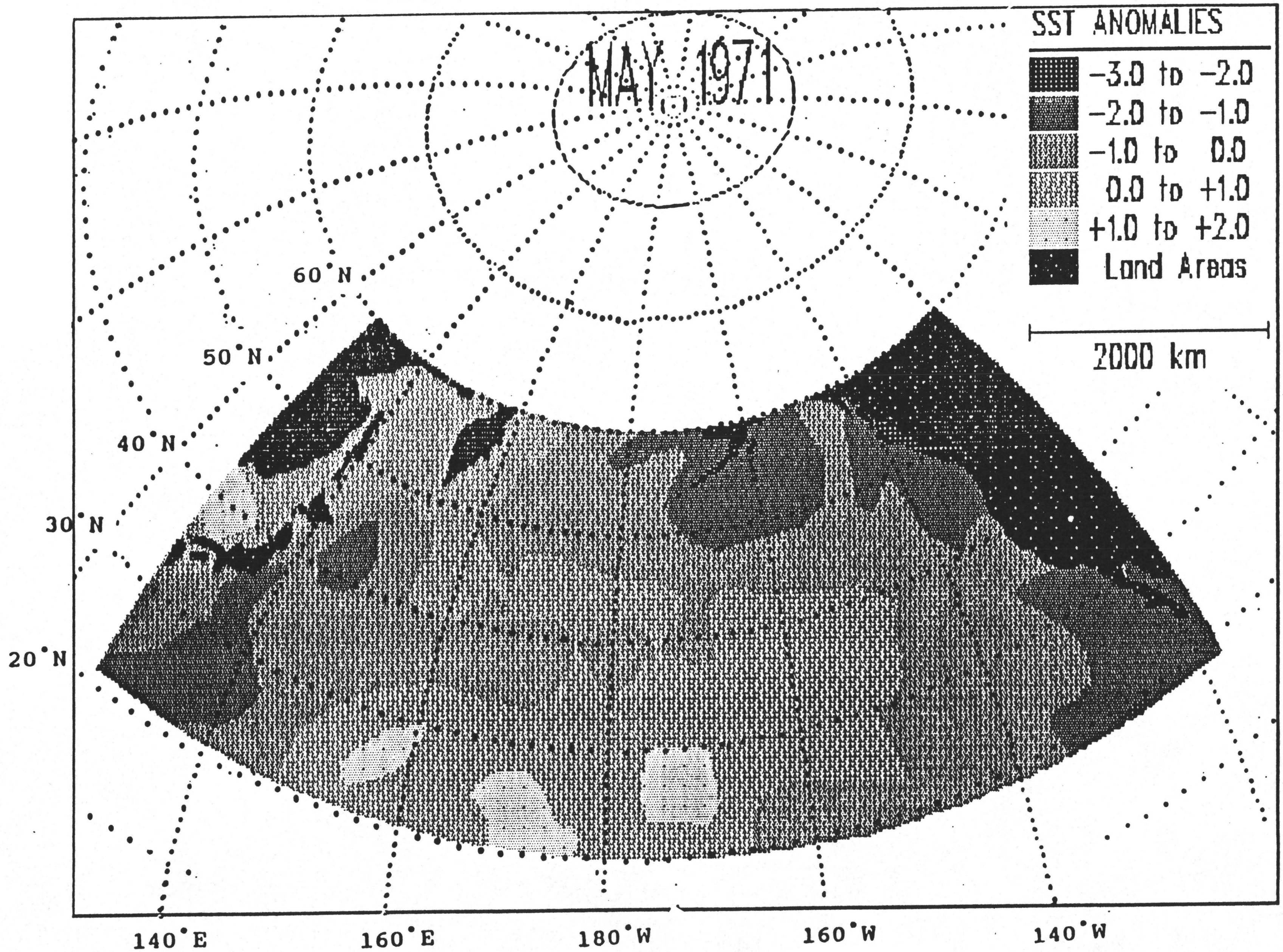


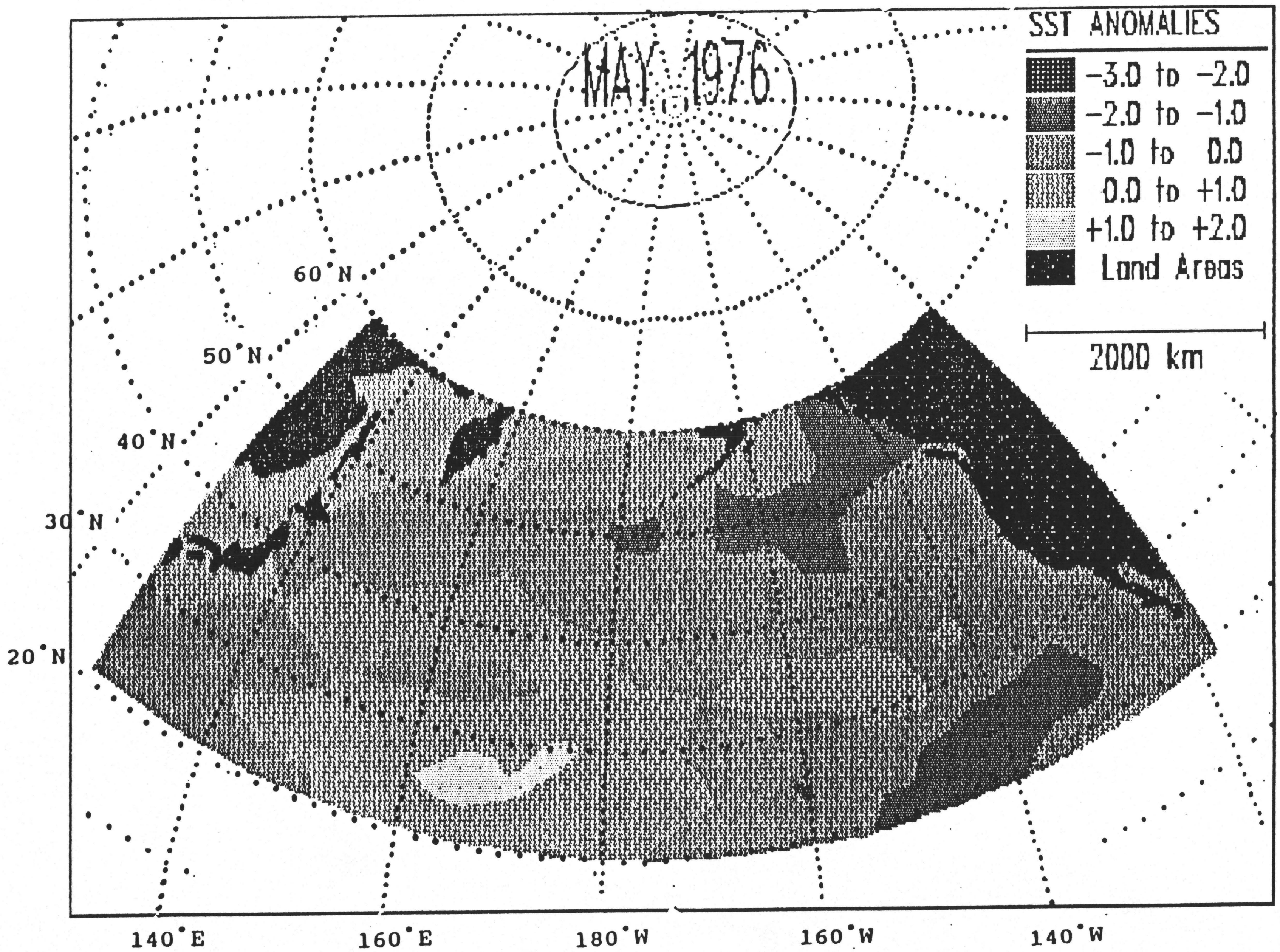
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
MAY 1973
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

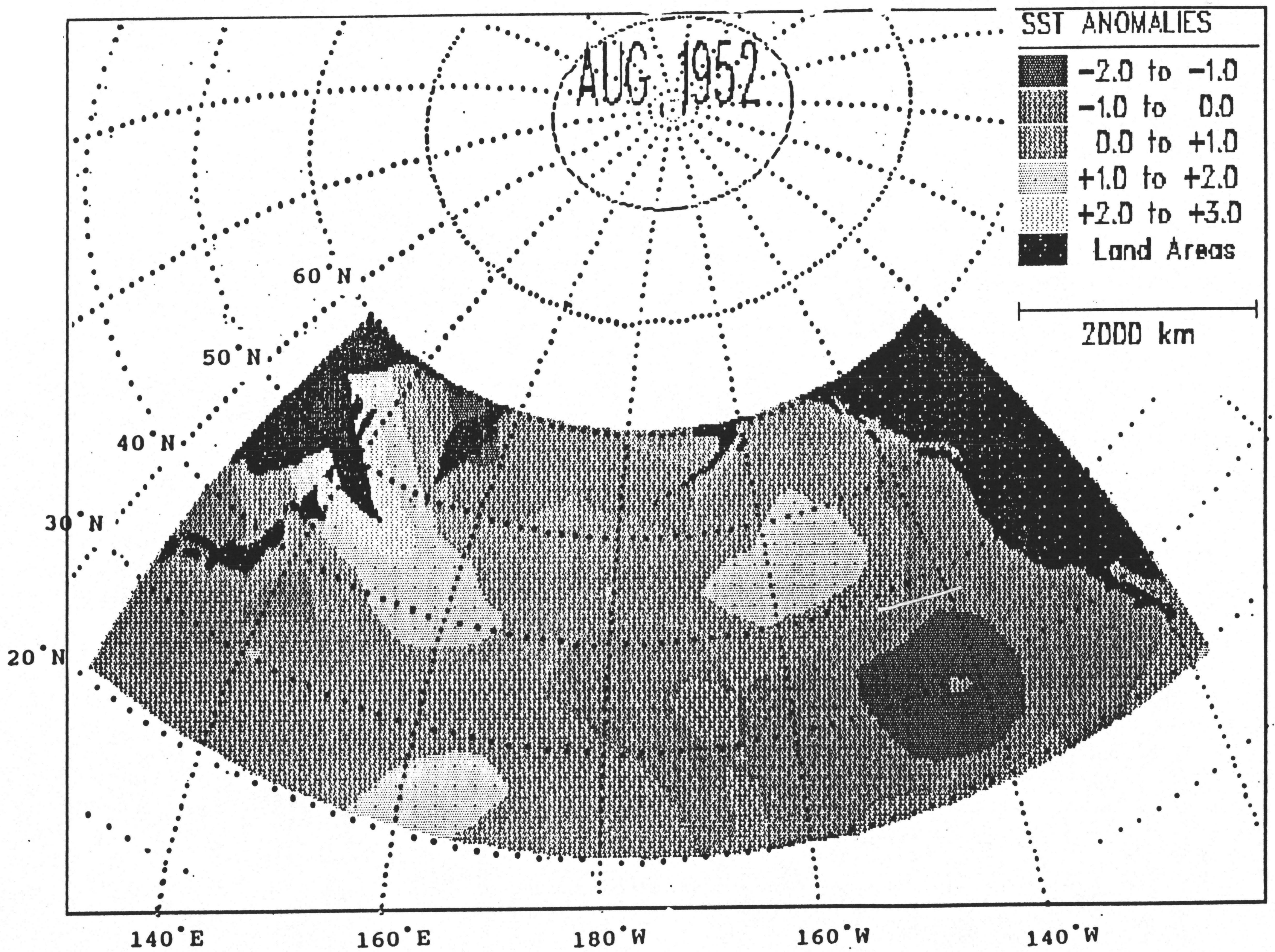

JULY, 1985
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

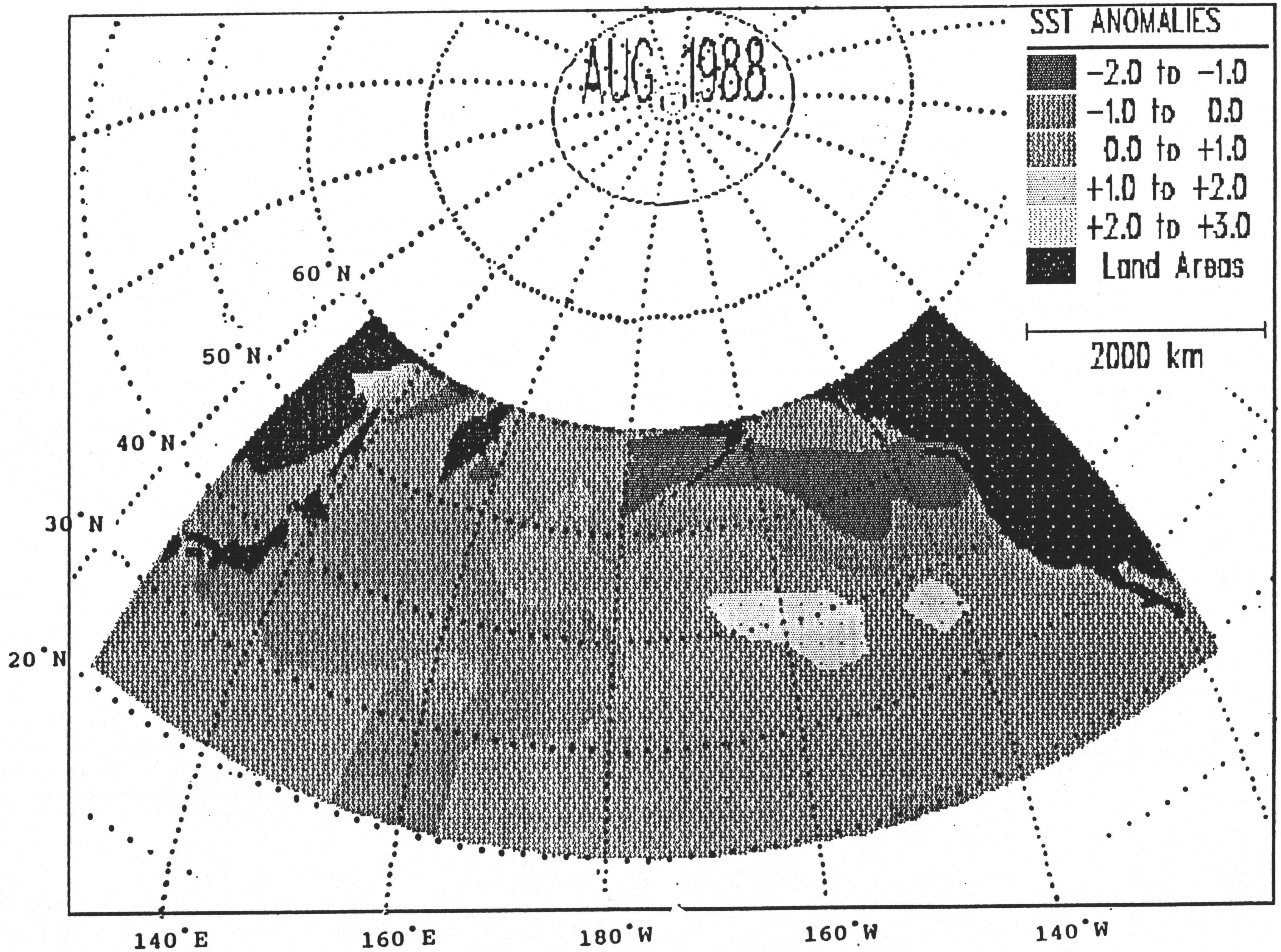


AUG 1969
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


MAY, 1971
SST ANOMALIES
−3.0 to −2.0
−2.0 to −1.0
−1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


MAY 1976
SST ANOMALIES
-3.0 to -2.0
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W


AUG 1952
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

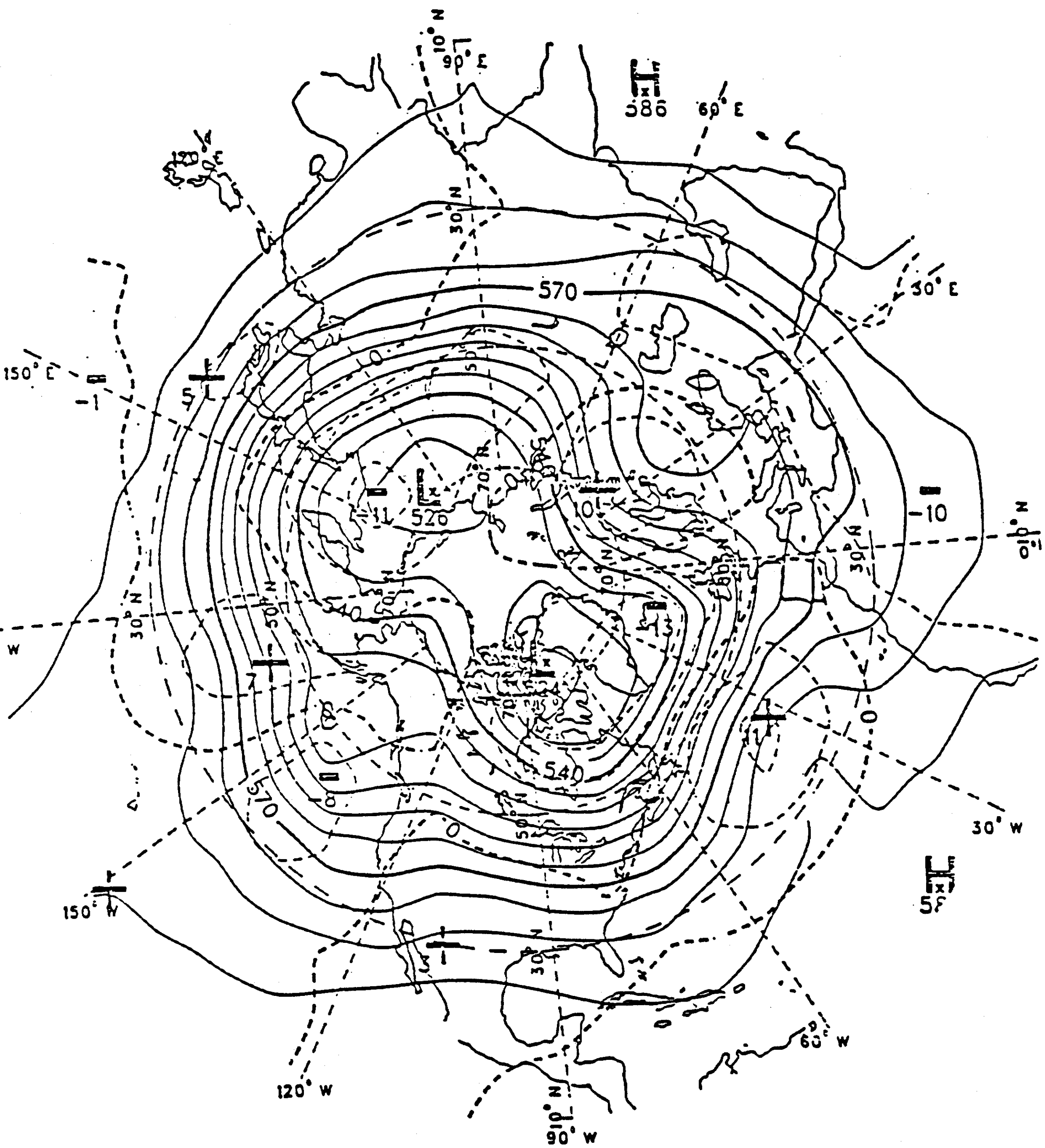

AUG. 1988
SST ANOMALIES
-2.0 to -1.0
-1.0 to 0.0
0.0 to +1.0
+1.0 to +2.0
+2.0 to +3.0
Land Areas
2000 km
60°N
50°N
40°N
30°N
20°N
140°E
160°E
180°W
160°W
140°W

APPENDIX C

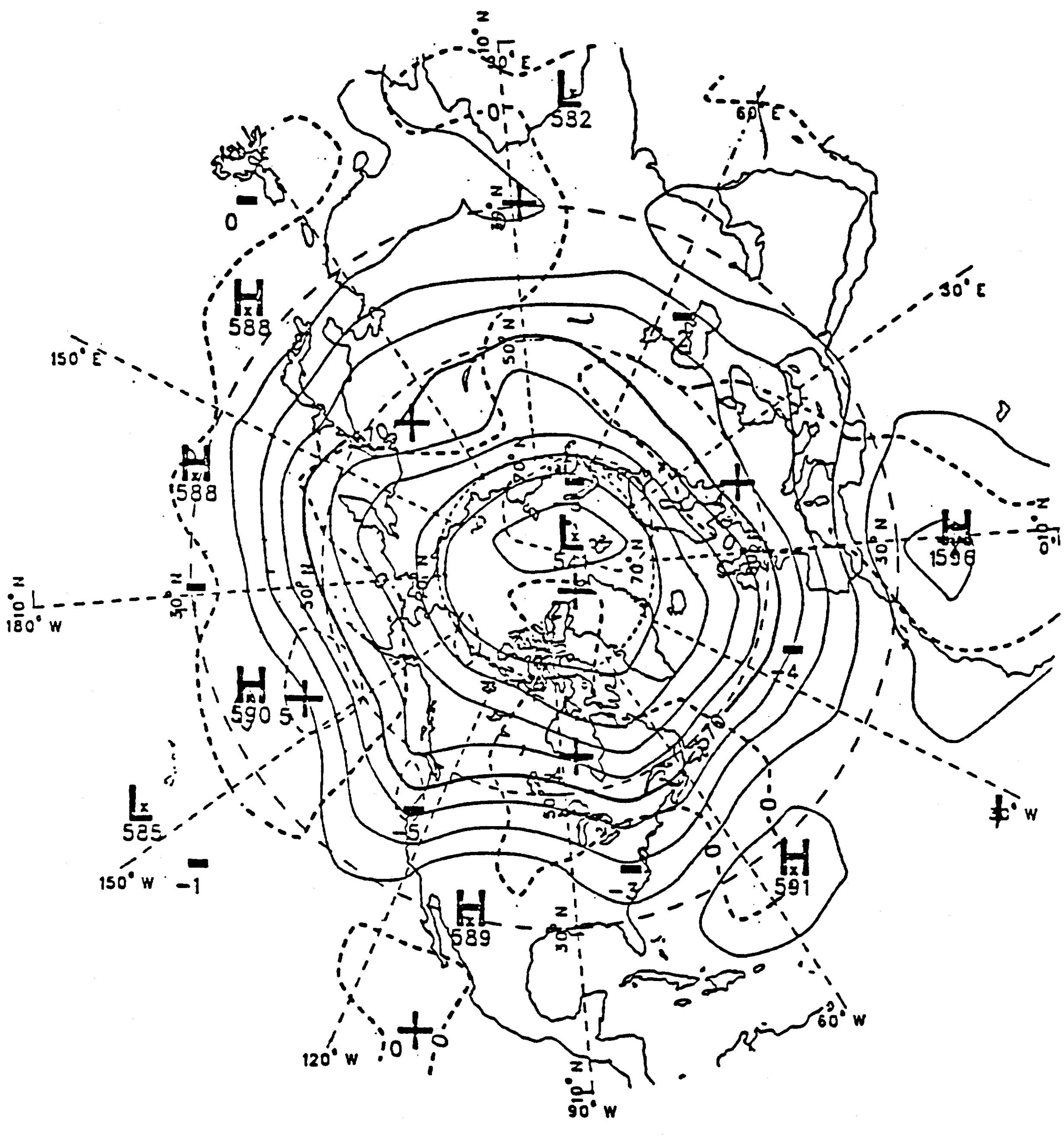
50 KPA ANOMALOUS HEIGHTS

Table C - C.1: Northern Hemisphere 50 kPa Anomaly Maps

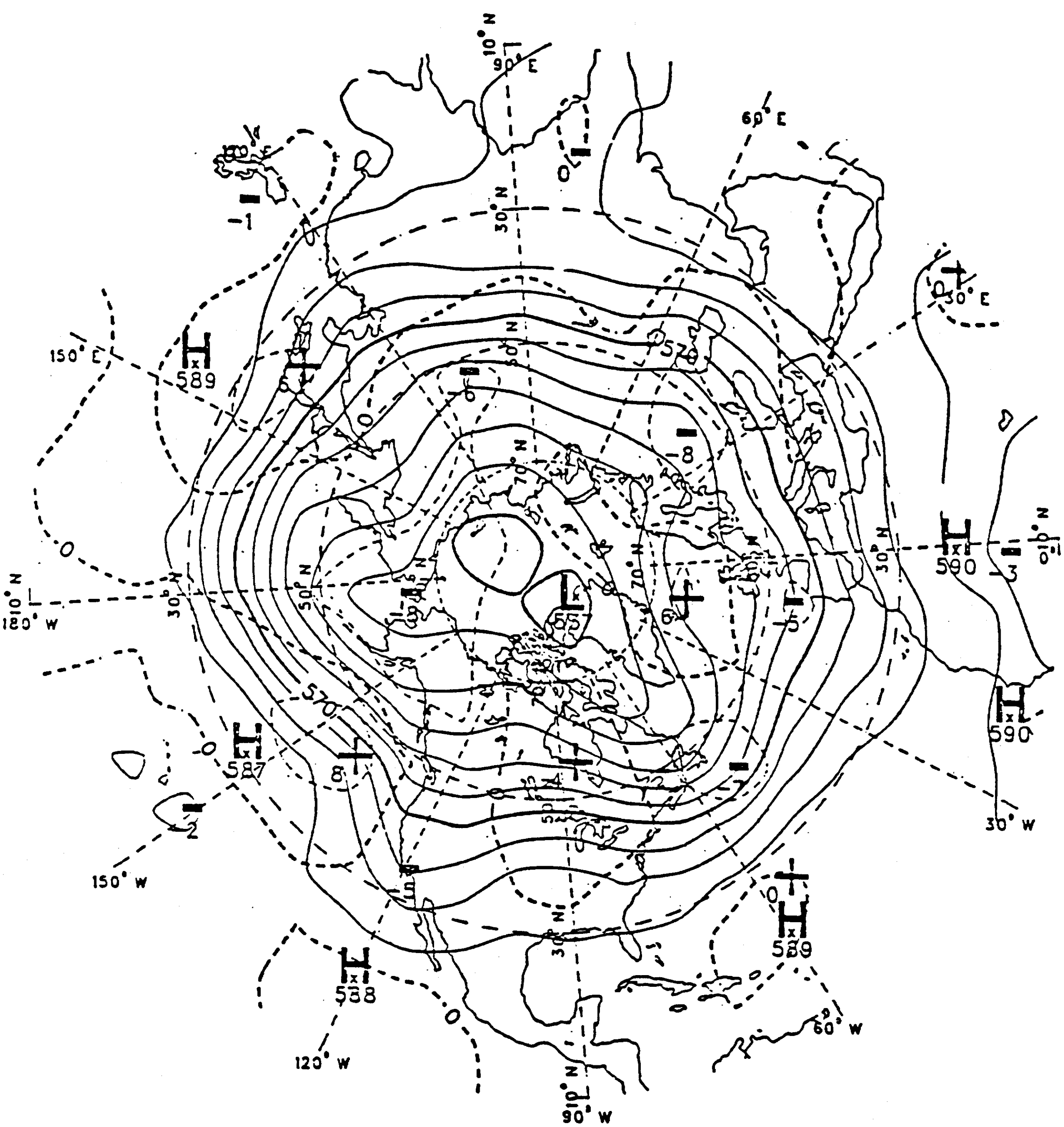
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
MAY 1963
CONTOUR INTERVAL: 5.0 DAM



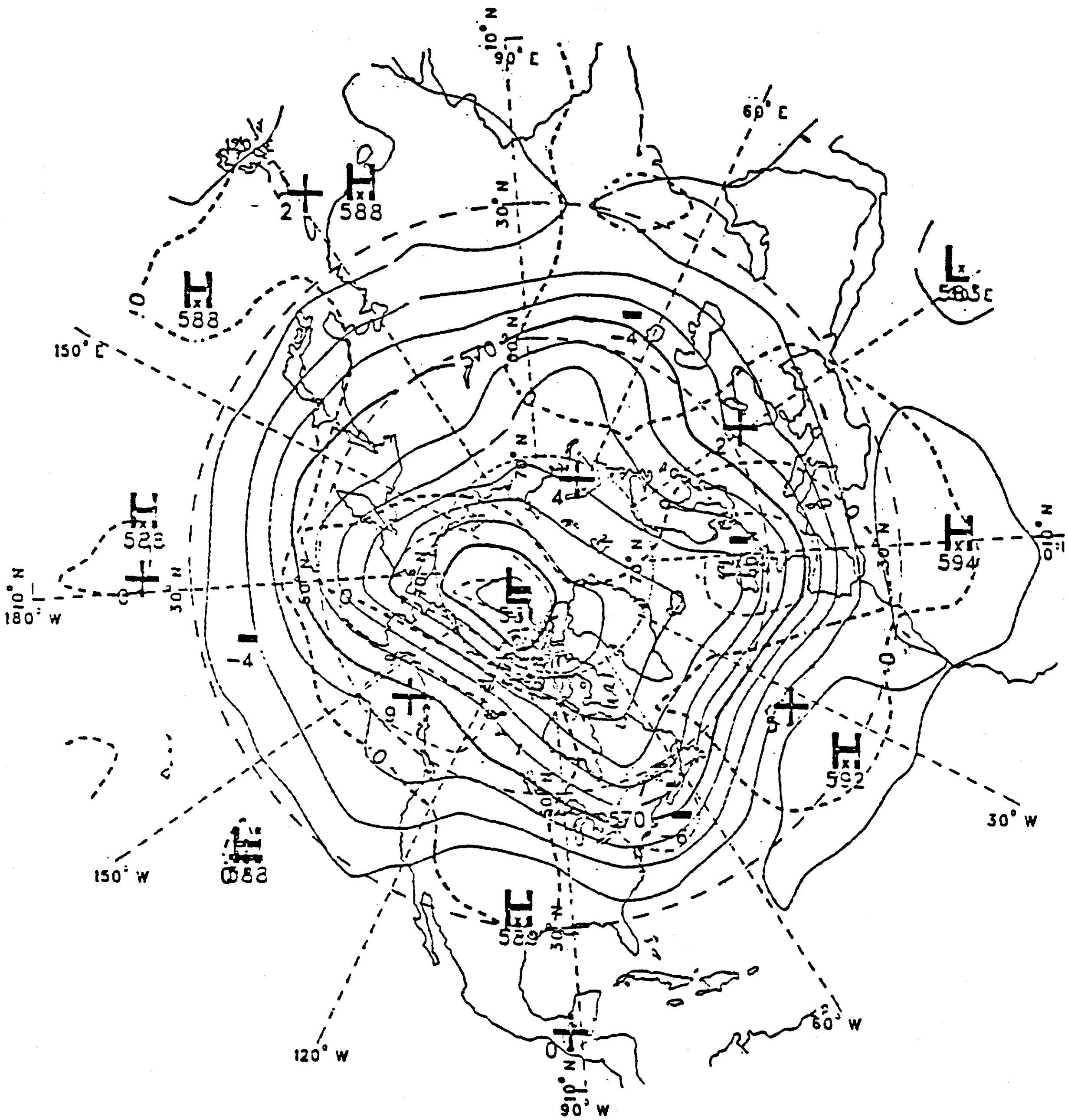
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JULY 1963
CONTOUR INTERVAL: 5.0 DAM



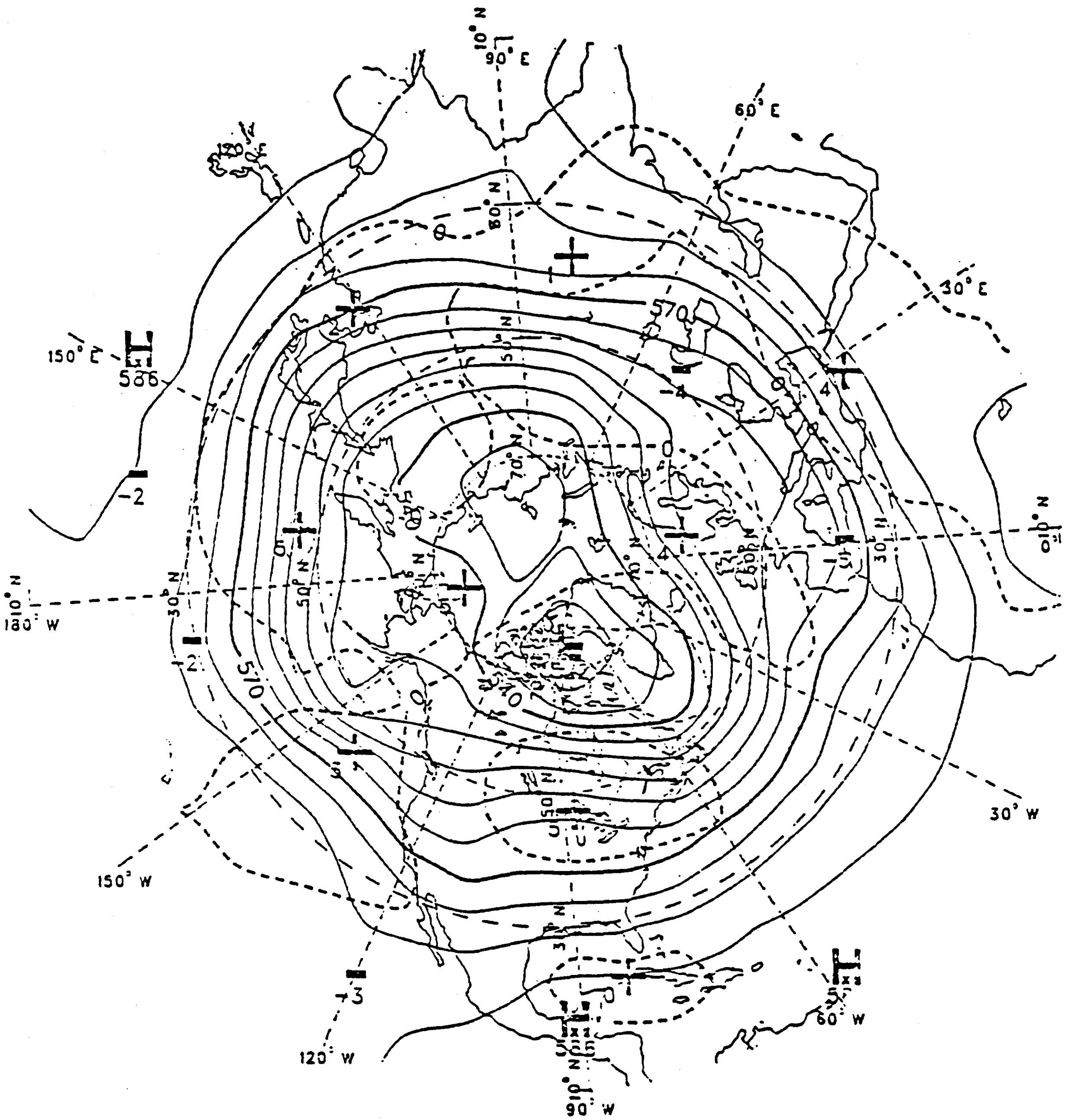
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JUNE 1963
CONTOUR INTERVAL: 5.0 DAM



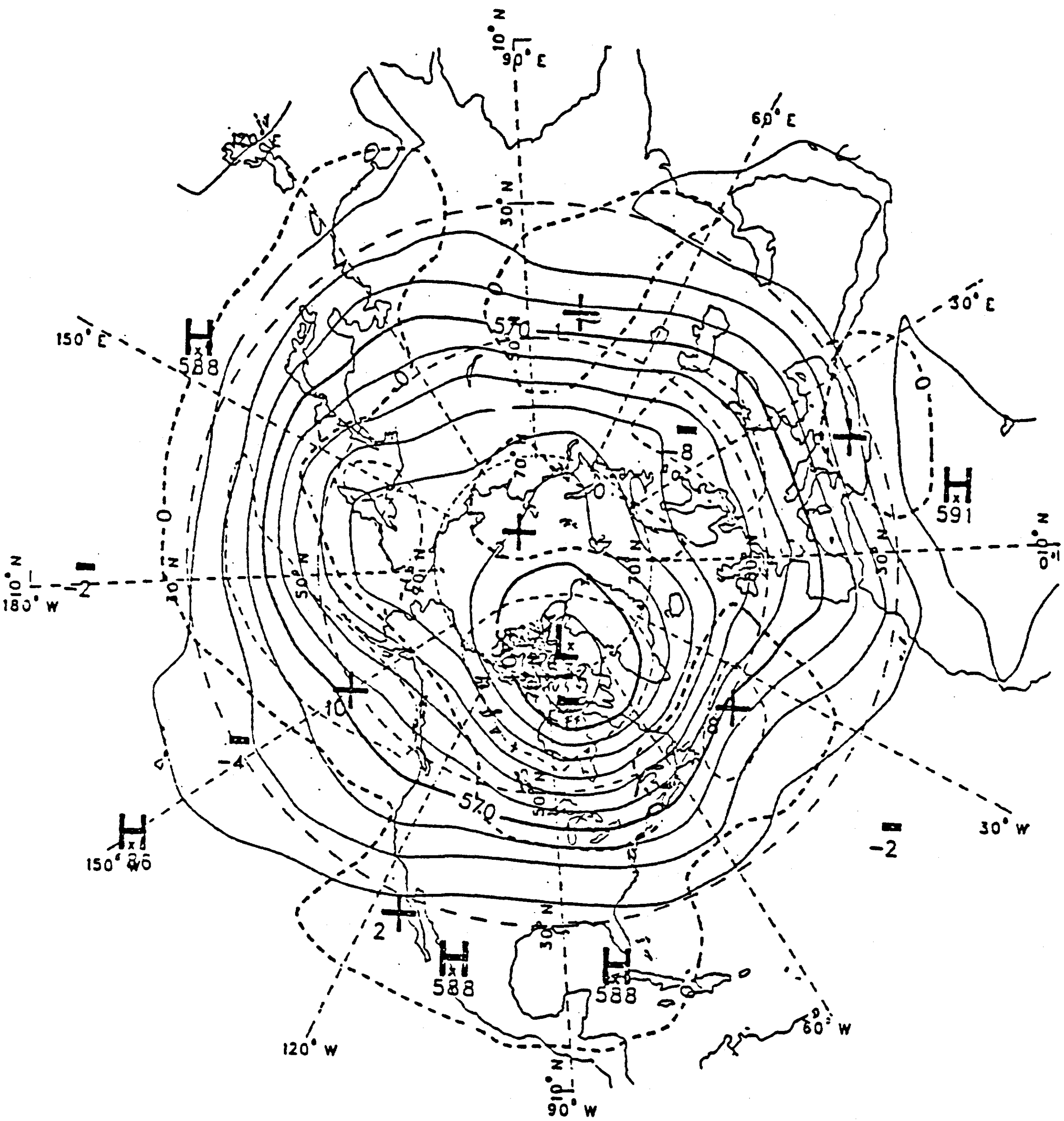
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
AUGUST 1963
CONTOUR INTERVAL: 5.0 DAM



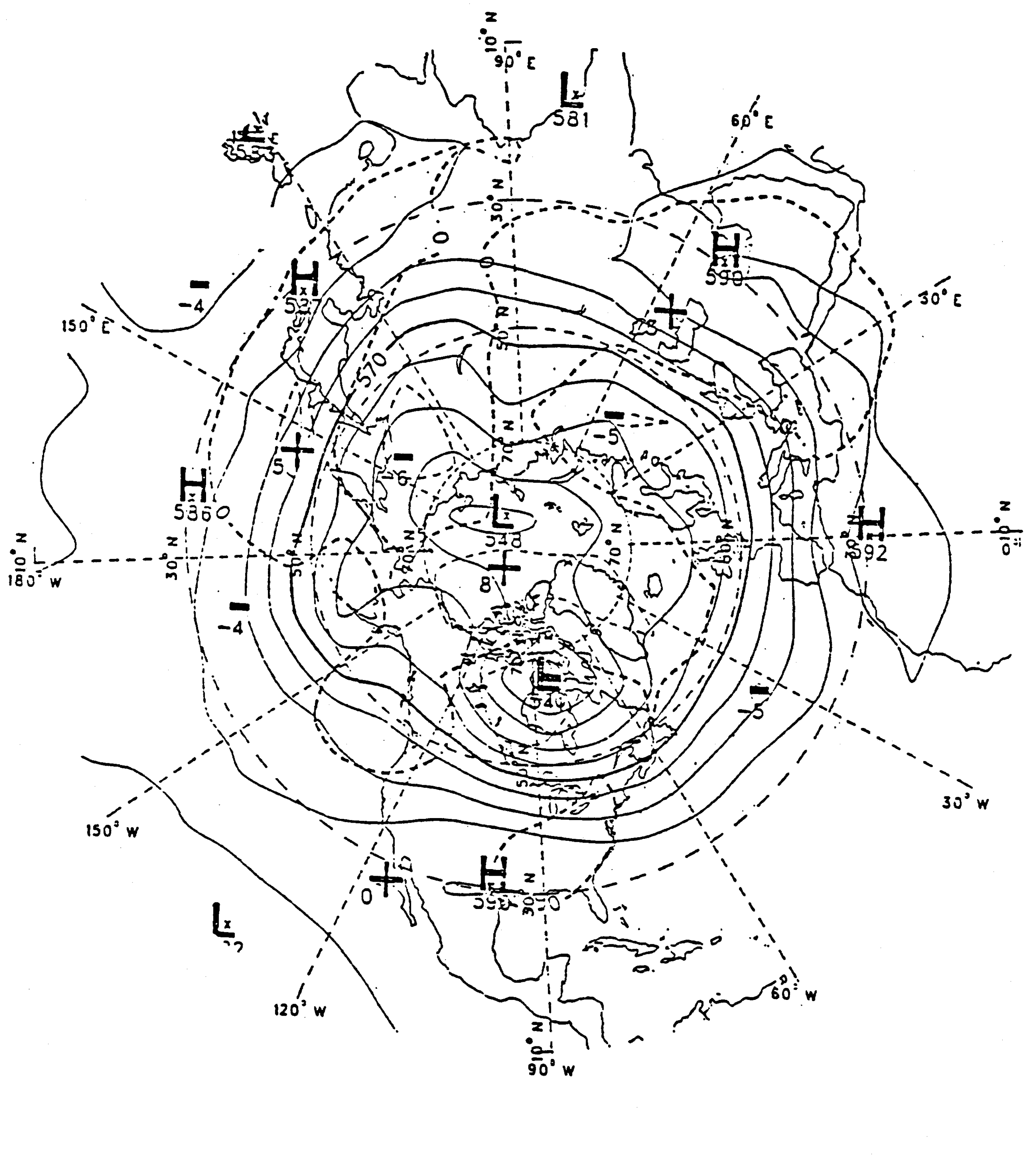
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
MAY 1978
CONTOUR INTERVAL: 5.0 DAM



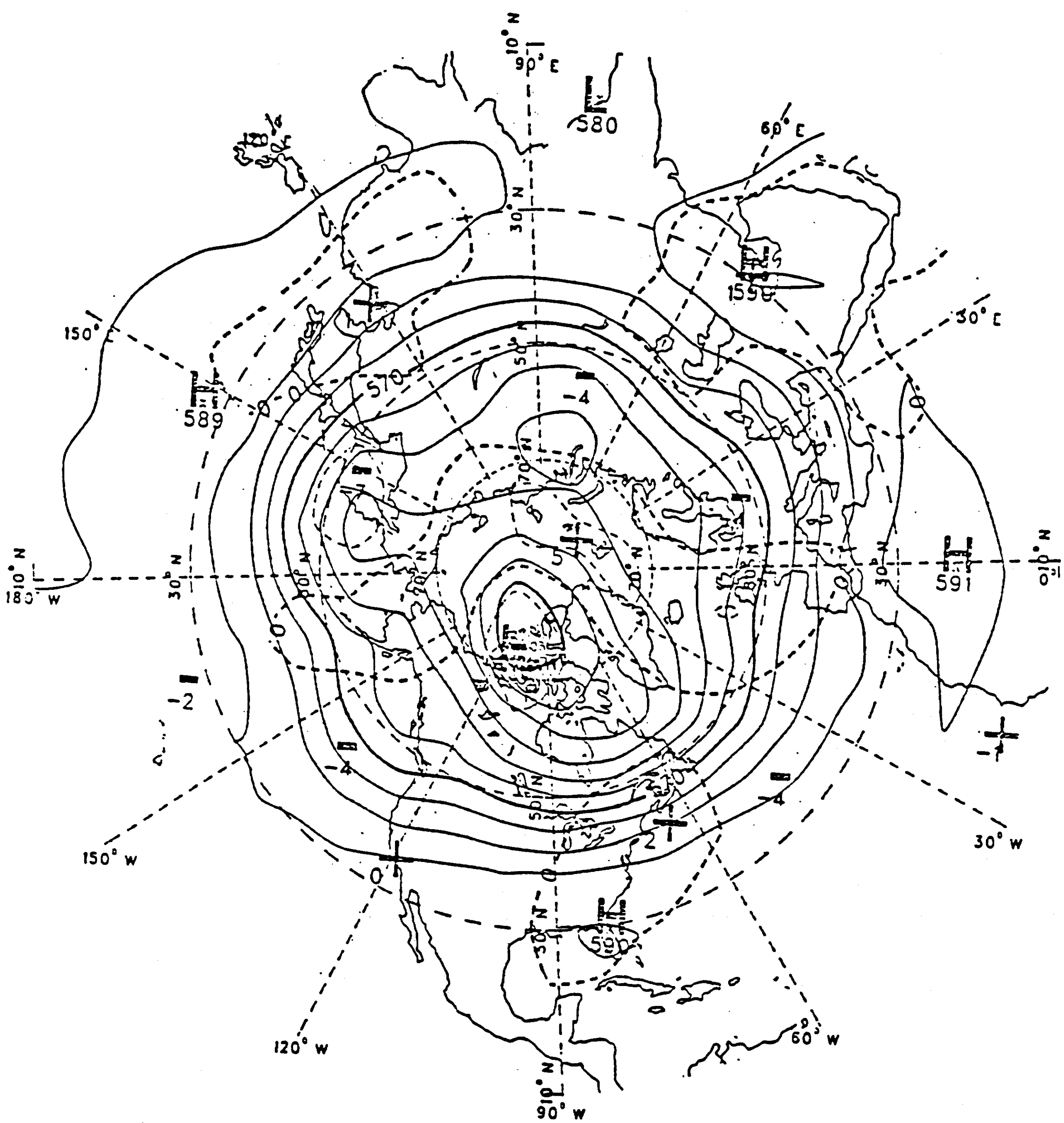
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JUNE 1978
CONTOUR INTERVAL: 5.0 DAM



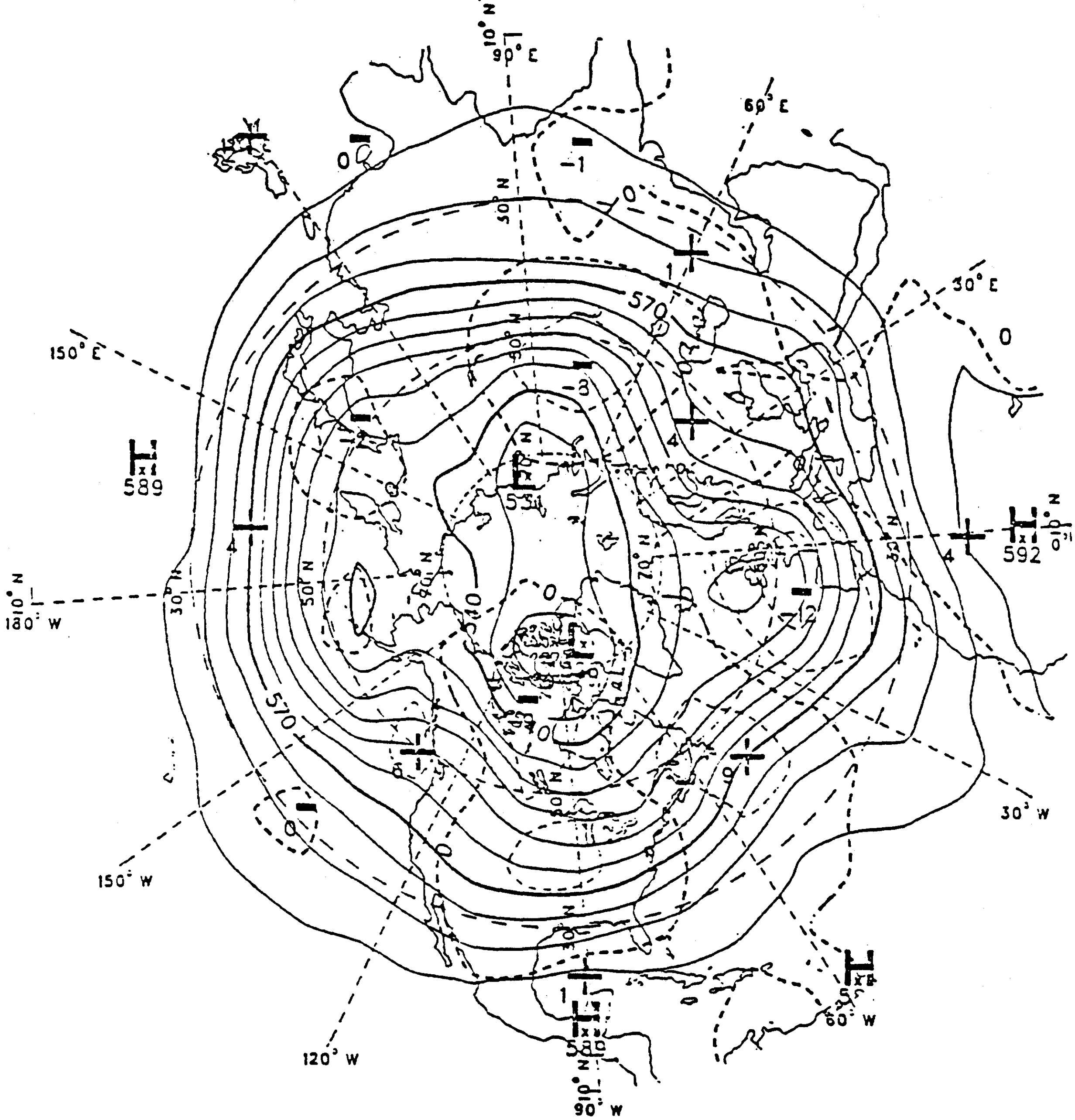
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JULY 1978
CONTOUR INTERVAL: 5.0 DAM



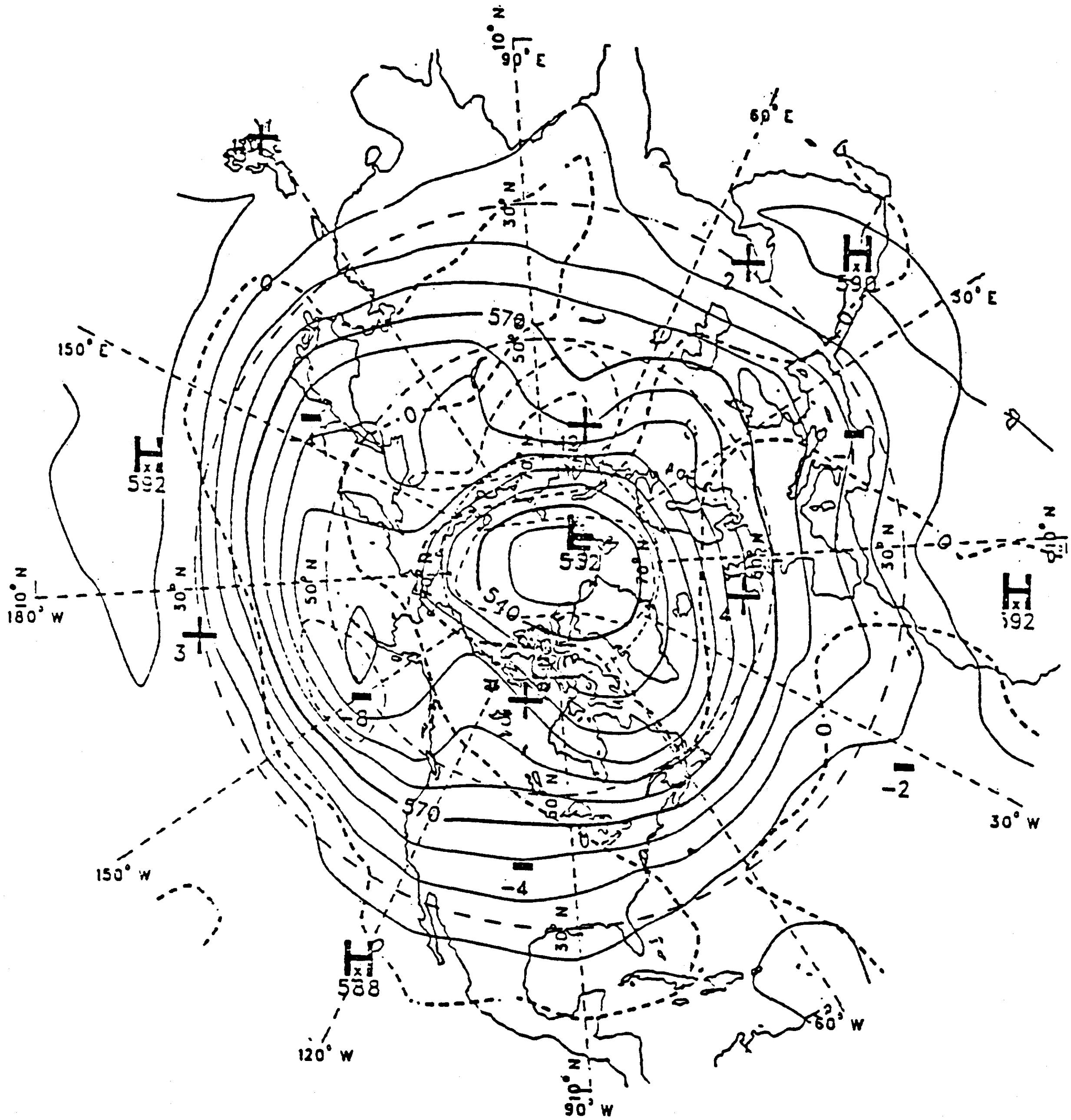
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
AUGUST 1978
CONTOUR INTERVAL: 5.0 DAM



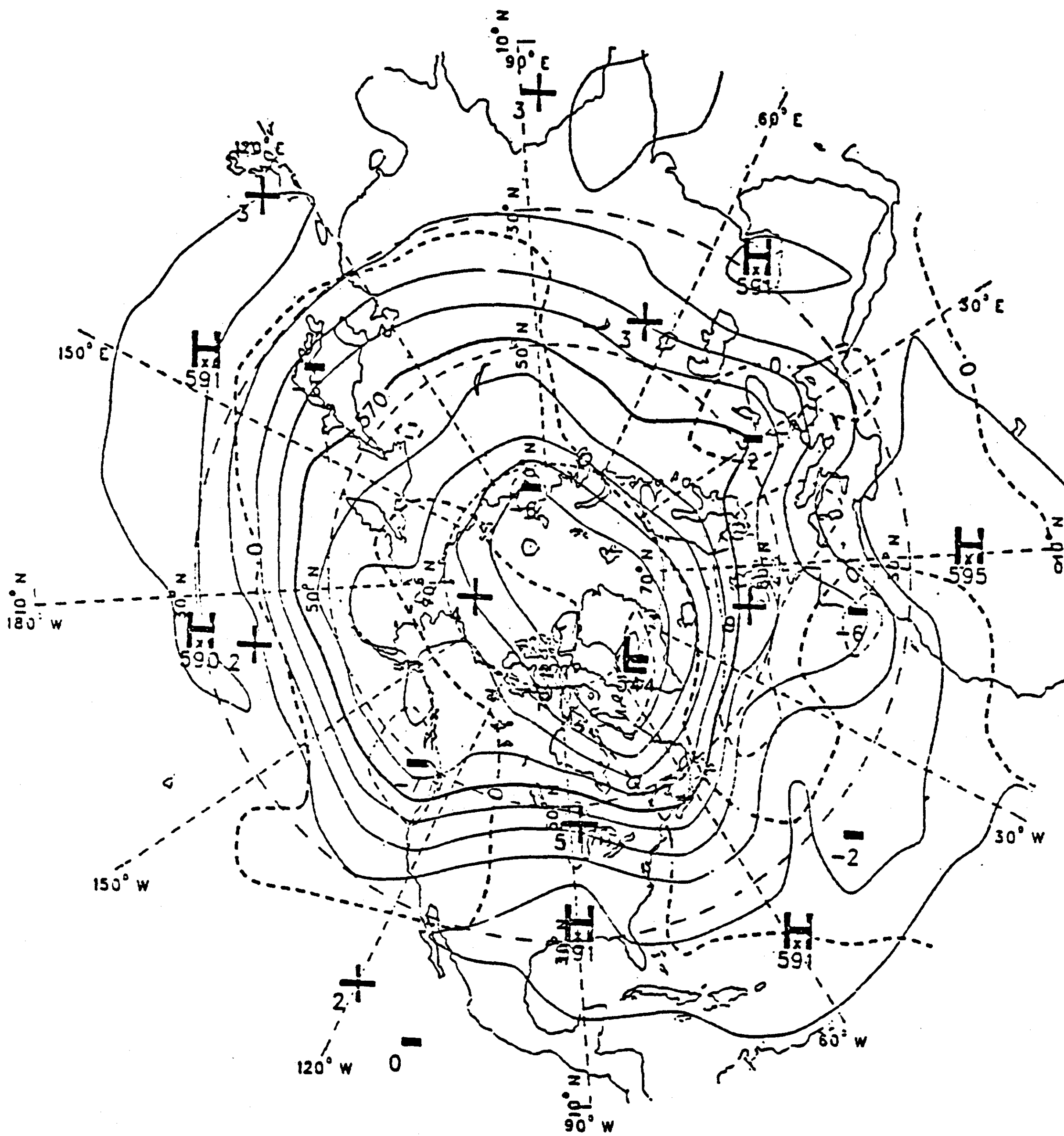
50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
MAY 1983
CONTOUR INTERVAL: 5.0 DAM



50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JUNE 1983
CONTOUR INTERVAL: 5.0 DAM



50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
JULY 1983
CONTOUR INTERVAL: 5.0 DAM



50 KPA HEIGHTS (SOLID)
AND 50 KPA HEIGHT ANOMALY (DASHED)
AUGUST 1983
CONTOUR INTERVAL: 5.0 DAM