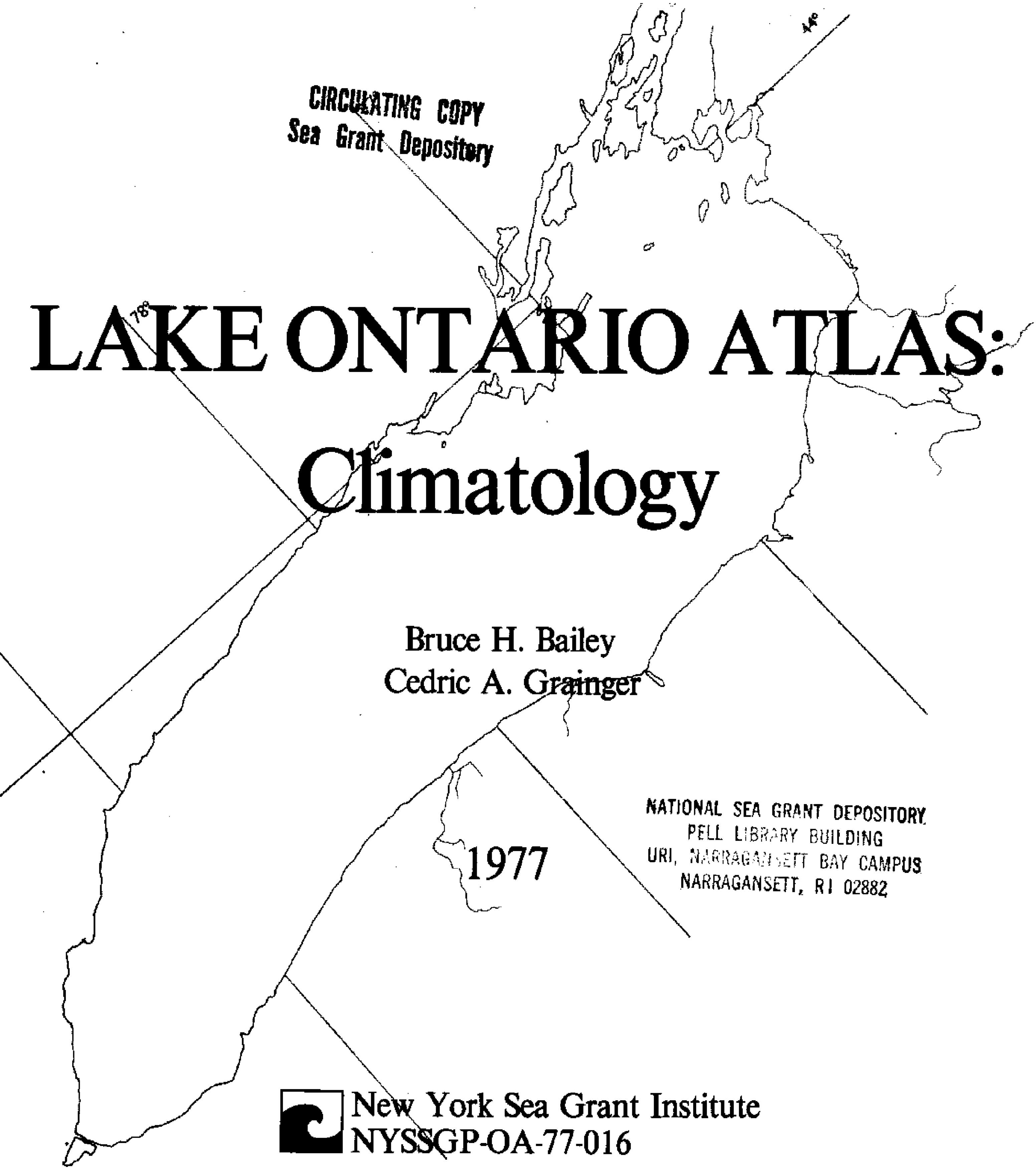

LAKE ONTARIO ATLAS:
Climatology

Bruce H. Bailey
Cedric A. Grainger

1977

New York Sea Grant Institute
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LAKE ONTARIO ATLAS MONOGRAPHS

THE LAKE ONTARIO ATLAS consolidates much of the available data on Lake Ontario into a series of monographs intended to be useful to industry and government. The eight monographs use graphics to aid interpretation of large amounts of data and to present information in summary form. The final product, a meld of the monographs, will be a nontechnical, graphic atlas for Lake Ontario.

I	Biology	Donald C. McNaught, SUNY Albany
II	Chemistry	Eric R. Allen, SUNY Albany
III	Climatology	Bruce H. Bailey, SUNY Albany, and Cedric A. Grainger, SUC Oswego
IV	Currents	Jon T. Scott, SUNY Albany
V	Internal Waves	Dennis Landsberg, SUNY Albany
VI	Lake Temperatures	Eugene Chermack, SUC Oswego
VII	Land Use	Michael Dobson and Floyd Henderson, SUNY Albany
VIII	Surface Waves	Glenn E. Myer, SUC Plattsburgh

ABSTRACT

THE CLIMATOLOGY MONOGRAPH presents a comprehensive analysis of the Lake Ontario region. Data tables and distribution maps are included for the approximately 80,000 km^2 of the region, one quarter of which is Lake Ontario. Factors governing its highly variable climate are discussed. This monograph will be useful for physical, chemical and biological limnological studies, as well as land use planning and coastal management.

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LAKE ONTARIO ATLAS: Climatology

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Abstract

A comprehensive climatological analysis of the Lake Ontario region is presented. The analysis includes data tables and several distribution maps. The region consists of approximately 80,000 square km, of which one quarter is occupied by Lake Ontario. The region's highly variable climate is basically governed by the mid-latitude quasi-continental location, a high frequency of cyclone and anticyclone activity, lake-induced influences, variable topography, and local urban effects.

Introduction

This monograph will investigate the climate of Lake Ontario and its surroundings, herein referred to as the Lake Ontario region. The borders of the region are adequately defined by the area between 42°30'N and 44°40'N latitude, and between 75°20'W and 80°20'W longitude. This area encompasses about 80,000 square km (30,000 sq mi), of which one quarter is occupied by the lake. Lake Ontario is the smallest of the Great Lakes in water surface area, and the lowest in average surface elevation above mean sea level.

The Great Lakes region of the United States and Canada possesses a distinctive climate which is actually unique to the world. The lakes and their connecting waters constitute the largest body of fresh water on the surface of the earth. Situated within continental mid-latitude North America and accessible by air masses originating from both polar and tropical latitudes, dramatic season-to-season, even day-to-day, changes in weather are typical. Locally, the lakes are an abundant source for both heat and moisture, particularly in fall and winter, which further stimulates high weather variability over the region, as well as across the northeastern United States.

Lake Ontario is located in the prevailing downwind direction of the other four Great Lakes, a fact which has a definite impact on the region's climate. In addition, a typical year in the Lake Ontario region sees temperatures ranging between -40°C (-40°F) and +35°C (100°F). Late fall and winter observes a number of localized lake-effect snowstorms which can individually deposit up to a meter or more of snow in lee areas. In fact, the snowiest United States location east of the Rockies is found just to the east of the lake.

Topography plays an important role in climatic variations within the Lake Ontario region, and it is one key reason for the eastern United States snowfall maximum. A relatively abrupt rise in land elevation to the east of the lake is part of the Tug Hill Plateau, which reaches a 640 m (2100 ft) maximum elevation above mean sea level 50 km (30 mi) to the east of the lake. The lake's average (since 1860) surface elevation (above msl) is about 74 m (246 ft) (Beeton and Chandler 1967). The only other significant increase in elevation near the lake is to its northwest where a rise to 520 m (1700 ft) above msl exists within 60 km (38 mi) of the shore. Most generally the gently rolling lake plain increases gradually in elevation to the south and north of the lake. Rougher, higher terrain is found further inland in both directions.

The climatology of the Lake Ontario region has been deduced from decades of weather observations taken at over 100 Canadian stations and at over 50 American stations (See Figure 1). The Meteorological Branch of the Canadian Department of Transport and both the National Weather Service and National Climatic Center of the National Oceanic and Atmospheric Agency of the US Department of Commerce were the sources of most data used in this study. In most cases, the data base represents the 1941-1970 period.

The Large Scale Circulation

It has long been recognized that the Great Lakes exercise substantial influences on the development and characteristics of synoptic-scale weather systems moving over them. Foremost among these influences are their massive source and sink potentials for heat. The entire Great Lakes region experiences a high frequency of cyclones (low pressure systems) and anticyclones (high pressure systems); the opportunities for modification are therefore several.

The degree of modification to the large scale circulation imposed by Lake Ontario itself, or by any other lake for that matter, is very difficult to assess. It can safely be assumed that the collective influences exerted by all five Great Lakes result in virtually all synoptic-scale weather systems being modified to some degree. Local scale and individual lake effects for Lake Ontario will be examined in another section of this monograph.

Klein (1956-1957) has shown that the prevailing tracks of cyclones in the United States converge on the Great Lakes region, moving in a general southwest to northeast direction. Highest cyclonic frequency over the Great Lakes is during the cold season (October to March) with a maximum in December when the temperature contrast between the water and surrounding land surfaces is greatest. During the warm season (April to September), cyclonic frequency decreases to a minimum in August when the westerlies are farther north than in any other month.

In contrast, anticyclonic frequency is greatest in August over the lakes region. During the summer months, the primary track of North American anticyclones is virtually unchanged, positioned zonally across the far northern United States through the Great Lakes. In October, the primary track of anticyclones shifts south of the lakes where it remains until May.

In addition to their geographical location, which predominantly accounts for the high degree of cyclonic-anticyclonic frequency, the lakes themselves exert an influence on both the nature and development of weather systems. Because the lakes are slower absorbers and emitters of heat than the adjacent land areas, a mean temperature contrast nearly always exists between lake and land. While on the local scale this condition is responsible for diurnal land-lake breezes and other effects, at the large scale, inclusive of all the lakes, the genesis of, or the alteration of, regional cyclones or anticyclones is often the result.

During the cold season when the lakes are warmer than the adjacent land, heating over the water provides a local source of cyclonic vorticity inducive for cyclogenesis (Petterssen and Calabrese 1959). (If no other processes are active, a heat source, such as that of the Great Lakes in winter, would result in horizontal convergence and the development of a cyclonic circulation around the source.) Colucci (1976) has shown that, over the eastern United States during the cold season, a distinct maximum for cyclone frequency occurs over the eastern Great Lakes. Fifty percent to 70 percent of all cyclones moving through the eastern lakes deepen with a net three-hour pressure fall of three to four millibars. Colucci concludes that, when cyclone deepening does occur, the deepening rate over large lake moisture sources is nearly double that of storms moving strictly over land.

One winter effect of the Great Lakes can be illustrated in this familiar scenario. A strong flow of arctic air across the lakes occurs with a cyclone to the east of the lakes and an anticyclone to the west and north of the region. Although no macroscale fronts or disturbances are present, cyclonic curvature is induced within a trough extending to the rear of the cyclone westward over the lakes area. This trough is created by the heat flux from the lakes into the overrunning air. Secondary perturbations or troughs produced by the lakes in this manner have been found in deep cyclonic systems which apparently play major roles in the development of lake-effect snowstorms which are so common and at times devastating to the lee shores of both Lakes Erie and Ontario (Jiusto et al. 1970).

In contrast, the lakes during the warm season are cooler than the surrounding land areas. Strong stabilities develop over the lakes region as a result of the cooling by conduction of air immediately above the lakes. This leads to the creation of low-level temperature inversions, which are strongest in spring just before the formation of the thermocline across the deepest portions of the lakes (Strong 1972). The following scenario illustrates this effect.

A strong inversion develops over a lake on a normal clear spring day. The lake is ringed by convective clouds, but they are absent over the lakes, as convective processes are suppressed. Even on days when convective rain systems are moving across the lake, cloudiness and precipitation are reduced. Thunderstorms have been observed to degenerate once over a lake surface and then regenerate over the downwind shores.

A shallow layer or dome of cold air over the lakes, extending vertically from 100 to 1500 m above the lake surface (Chagnon and Jones 1972), often protects them from the surrounding atmospheric influences. The suppression of turbulent mixing by the stable overlying layer of air shields the lakes from a transfer of both atmospheric heat and momentum.

Klein's study has shown the prevalent anticyclonic spring and early summer weather in the Great Lakes region. The tendency toward anticyclogenesis can be noted from April through July when the water temperature lags well behind the air temperature. As the thermocline develops and the spring overturn period is halted, more rapid heating of the surface water is possible. Only then does anticyclonic inducement diminish.

In summary, the Great Lakes are instrumental in creating instability throughout their region during the cold season because of their nature as heat sources. Cyclogenesis and cyclone deepening frequently result. During the warm season, the lakes cool the overlying air, thus creating a stable temperature lapse rate over the region. Vertical convection is either suppressed or prevented within the regions, and anticyclonic activity prevails.

Lake-Effect Snowstorms

One outstanding characteristic of the southern and eastern Lake Ontario region in late autumn and winter is the occurrence of so-called "lake-effect" snowstorms. Severe storms can deposit a meter or more of snow on localized lee areas in a single day. The Tug Hill Plateau, east of the lake, holds the distinction of having the greatest annual snowfall (>5 m, or 200 in) in the United States east of the Rocky Mountains (Muller 1962). Lake Erie contributes an influence on snowfall in the region's southwestern portion in November and December. But that lake typically freezes over by mid-winter, while Lake Ontario rarely freezes over totally.

The Canadian portion of the Lake Ontario region experiences little lake-effect snowfall because of its mean upwind location relative to the lake. The bulk of its snowfall is the consequence of passage of mid-latitude cyclones (Muller 1966). However, lake-effect carry-over from Lake Huron and Georgian Bay to the west and northwest is responsible for some of the area's annual snowfall. Shadowing highlands directly to the lee of those water bodies minimize this contribution.

Lake-effect snowstorms result, basically, from very unstable conditions arising when cold arctic air flows across relatively warm large water bodies. Synoptic conditions favorable for such storms are usually post cold-frontal and characterized by: the presence of a deep closed low aloft, a feature that lends upper air support to surface systems; or by the presence of a residual trough of low pressure, maintained by vorticity created by the heating of cold air flowing across the warmer lakes (Wiggin 1962). Paine and Jiusto (1970) concluded that the most intense lake storms are generated when a secondary trough forms and couples with the lake-induced vertical fluxes of heat, vapor, and momentum. The slower the trough movement, the greater the snowfall effect.

Synoptic scale and lake induced influences alone do not account totally for the observed highly variable snow distribution characteristic of lake-storm situations. There is still question as to all mechanisms that account for all observed features of the storms. Well-defined snowfall maxima on the windward slopes of hills and mountains are in response to orographic lifting, along with the rapid cooling of moist air, to produce the heaviest areas of snowfall. The friction differential of land and lake surfaces is believed to be a cause for convergence along shorelines when winds are on-shore or parallel to shore. This friction mechanism is in addition to a lake-induced thermal convergence mechanism that may be augmented by air passing over industrial areas (Holroyd 1971). A long wind fetch across the lakes is usually necessary for significant storm development, in addition to a large air-water temperature difference. A temperature difference of 13°C (adiabatic lapse rate) or greater is required between the lake surface and the 850 millibar level, which implies that the temperature lapse rate of at least one intermediate layer is super-adiabatic.

McVehil and Peace (1965) have detected by radar echoes that snowstorms are banded in structure, the majority of which showing precipitation limited to a single band. Multiple bands are frequently transient features occurring before a more stable single band becomes established. In other cases, they occur when winds are cross-lake (short-trajectory), as opposed to along-lake (long trajectory), and are oriented parallel to the wind flow, extending inland.

The predominant single band, dimensioned 4-35 km wide and 80-200 km long, is typically located either over-lake or along the shoreline. When over-lake, the band is invariably oriented parallel to the prevailing wind, particularly when it blows along the lake's major axis. When located over-land, the band is usually parallel to the shoreline, often oriented at an angle to the wind. These findings indicate that the land-water boundary can exert a strong influence on the convective regime (by frictional uplifting), and that band characteristics are a function of wind direction.

Lavoie (1972) has shown by means of a mesoscale model that by considering air versus water temperature differences, lake fetch, terrain and surface roughness influences, plus diabatic contributions, one is able to describe many of the lake-storms' primary features. His model was most sensitive to changes of wind direction. Findings that a wind flow from the 250°-280° compass range produces the heaviest accumulations corroborate with observational findings by Jiusto and Kaplan (1972). This direction range coincides with the major-axis orientation of both Lakes Erie and Ontario, thus implying that the longest fetch allows maximum momentum, heat, and water vapor contributions to the overrunning air, and subsequent maximum deposition of snow to the lee shores.

Temperature

The Lake Ontario region, located within the active mid-latitudes, experiences a wide daily and seasonal variability in temperature. Geographically located within the reasonable reaches of warm tropical air as well as of frigid polar air, the temperature variability can be quite extreme over short periods of time, particularly in the transitional fall and spring seasons.

The coldest month of the year is January, the warmest is July. The mean annual temperature of the region is mainly between 6° and 9°C (42-49°F), the variation a function of lake proximity, latitude, and elevation. Long-term weather records (50 years or longer) have indicated that warmest temperatures ever recorded in the region fall within the 38° to 41°C (100-106°F) range; coldest readings vary from the mid -30s to low -40s°C (-30s to -40s°F) north and west of the lake, and from the mid -20s to low -30s°C (minus teens and -20s°F) to the south and upper -30s°C (-30s°F) to the east.

The region's normal mean January temperature centers around -6.5°C (20°F) ranging from up to 3°C colder north of the lake to 3°C warmer to the south. In a normal winter, coldest temperatures will range between

-20 to -25°C (-3 to -13°F) to the lake's south within the lake plain, while the less-moderated lake-adjacent areas reach -26 to -32°C (-15 to -25°F). Highlands further away from the lake, mainly to the north, may experience even colder readings. Minimum daily temperatures below freezing occur about 130-150 days out of the year across the general southern portion of the region, 150-170 days for the northern portion.

The normal mean July temperature is 19-22°C (66-72°F). In a normal summer, warmest temperatures will reach to or above 32°C (90°F) on anywhere from 2 to 10 days, depending on latitude, altitude, and nearness to the lake. Hot, sultry periods occur only occasionally and briefly.

The regional frost-free growing season averages about 175 days to the lake's south, 160 days elsewhere. The mean date of the January "thaw" is January 14 or 15 (Frederick 1966).

Various temperature distribution maps for the Lake Ontario region are displayed in Figures 2 through 47. Temperature records used in this study represent the 1941-1970 period. Canadian stations with records longer than 15 years were included with some of the records adjusted to the 30-year period as described by the Atmospheric Environment Service in Temperatures and Precipitation, 1941-1970, Ontario. The US station records were adjusted to the 30-year period if any years were missing by using nearby stations with complete records. Over-lake temperature records were insufficient to represent them here. Lake temperature information may be found in Monograph VI of the Lake Ontario Atlas.

Mean monthly isotherms are shown in Figures 2 through 13, and the distribution of the mean temperature for the entire period is depicted in Figure 14. This last figure indicates that the temperature consistently increases as one approaches the lake from almost any direction. This increase is largely due to changes in elevation, in addition to the moderating influence of the lake which is most pronounced in winter. The warmest temperatures immediately adjacent to the lake are found around its western tip where industrial activity is heavily concentrated.

The prevailing wind plays a strong role, particularly in winter, in directing the lake's moderating influence inland. Considerably warmer temperatures to the south of the lake in winter reflect this role since winds prevail from the northwest. These warmer temperatures are also a result of the greater cloudiness in this area, which results from induced instability as the cold prevailing northwesterlies flow across the relatively warm moist lake waters. A cloud cover suppresses nocturnal radiational cooling of the earth's surface and thus accounts for warmer overnight temperatures than are found in areas under clear skies. In addition, local wind circulations, induced by the lake-land temperature differential, tend to prevent or suppress overnight radiational cooling surface temperature inversions along the shores, thus inhibiting potentially colder temperatures.

While the lake's moderating influence on temperature is substantial in winter, particularly to the south, it is considerably less important during the warmer months. In spring and summer, the lake acts as a tremendous heat sink as most solar energy is absorbed by the water. (The estimated net total solar radiation contribution to the total energy budget of the lake in the warm seasons is probably greater than 85 percent [Bellaire 1965]). In contrast, the adjacent land areas are quickly heated with heat transferred to the atmosphere by thermal convection, as is commonly indicated by cumulus clouds. Such clouds do not form over the open lake in these seasons, and they usually dissipate when moving over the lake from the land.

The stable regime which is characteristic of the over-lake lower atmosphere in spring and summer acts to inhibit air-water interactions. Adjacent air is cooled by conduction, and on a normal clear spring day, a strong inversion develops over the lake. Water-air heat energy transfer becomes negligible as warm air is buoyed above the cooler air at the lake surface; momentum transfer in the inversion becomes drastically reduced (Strong 1972). Typical of the other Great Lakes, this phenomenon often leads to the frequently observed shallow over-water mesoscale high pressure system--the lake anticyclone. As a consequence of little air to water heat transfer, little modification of air temperature is evident well downwind of a shoreline.

The distribution of mean daily maximum temperatures by months is shown in Figures 15 through 26, and the mean for the entire period is shown in Figure 27. Mean maximum temperatures are generally kept above freezing to the south of the lake during the coldest months of January and February. Significant shoreline cooling is evidenced in spring and summer along the northern and eastern shores. Both warming and cooling lake effects are clearly directed by the seasonal prevailing winds. Daily maximum temperatures almost consistently reach a maximum to the south of Rochester, New York. This is a relatively low topography area strongly influenced by winter lake moderations and cloudiness, and it is unaffected by summer cooling lake influences.

Mean daily minimum temperatures for each month and for the year are shown in Figures 28 through 40. (Because the range of these temperatures is relatively large, isotherms were drawn at 1.0°C intervals rather than 0.5°C intervals characteristic of the other temperature maps.) The locally warm area around the lake's western tip is very much in evidence, especially in winter. The overall effect of Lake Ontario is to keep minimum temperatures relatively high near and around the lake, most strong to its south. This general effect is smallest in spring when the land-lake surface temperature difference is a minimum.

The distribution of five-year return period maximum and minimum temperatures for January and July were computed for the Lake Ontario region, and are shown in Figures 41 through 44. These values represent the highest and lowest temperatures that can be expected for a given month in a five year period. The temperatures were estimated from the climatological data as follows:

The distribution of the daily maximum and minimum temperatures for each month were assumed to fit a Gumbel distribution with a mean equal to either mean daily temperature extreme, and for which the coinciding extreme observed temperature is taken as appropriate to a return period equal to the length of the record. From these two values (the mean and the extreme), the extreme temperature that would be exceeded once every five years was interpolated. The interpolated value may be in error, however, because the daily maximum or minimum temperatures do not fit the Gumbel distribution very well as the daily temperatures are not randomly distributed (Court 1952); or because the extreme observation may have a return period longer than the length of record. While both of these points are valid, it was felt that the extreme temperatures computed on this basis for a five year period should be relatively insensitive to these potential sources of error if the station record is long enough. Only stations with records of 20 years or more were used for this analysis.

Figures 45 through 47 depict the January, July, and annual daily temperature ranges of the region, defined as the differences between the mean daily maximum and minimum temperatures. One would expect the smallest range nearest the lake, and this verifies to be the case. The July range is greater because of strong daytime heating resulting from a greater intensity and longevity of solar insolation.

Precipitation and Snowfall

The Atlantic Ocean and the Gulf of Mexico are the prime sources of moisture for nearly all precipitation experienced in the northeastern United States. The Great Lakes, to a lesser degree, collectively serve as a local moisture source in fall and winter, while individual lakes contribute additional amounts to their lee shores during the same seasons. In contrast, the stabilizing influence of the cool lakes in spring and summer diminishes convective rainfalls along lee shores.

Precipitation in the Lake Ontario region, as for most of the northeastern United States, is distributed fairly uniformly throughout the year. Throughout the region, precipitation is pretty evenly distributed except to the east and southeast of the lake. There a maximum is realized which is most pronounced in fall and winter. During these seasons in this area, especially on the Tug Hill Plateau, precipitation is double that observed in some other areas of the region. While topography holds a major responsibility for the precipitation maximum in the prevailing downwind portion of the region, it plays a slighter role elsewhere where terrain features are not so dramatic. Lake Erie is responsible for a secondary precipitation maximum south of Lake Ontario's southwestern end.

Measurable precipitation ($\geq .25$ mm, or $\geq .01$ in) occurs on the average about 160-170 days out of a year. On an annual basis, this amounts to 900-1200 mm (35.4-47.2 in) to the east and southeast of the lake, 750-900 mm (29.5-35.4 in) elsewhere. Monthly totals typically fall in the 60 to 80 mm (2.4-3.2) range except for the wetter eastern sections where up to 130 mm (5.1 in) in winter is common. Month to month precipitation amounts can be highly variable as can amounts for a given month from year to year. Almost any month can be the wettest or driest for a given calendar year.

The distribution of the monthly means of total precipitation are shown in Figures 48 through 59; the mean annual total is depicted in Figure 60. Care should be taken in comparing winter precipitation amounts of Canadian stations with those of the United States. Different methods are used in determining the water equivalent of snowfall. In Canada, snow depth is measured and divided by 10 to obtain a water equivalent. In the United States, snow is actually melted in a gauge and the water measured directly.

Snowfall shows a heavier tendency to the southern and eastern leeward portions of the lake where significant lake-effect snow situations are experienced. A maximum greater than 300 cm (118 in) appears on the Tug Hill Plateau east of the lake where topography plays a strong supporting role (even greater amounts are experienced further inland). The average date for the first one cm snowfall is November 1-15; the average date for the last one cm snowfall is April 1-15 (Bryson and Hare 1974). The mean annual snowfall distribution of the Lake Ontario region is shown in Figure 61.

Varying snowfall depth with inland distance from shore can often be partially explained by different predominating snow crystal forms associated with lake-effect snowstorms. Crystal forms possess particular spatial, structural, and density characteristics which account for varying snowfall densities and snowfall-meltwater ratios. Jiusto and Kaplan (1972) have found a high positive correlation between lake-effect snowfall-meltwater ratios and inland distance for downwind areas of both Lakes Erie and Ontario. Heavier, denser snow (rimed snow crystals and graupel) is typically characteristic along shoreline areas, especially during early winter, while lighter, less dense snow (snowflakes and dendritic crystals) is carried further inland. The customary 10:1 snowfall-meltwater ratio often overstates the ratio for lake-effect snow found along shorelines; further inland, this ratio is often underestimated, and observed ratios have exceeded 30:1. Hence, a variation of snow depth with distance inland need not necessarily imply greater meltwater amounts. A significant snowfall maximum is coincident with a precipitation maximum to the east of Lake Ontario, but a comparison of winter snowfall values to precipitation values also reveals a higher snowfall-meltwater ratio inland to the east of the lake than along the eastern shore and for most other areas of the region.

Vapor Pressure and Dewpoint

It has been estimated that the Great Lakes raise the vapor pressure of the air in their region by approximately 10-20 percent (Richards 1969; Phillips and McCulloch 1972). Figure 62 gives the average daily mixing ratios for four stations as a function of time. The mixing ratio changes from a minimum of one to two g/kg in January and February to a maximum of 10 to 12 g/kg in July and August. Qualitatively the curves appear similar although there is an apparent tendency for the air to be drier by 10 to 20 percent in the northern part of the region than in the southern part.

Regional monthly and annual dewpoints are listed in Table 1 below (Dodd 1965; US Dept. Commerce 1968).

TABLE 1

Mean Dewpoint Ranges for the Lake Ontario Region

January	-9 to -6°C (15-20°F)
February	-9 to -6°C (15-20°F)
March	-6 to -3°C (21-26°F)
April	-1 to 2°C (30-35°F)
May	5 to 8°C (41-46°F)
June	11 to 13°C (51-56°F)
July	13 to 16°C (56-61°F)
August	13 to 16°C (56-61°F)
September	10 to 12°C (49-54°F)
October	5 to 7°C (40-45°F)
November	-2 to 1°C (29-34°F)
December	-7 to -5°C (19-24°F)
Annual	2 to 4°C (35-40°F)

Solar Radiation, Hours of Sunshine, and Cloud Cover

Solar radiation received at the earth's surface is a function of latitude, time of day and year, amount and thickness of cloud cover, and atmospheric turbidity. The approximate two degree difference in latitude between the north and south borders of the region results in an annual total available radiation reaching the surface in the north of about three percent less than that reaching the south. A maximum 11 percent deficiency of north relative to south occurs around December 21 when the sun angle is at its lowest in the northern hemisphere; however, essentially no difference exists around June 21.

Measurements of total solar radiation (direct plus diffuse) around Lake Ontario representing a five-year or longer period are restricted to only a few locales: Toronto, Ontario; Brockport, New York (located 12 miles south of the lake and 15 miles west of Rochester, New York); and Geneva, New York (located 30 miles south of the lake and 35 miles southeast of Rochester, New York). Their annual and monthly means are given in Table 2 (Bailey et al. 1976; Atmospheric Environmental Service 1970-1975). The radiation-measuring pyranometers at the three locations are placed sufficiently apart from urban centers to consider their quality as reasonably representative. Instrument accuracy, however, can only be considered as plus or minus five percent at best.

TABLE 2

Mean Daily Total Solar Radiation (Langleys), 1970-1975 period

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Toronto	139	209	295	413	473	505	525	438	327	212	103	92	311
Brockport	142	200	282	412	458	521	522	450	318	212	114	87	310
Geneva	133	202	266	380	423	477	509	422	306	206	109	77	292

Supported by additional radiation information near, but outside the defined region, an annual mean daily radiation amount ranges around 305 ± 15 ly for the entire Lake Ontario region. A maximum of 520 ± 15 ly is realized in July, a minimum of 85 ± 10 ly in December.

A slightly less amount of radiation is indicated to the south and east of Lake Ontario than to the north in late autumn and winter due to lake-induced increased cloudiness. This is clearly illustrated by the Geneva values. This cloudiness counteracts the otherwise greater available solar radiation for this area. In spring and summer, the cool lake's stabilizing effect suppresses cloudiness immediately adjacent to the lake, while slightly less radiation amounts are realized further inland where convective processes become more effective in producing clouds. This case is exemplified by comparing spring or summer radiation values for either Toronto or Brockport with Geneva.

Over-lake radiation has yet to be adequately measured; a significant month to month difference most probably exists between over-water and over-land radiation amounts. From basic principles, one would expect on the average: 1) greater cloud cover over land than over lake in the late spring to early fall period due to diurnal heating of the land and subsequent cumulus cloud development; 2) greater cloud cover over lake than over land in the mid-fall to early spring period with the development of cumulus and stratocumulus cloud in cold air as it moves over relatively warm water; and 3) frequent formation of stratus and fog over a lake in early and mid-spring due to the intrusion of relatively warm moist air over the still cold lake waters.

Richards and Loewen (1965) have offered a preliminary quantitative comparison of incoming total solar radiation over lake and over land during different seasons. Radiation measured onboard a research vessel during a four-year period in the early 1960s were compared with simultaneous recordings from three nearby (100 miles or less) land stations of the Great Lakes (Sault Ste. Marie, Cleveland, and Toronto). Since icing of the pyranometer posed measurement problems in winter, only April-December measurements were considered reliable. Their findings supported the anticipated relative differences implied in the last paragraph, but the magnitude of the differences are questionable because of: a "fair-weather" bias; a low number of cases; and the dubious quality of the involved land stations in representing other lake regions.

April indicated a lesser amount of radiation over water, possibly as a result of conditions described in 3) above. The summer months showed a greater over-lake insolation, and an opposite trend was apparent toward winter.

The monthly and annual normal hours of sunshine are listed in Table 3 for three sites within the Lake Ontario region. There is an obvious major difference between the Toronto values and those of Buffalo and Rochester because of a difference in instrumentation. The Campbell-Stokes instrument is predominantly used in Canada (Yorke and Kendall 1972) and is apparently less sensitive than the American Marvin or Foster instrument. Canada reports hours of "bright" sunshine as opposed to unspecified sunshine in the United States. On an annual basis, approximately 2000 hours of "bright" sunshine are realized for the region (Yorke and Kendall 1972; Bryson and Hare 1974), and about 2400 hours of unspecified sunshine (US Dept. of Commerce 1968).

TABLE 3

Hours of Sunshine

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
*Toronto	87	110	145	179	221	256	281	257	197	153	82	77	2045
Buffalo	110	125	180	212	274	319	338	297	239	183	97	84	2458
Rochester	93	123	172	209	274	314	333	294	224	173	97	86	2392

*"Bright" sunshine, as opposed to unspecified

Cloud cover is a function of several factors and is often highly variable across a particular region. Factors influencing regional cloudiness variations include terrain and roughness effects, elevation, proximity to water bodies, temperature contrast between air and water body surfaces, proximity to a prevailing storm system track, storm frequency, time of year, prevailing wind direction, and urban effects.

Mean monthly cloud cover percentages for the daylight hours are given in Table 4 for some Canadian and American stations. Most notable is the marked increase of winter cloudiness for the downwind areas (American side) of the lake.

TABLE 4

Mean Sunrise-to-Sunset Cloud Cover Percentages, in Tenths

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Buffalo	8.3	8.1	7.5	7.1	6.7	6.1	5.8	5.8	6.2	6.3	8.3	8.4	7.1
Rochester	8.1	7.8	7.3	6.7	6.5	5.8	5.6	5.7	5.9	6.3	8.1	8.3	6.8
Syracuse	7.9	7.8	7.4	6.8	6.5	6.0	5.7	5.9	6.0	6.4	8.2	8.3	6.9
Toronto	7.3	6.8	6.3	6.2	6.3	5.7	5.0	5.1	5.3	5.6	7.3	7.3	6.2
Trenton	6.7	6.6	6.2	6.3	6.0	5.8	5.2	5.2	5.3	5.6	5.8	7.1	6.1
Stirling	6.6	6.3	6.1	6.2	6.2	5.5	5.2	5.2	5.2	5.5	7.0	6.8	6.0

Wind

Mean annual wind roses for eight compass points of stations located around the lake are depicted in Figure 63. A west to southwest wind direction predominates with a strong northwesterly component to the lake's northwest. Typical mean annual windspeeds vary from four to five m s^{-1} (9-11 mph) for anemometer heights near 10 m. Caution is warranted when attempting to extrapolate values horizontally. Wind speeds and directions can vary considerably, depending upon elevation, topography, surface roughness, and local features. Most wind measurements are presently taken at flat, open airport locations.

A general wind speed maximum is observed in winter when speeds are 10 to 20 percent higher than the annual mean; conversely, winds are lightest in summer, 10 to 20 percent lower than the mean.

Fog, Thunderstorms and Tornadoes

Fog, by nature, is largely a localized weather phenomenon affected by moisture and cooling factors which are greatly influenced by local terrain and geography. Heavy fog, having a visibility of one quarter mile (400 m) or less, generally occurs approximately 20 times per year throughout the region (Peace 1969). Stations nearest the lake tend to experience a spring season fog occurrence maximum.

Thunderstorms occur most commonly during the summer season when normal convective activity is at its height. Maximum frequency is during the late afternoon hours. Thunderstorms within lake-effect snowstorms are not uncommon in late fall and early winter along the lee shore of Lake Ontario. Buffalo, New York, typically experiences 30 days with thunder per year, Rochester, New York, about 29. Toronto, Ontario, annually experiences about 22 days with thunder, Trenton and Stirling, Ontario, 22 and 24 days, respectively.

Tornadoes are quite rare but not unknown to the region. About one to two individual tornadoes are reported per year on the average, which occur almost exclusively between April and September. Waterspouts have been observed over Lake Ontario and northern Lake Erie during the first cold outbreaks in the fall.

Urban Effects on Local Climate

The aim of discussion of this topic is to emphasize that significant variations in climate are found in urban areas as opposed to rural areas. These variations are not satisfactorily detailed in the weather parameter maps that accompany this monograph because of the scale involved and because of the absence of dense atmospheric monitoring networks in and around most cities. The Lake Ontario region consists of a heavily industrialized region stretching from Buffalo, New York, around the lake's western tip to Toronto, Ontario, in addition to several other cities varying in size and location around the lake.

Much has been documented on the subject of urban weather and climate modification for several US and worldwide cities, many of which are comparable in both size and industrial activity to Buffalo or Toronto. Unfortunately, these studies have not included any part of the Lake Ontario region. Yet nearly all studies have revealed common qualitative climatic effects. These effects are briefly discussed below, and although no definitive qualitative measure can be derived for cities particular to the Lake Ontario region, the existence of some effects on local climate can safely be assumed for at least the large industrial areas of Toronto and Buffalo.

The changes wrought by urbanization include most major surface weather conditions. "Heat islands" and "smog" are household words; Munn et al. (1969) have studied the Toronto "heat island". Visibilities are typically decreased in urban areas resulting from contaminants in the air. Urban areas act as an obstacle to decrease winds near the surface, to increase turbulence and vertical motions in the atmosphere above cities, and to create occasionally a localized rural-urban circulation. Variations in natural precipitation are affected by the urban release of aerosols, heat, and moisture, plus added mechanical turbulence. Potter (1961) has discovered a snowfall anomaly within the Toronto area. Alterations by cities also include fogginess, cloudiness, solar radiation, humidity, atmospheric electricity, severe weather events (such as thunderstorms, hail, severe rainstorms), and certain mesoscale synoptic weather features.

The degree of change in any one of these weather elements is dependent upon several factors. They include the areal extent of the urban complex, the components of the industrial complex, its location relative to major water bodies and other topographical features, time of day, season of year, existing weather conditions, and climate.

Landsberg (1962) has compiled degrees of change for several parameters which have been reported at various American and European cities. Table 5 shows an average of these changes, expressed as percent of rural conditions. The values in Table 5 are intended to only give a sense of degree of urban modification effects, not specific values to be applied to cities within the Lake Ontario region.

TABLE 5

Worldwide Data Showing Average Changes
Expressed as Percent of Rural Conditions

	Annual	Cold Season	Warms Season
Contaminants	+1000	+2000	+ 500
Solar Radiation	- 22	- 34	- 20
*Temperature (°F)	+ 1.5	+ 2.0	+ 1.0
Humidity	- 6	- 2	- 8
Visibility	- 26	- 34	- 17
Fog	+ 60	+ 100	+ 30
Wind Speed	- 25	- 20	- 30
Cloudiness	+ 8	+ 5	+ 10
Rainfall	+ 11	+ 13	+ 11
Snowfall	± 10	± 10	-
Thunderstorms	+ 8	+ 5	+ 17

*Percentages not applicable

How might the precipitation values in Table 5 compare with those experienced at a large, industrial city located on the shore of one of the Great Lakes? Conveniently, an urban precipitation study (1954-1968) for Cleveland, Ohio, located on Lake Erie, has been performed by Huff and Changnon (1973). Their results have indicated a year-round urban-related enhancement of precipitation at downwind (east and southeast) locations of the order of 5-15 percent during the summer months, and by at least that much in winter. A precipitation study of the Chicago, Illinois, area revealed very similar results (Huff and Changnon 1973). An investigation into the frequency of thunderstorms downwind of Cleveland have shown an increase as well of 14 percent during the 1960-1968 period. Downwind hail day increases in summer showed a near-doubling.

These results may or may not compare with possible precipitation modifications in the Buffalo and Toronto areas; comparable studies have not been performed specifically for these two cities. But the collective findings of Landsberg (1962), Munn et al. (1969), Potter (1961), plus those of Huff and Changnon, which were carried out on cities similar in urban dimension and geographical setting to Buffalo and Toronto, do strongly suggest that significant urban modifications are probably active around both Buffalo and Toronto.

Regional Climate Change

A noticeable change in the climate of a particular region can be the result of local influences, such as urbanization and all of its ramifications, or the result of external influences, such as global climatic changes, whatever their causes, or a combination of the two. It has been established that urbanization can substantially alter the climate of city and surrounding environs, but it is presently only speculation as to whether anthropogenetic activities have already affected large scale or global climate. The possibility that natural variations in climate, which have occurred throughout the earth's lifetime, are coexisting with anthropogenetic influences makes the ability to distinguish natural from inadvertent causes and effects an exercise in futility.

The last million years of earth's history have been characterized by a sequence of several glacial and interglacial periods. Some four to five major glaciations are known, each having developed over a period of 90,000-100,000 years and terminating rather quickly in about 10,000 years. The Great Lakes were glacially dug out during this period. The last glacial maximum, the Wisconsin in America and the Würm in Europe, occurred in both hemispheres 20,000-18,000 years ago (NAS 1975).

A number of noticeable smaller-scale variations in climate have taken place in the Northern Hemisphere in recent centuries. The mild climate of the early Middle Ages (800-1200 AD) favored Viking exploration in the North Atlantic and allowed for the cultivation of Iceland and Greenland. The "Little Ice Age" between 1500 and 1700 AD produced an exceptionally high frequency of severe winters in western Europe. Most recently, a worldwide warming trend was experienced between the 1880s and the 1940s, followed by a cooling trend up to the present.

Year to year variations in weather accumulate to define climate, and variations in climate can only be distinguished by suitable long-term records. Within the Lake Ontario region, the cities of Oswego, New York and Toronto, Ontario have maintained weather records for over 130 years. Unfortunately, the Oswego station has changed location several times, making it difficult to separate true climatic changes from ones induced by relocation. The station was ultimately moved from within 250 m (800 ft) of the lake to its present location about 1.6 km (1 mi) inland. The Toronto station (Toronto City Meteorological Observatory) was also moved several times, but only within a three city-block area. Its records have indicated a warming trend of about 2.4°C (4.3°F) per century (Gargett 1965). But here the unanswerable question arises as to the total effect of the city's growth on the rising temperature trend. And surely, these temperature changes cannot be fully representative of the surrounding rural areas, if at all.

These and other sorts of problems have plagued other cities and other parts of the world by making it difficult to distinguish true large-scale climate change from local modification. But it has become increasingly apparent that urbanization, surface modification, and other results of man's activities have a striking impact on climate at the local scale.

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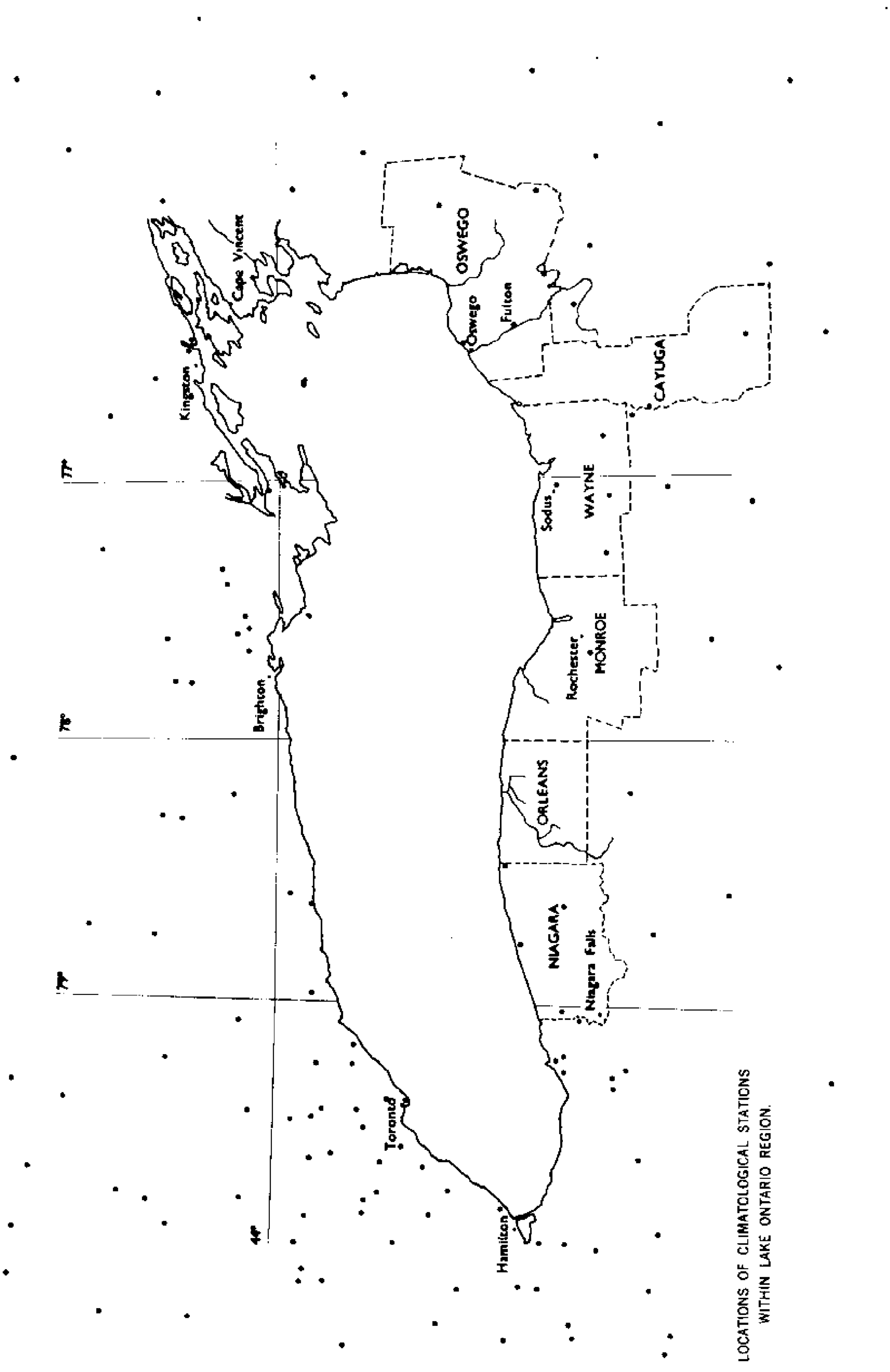
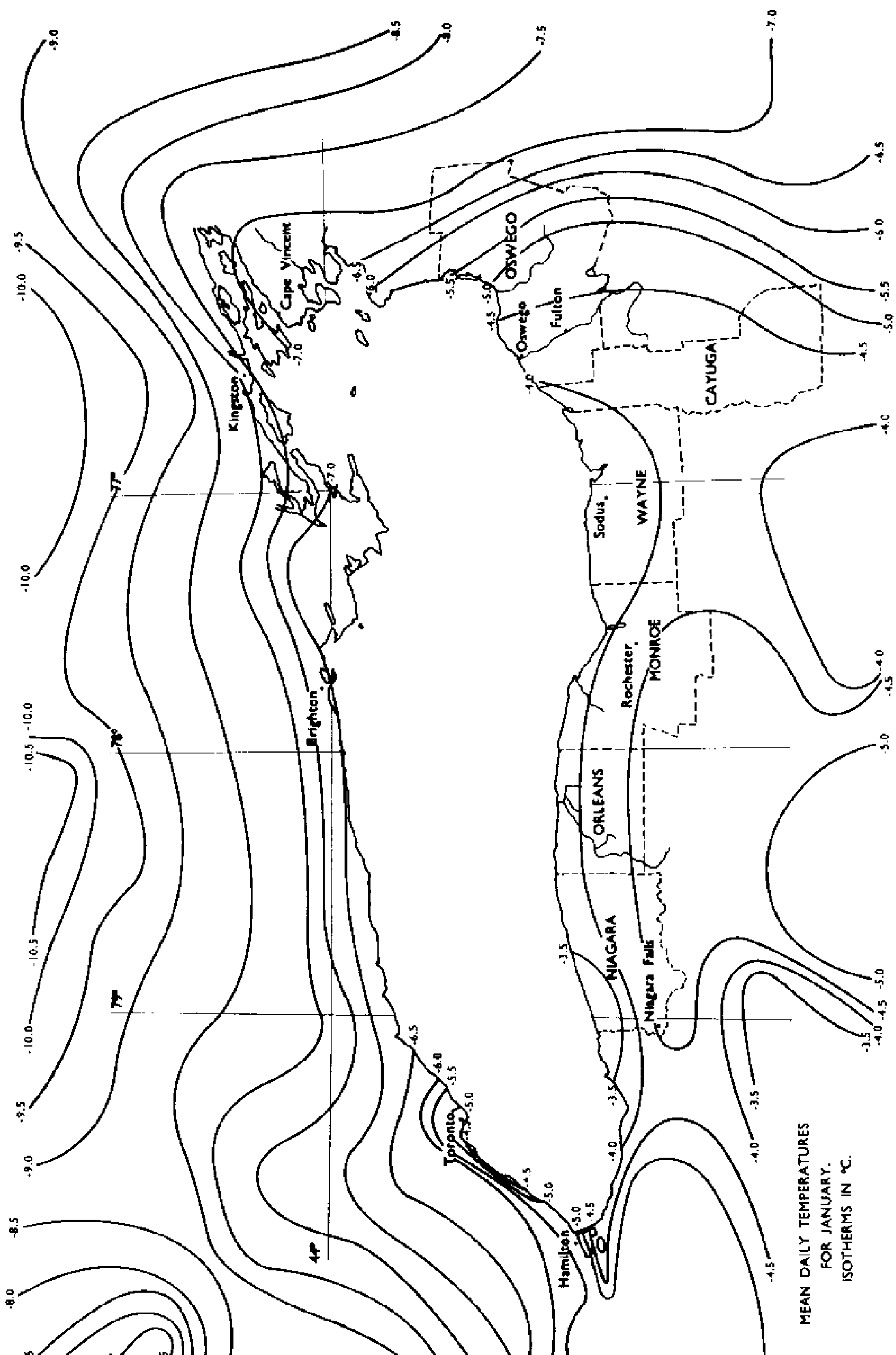
FIGURE CAPTIONS

Figure 1



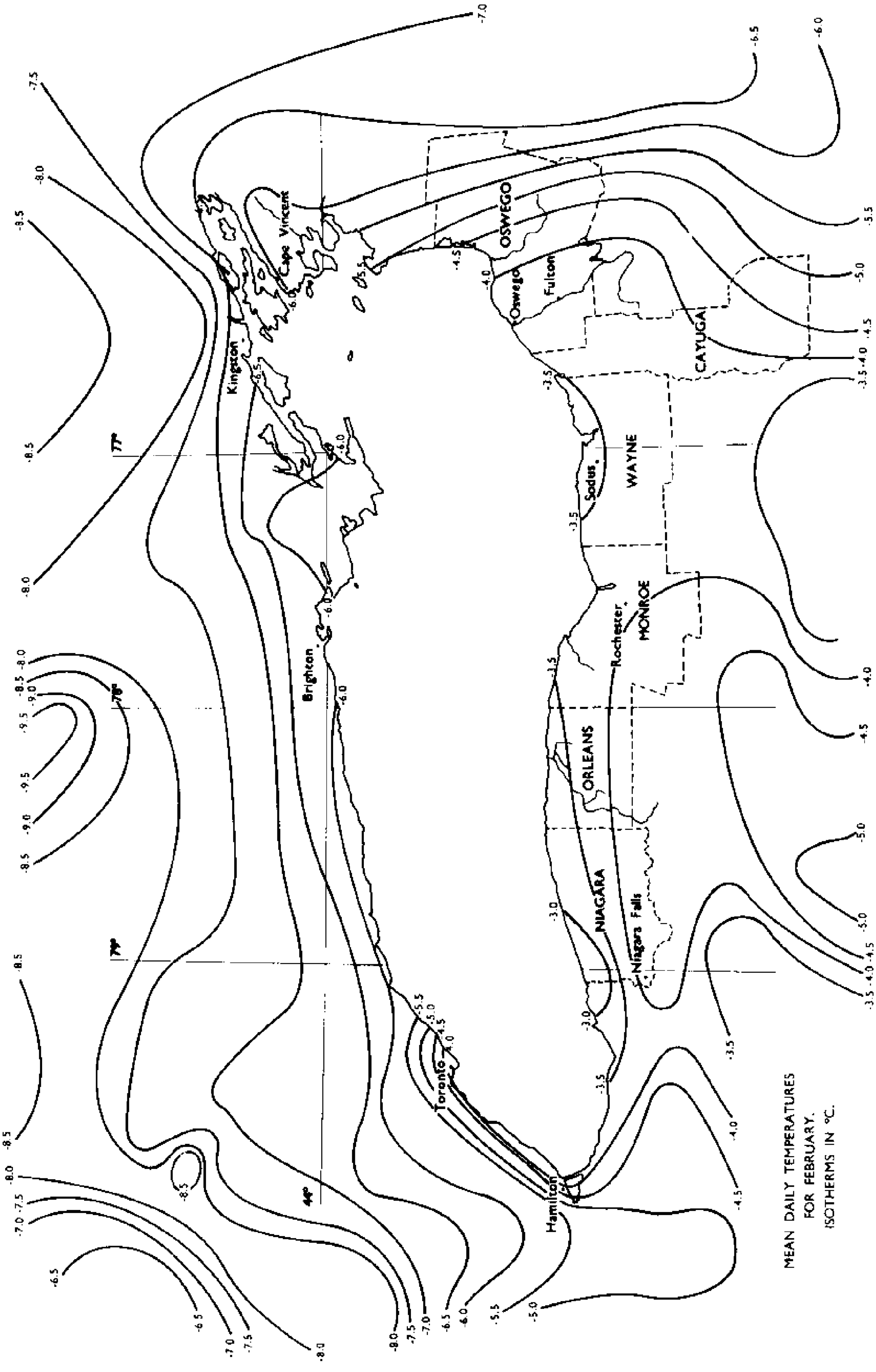
LOCATIONS OF CLIMATOLOGICAL STATIONS WITHIN LAKE ONTARIO REGION.

Figure 2



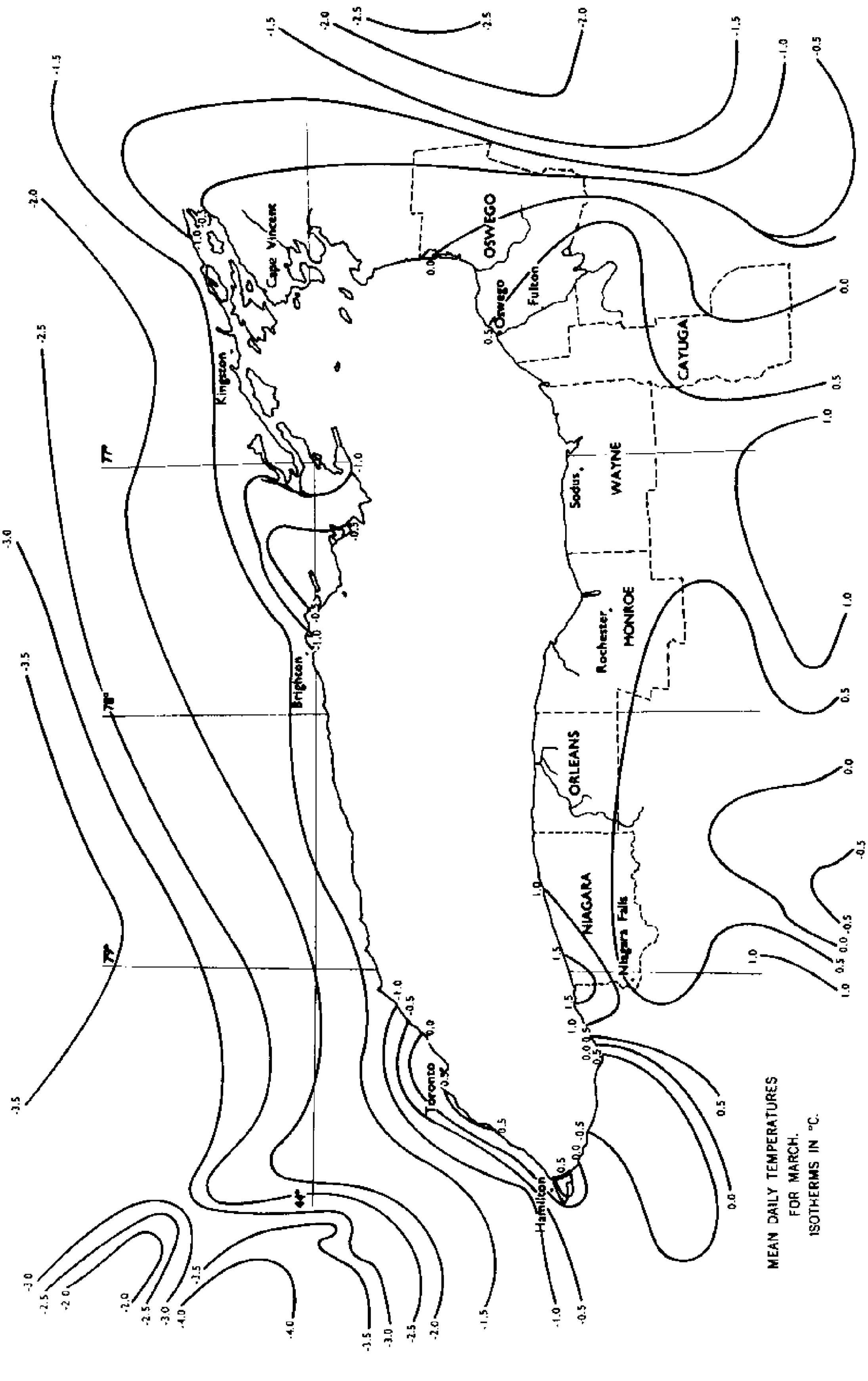
MEAN DAILY TEMPERATURES FOR JANUARY. ISOTHERMS IN °C.

Figure 3



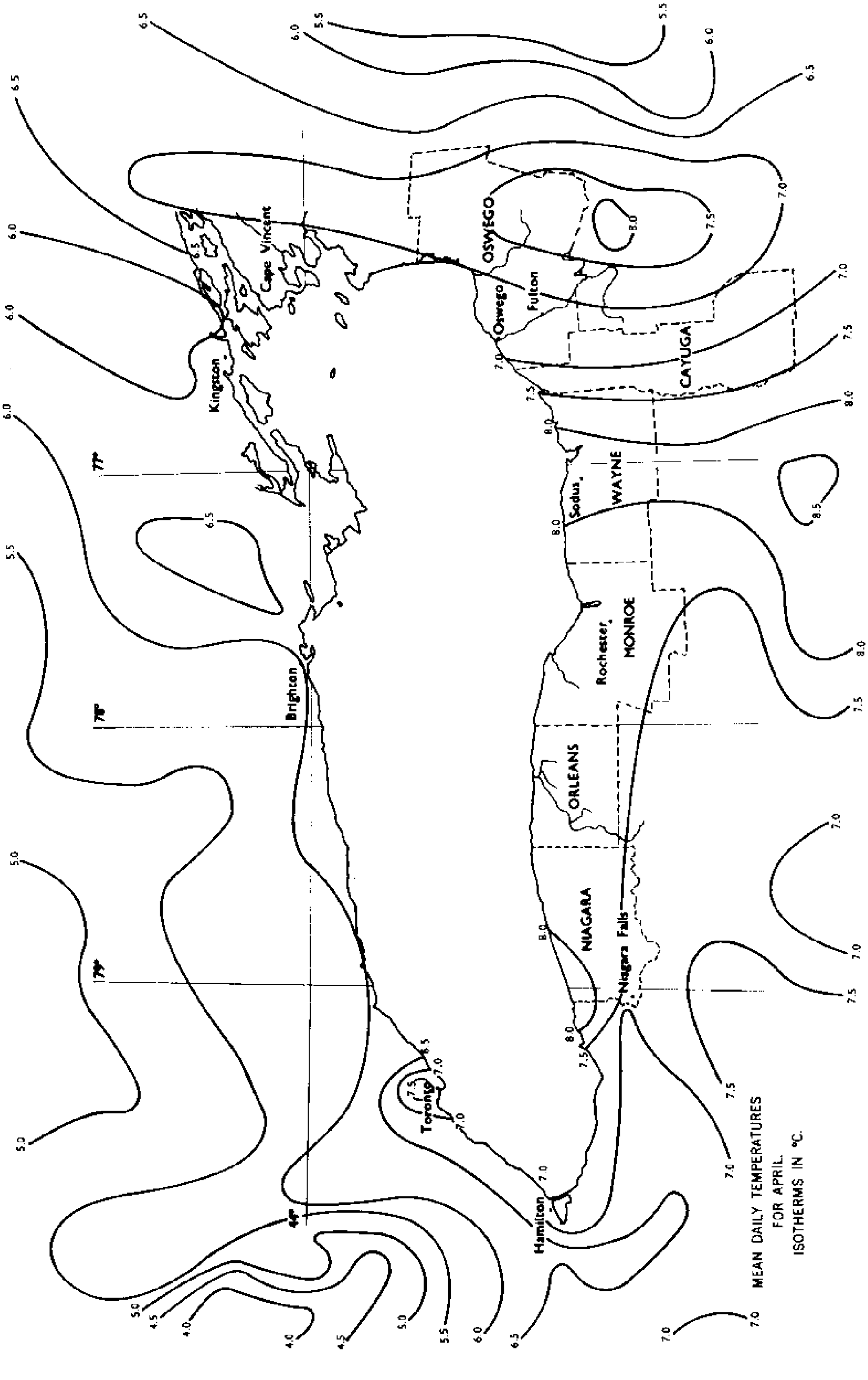
MEAN DAILY TEMPERATURES FOR FEBRUARY. ISOTHERMS IN °C.

Figure 4



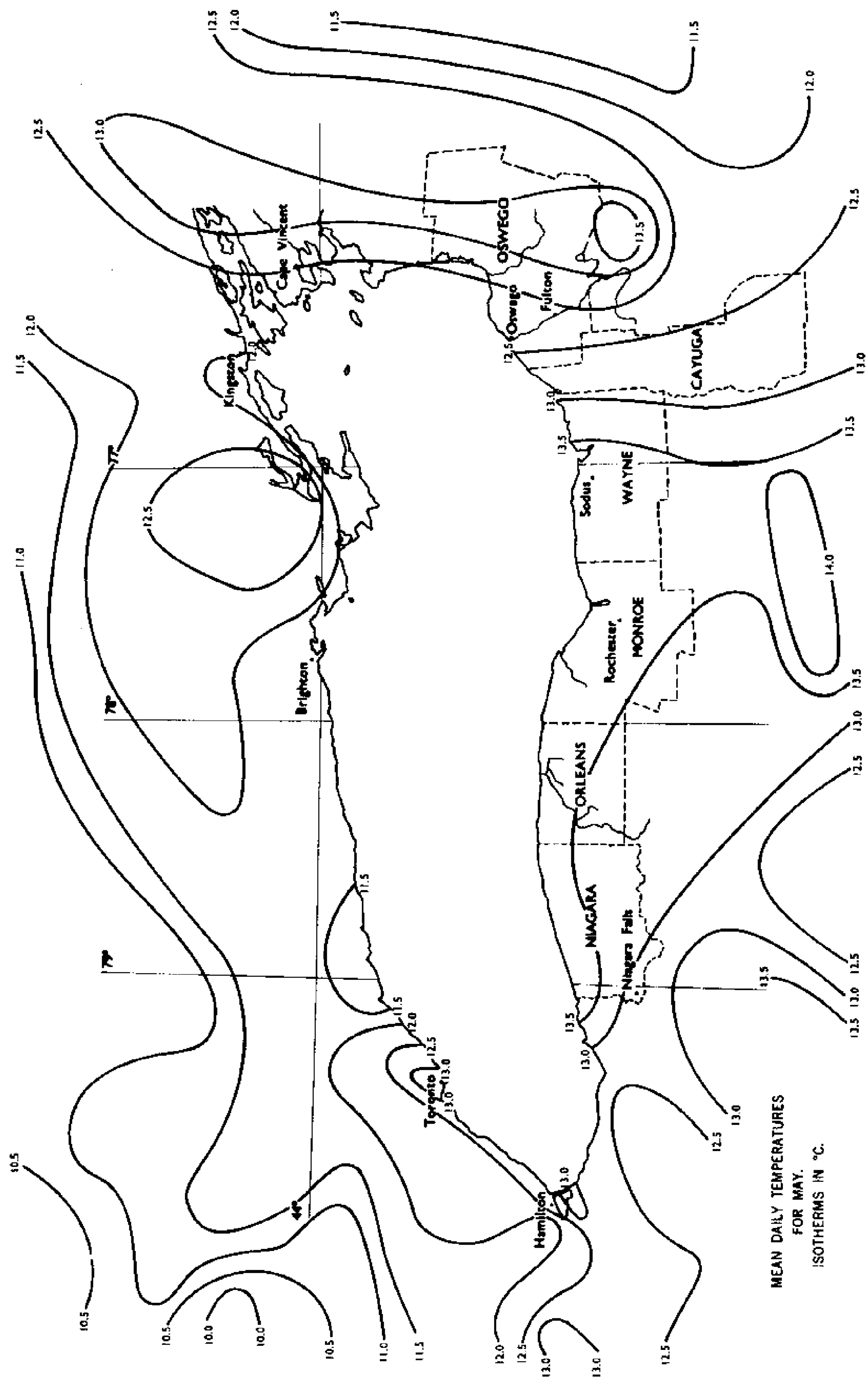
MEAN DAILY TEMPERATURES
FOR MARCH.
ISOTHERMS IN °C.

Figure 5



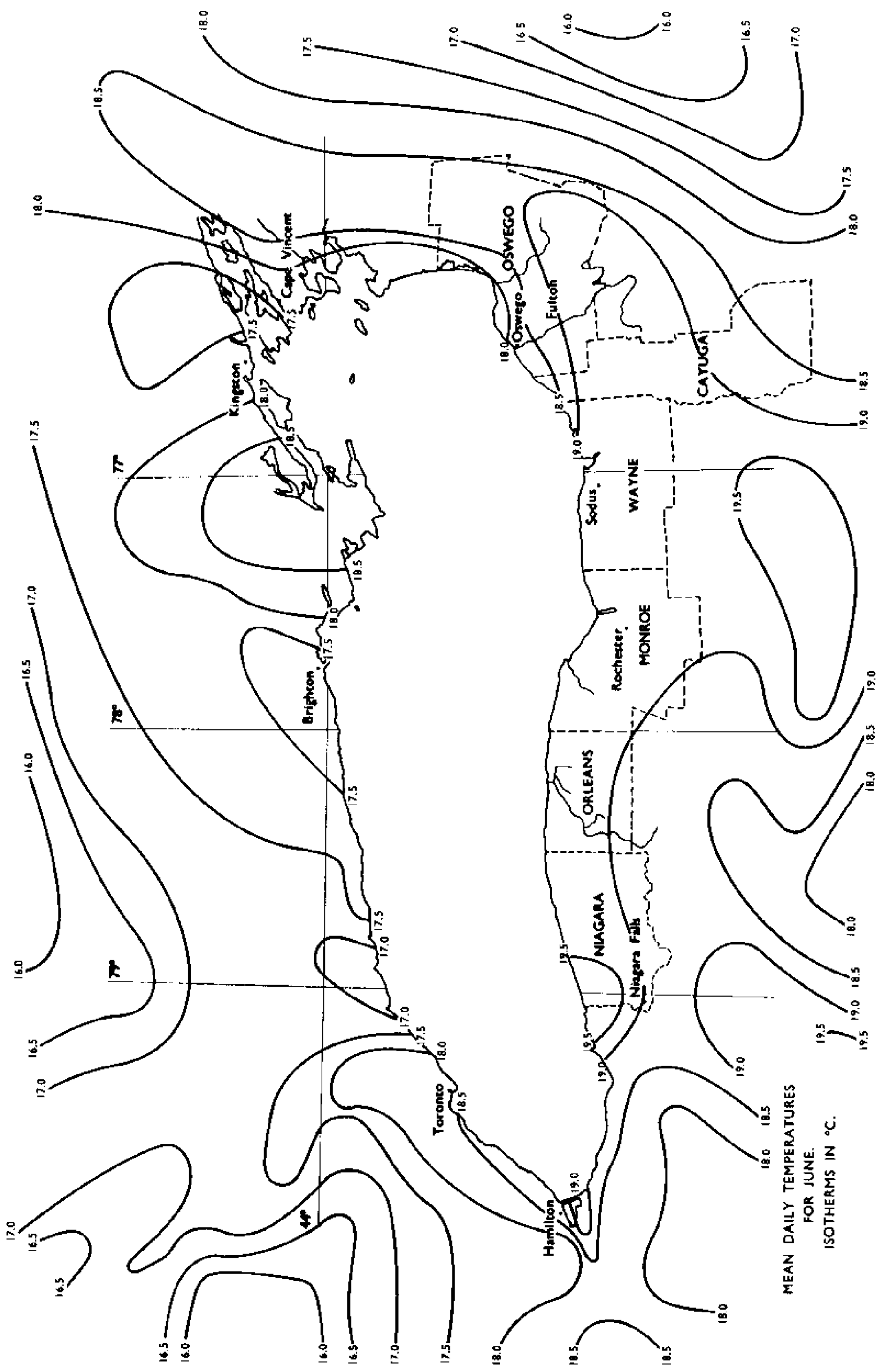
MEAN DAILY TEMPERATURES
FOR APRIL.
ISOTHERMS IN °C.

Figure 6



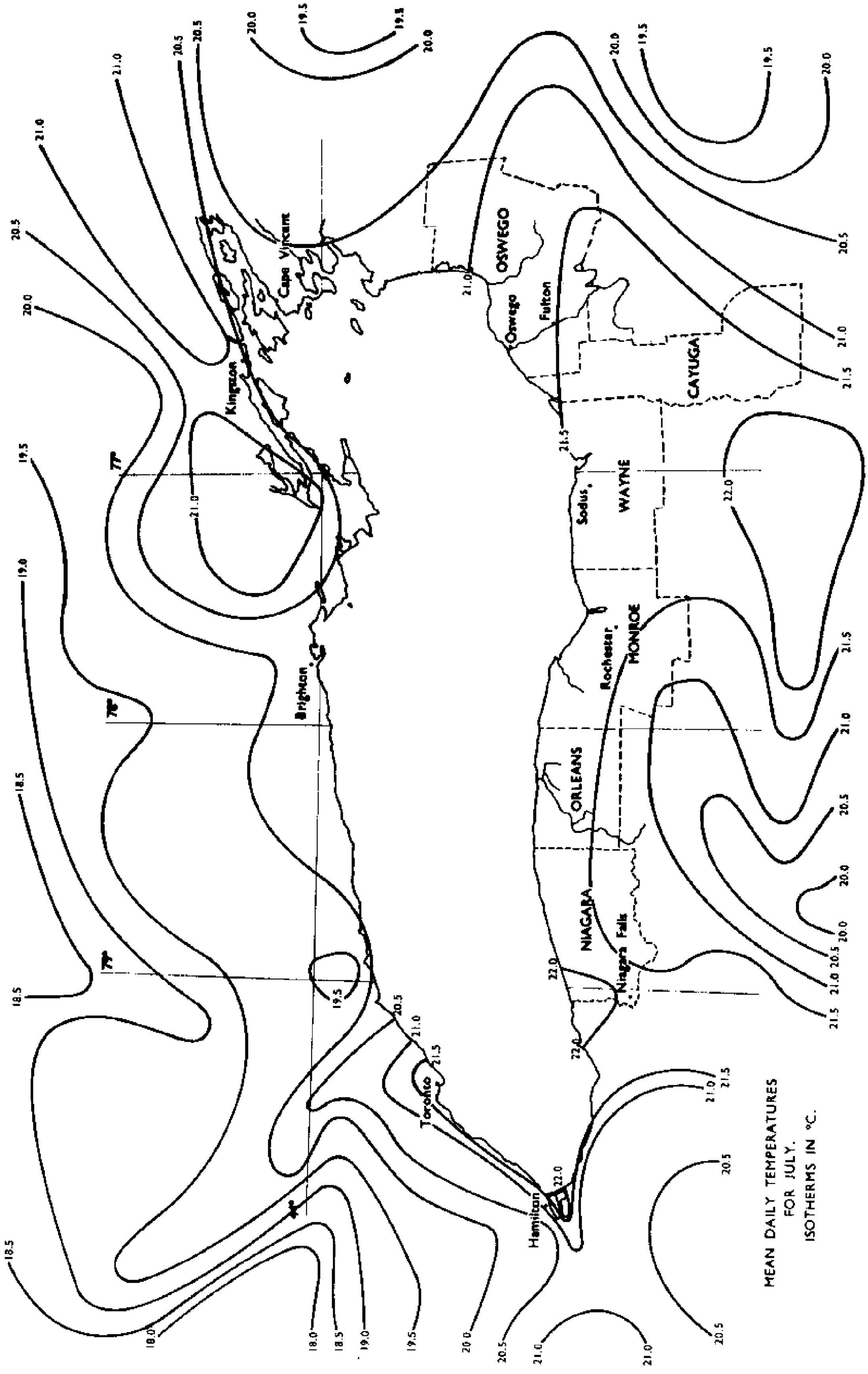
MEAN DAILY TEMPERATURES
FOR MAY.
ISOTHERMS IN °C.

Figure 7



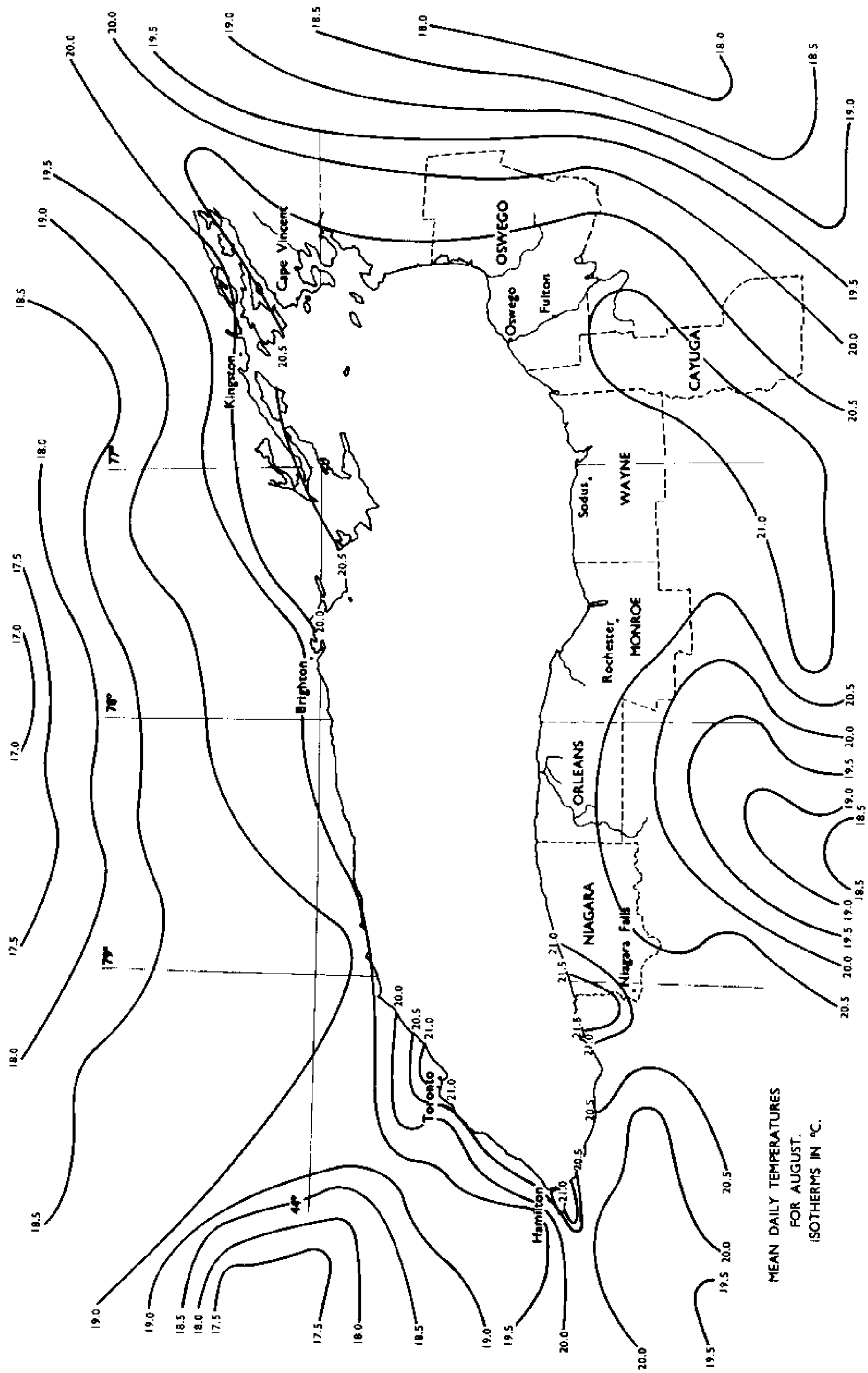
MEAN DAILY TEMPERATURES FOR JUNE. ISOTHERMS IN °C.

Figure 8



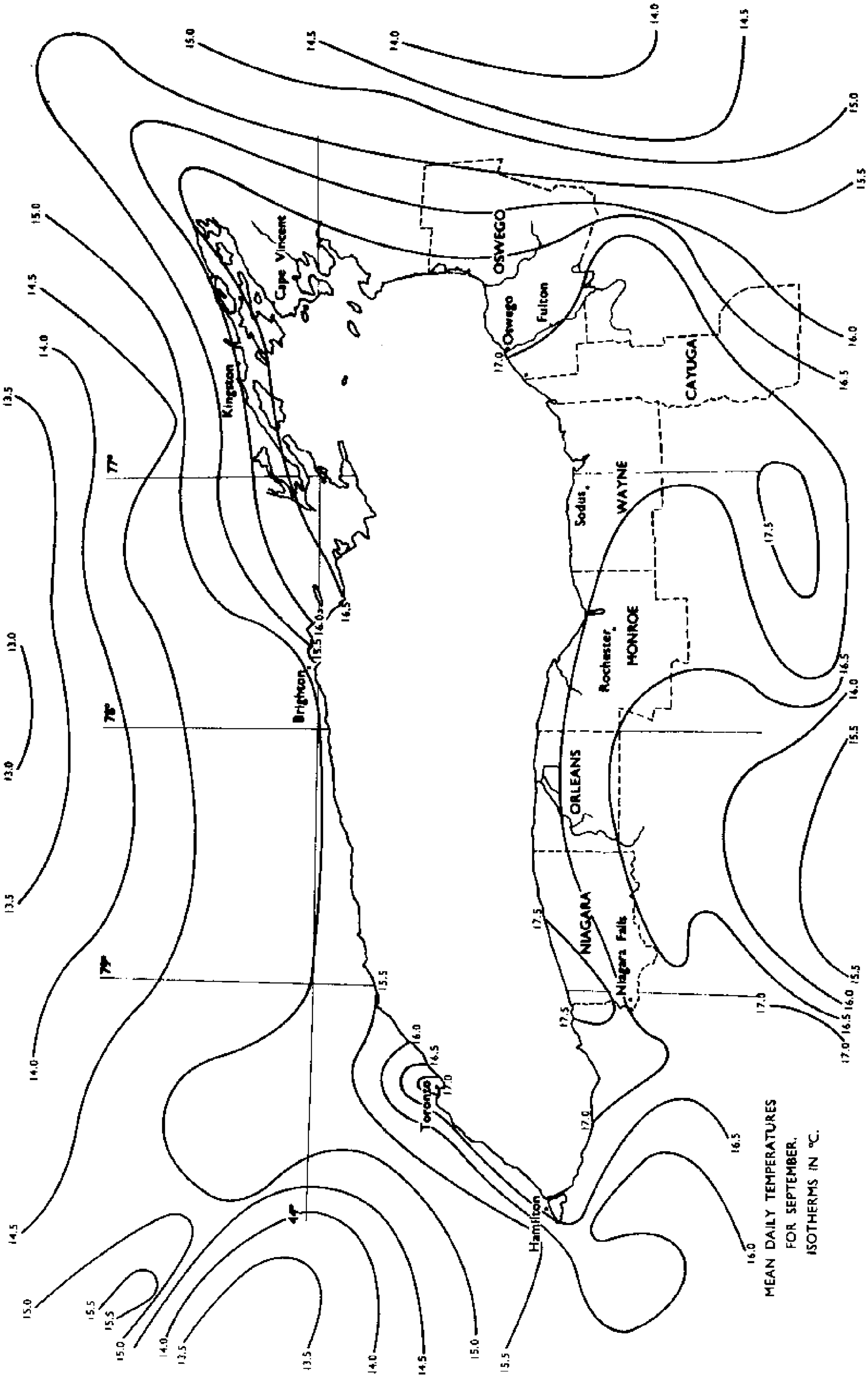
MEAN DAILY TEMPERATURES FOR JULY.
ISOTHERMS IN °C.

Figure 9



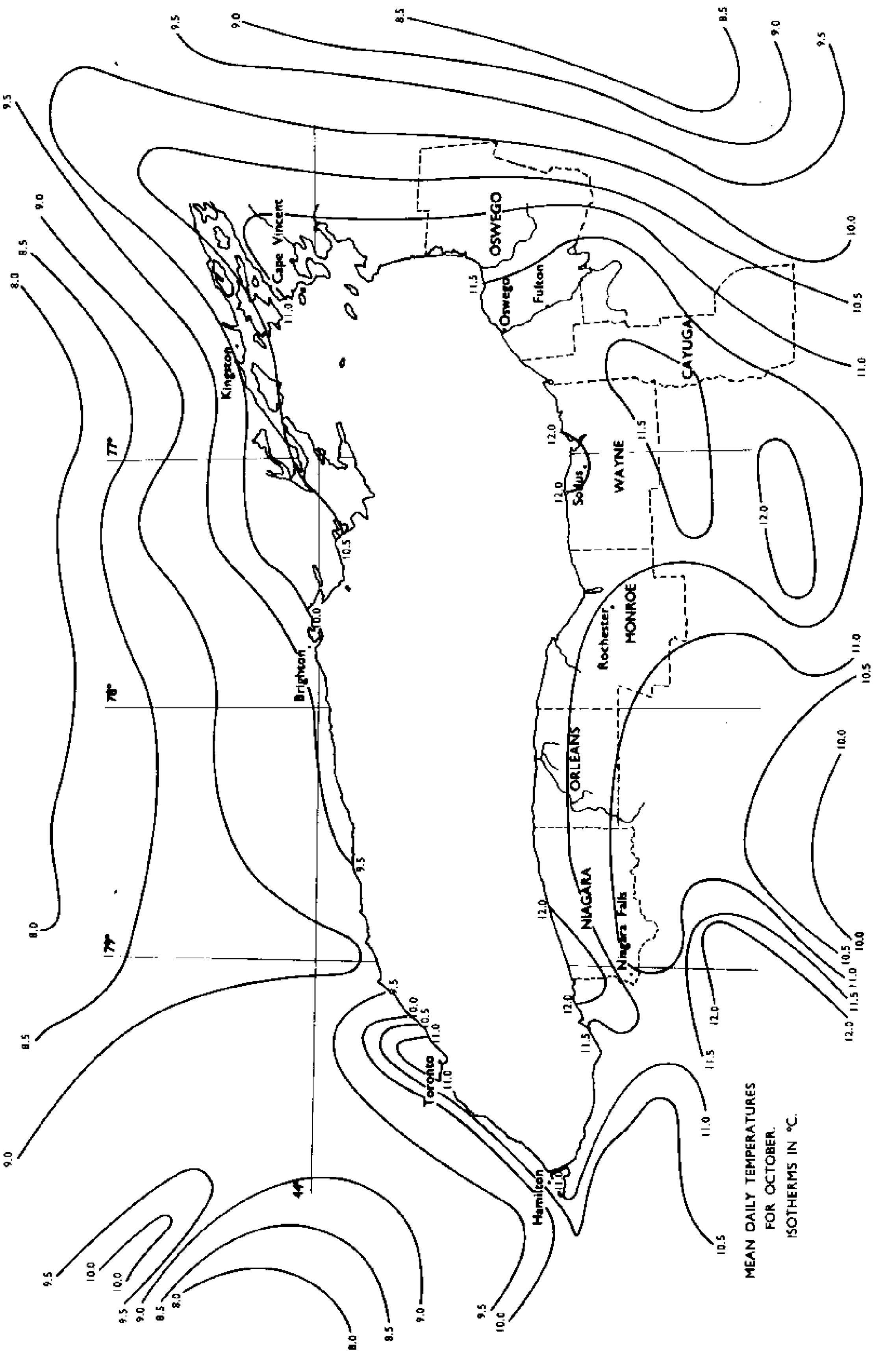
MEAN DAILY TEMPERATURES
FOR AUGUST.
ISOTHERMS IN °C.

Figure 10



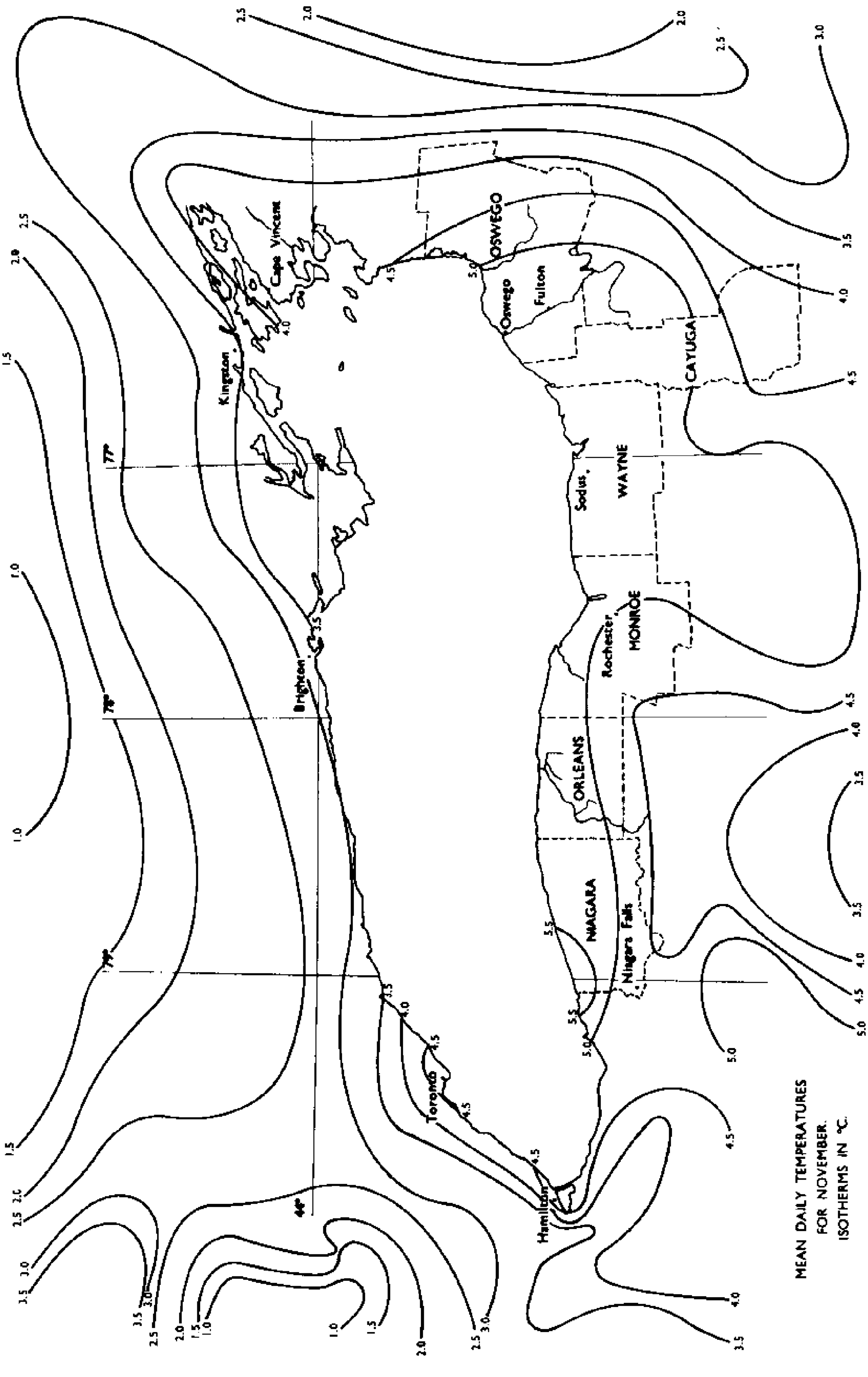
MEAN DAILY TEMPERATURES FOR SEPTEMBER. ISOTHERMS IN °C.

Figure 11



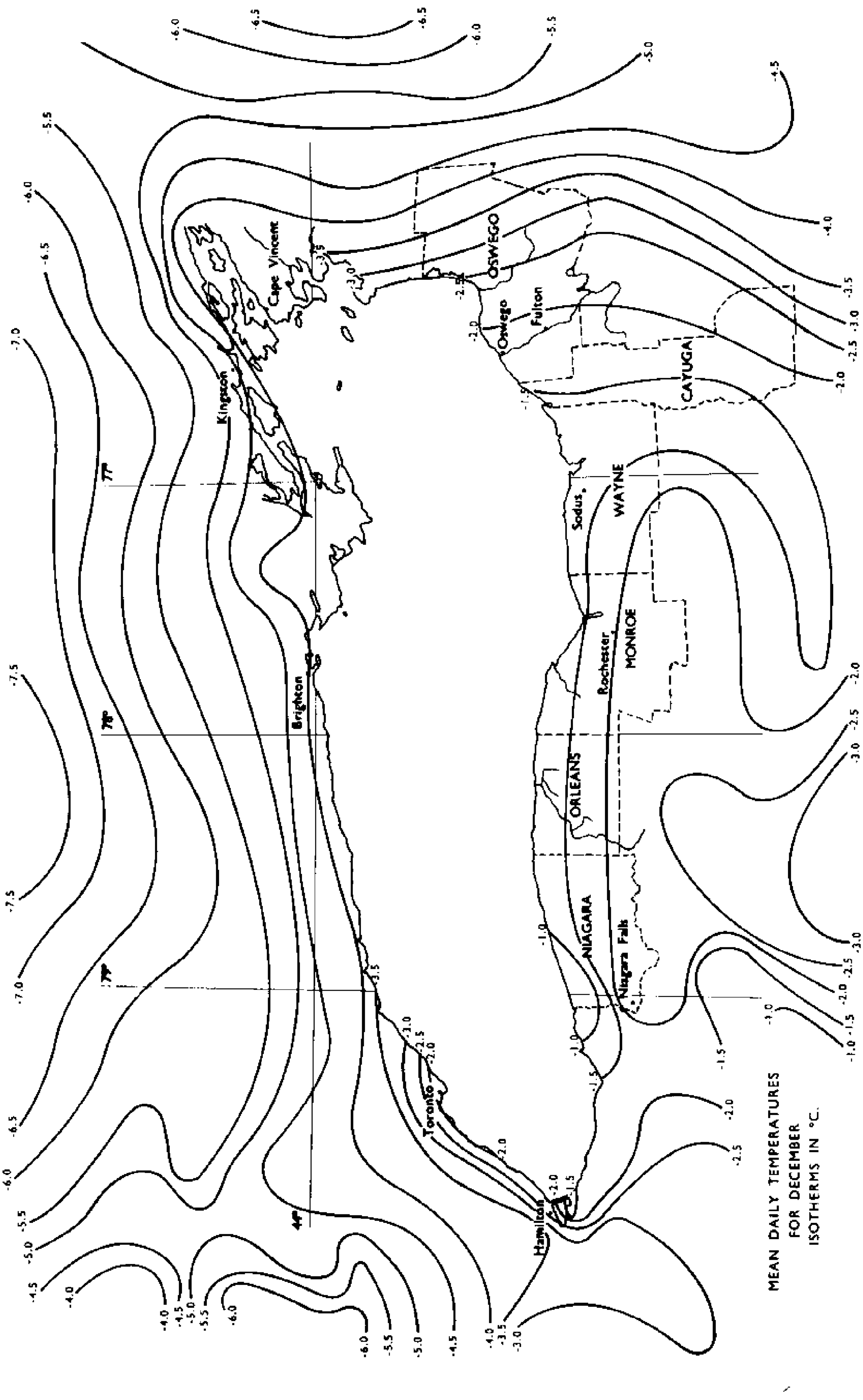
MEAN DAILY TEMPERATURES
FOR OCTOBER.
ISOTHERMS IN °C.

Figure 12



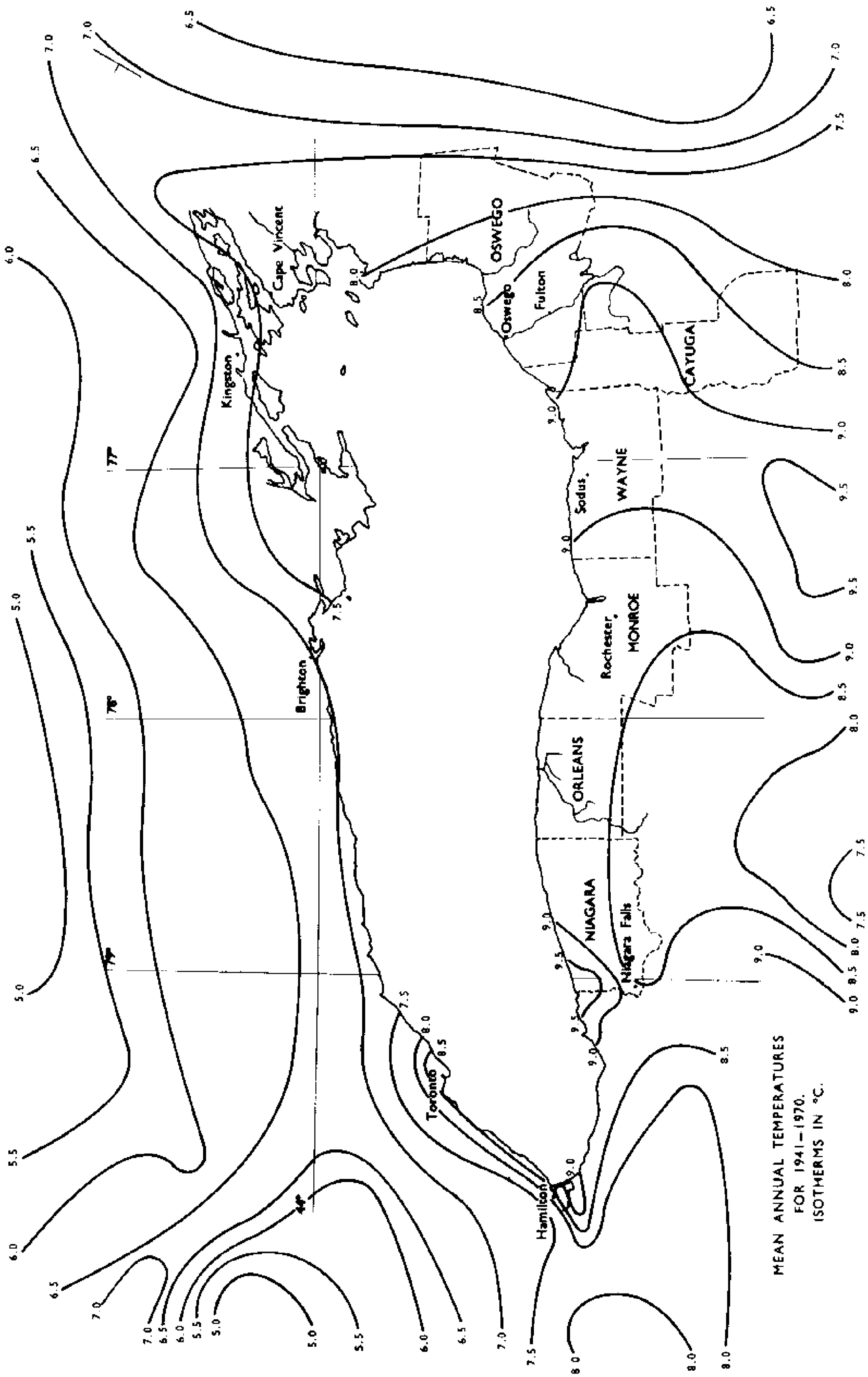
MEAN DAILY TEMPERATURES
FOR NOVEMBER.
ISOTHERMS IN °C.

Figure 13



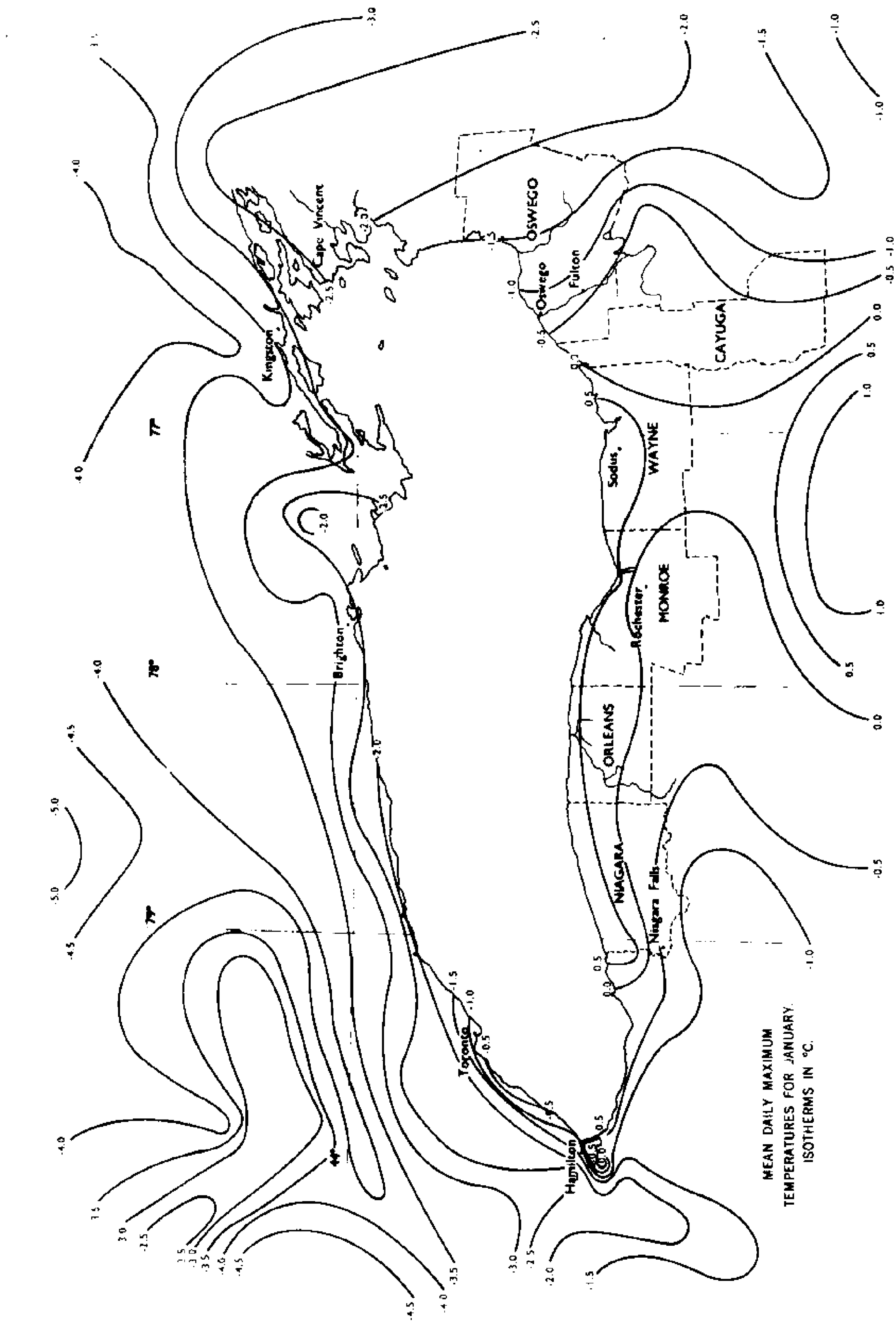
MEAN DAILY TEMPERATURES
FOR DECEMBER
ISOTHERMS IN °C.

Figure 14



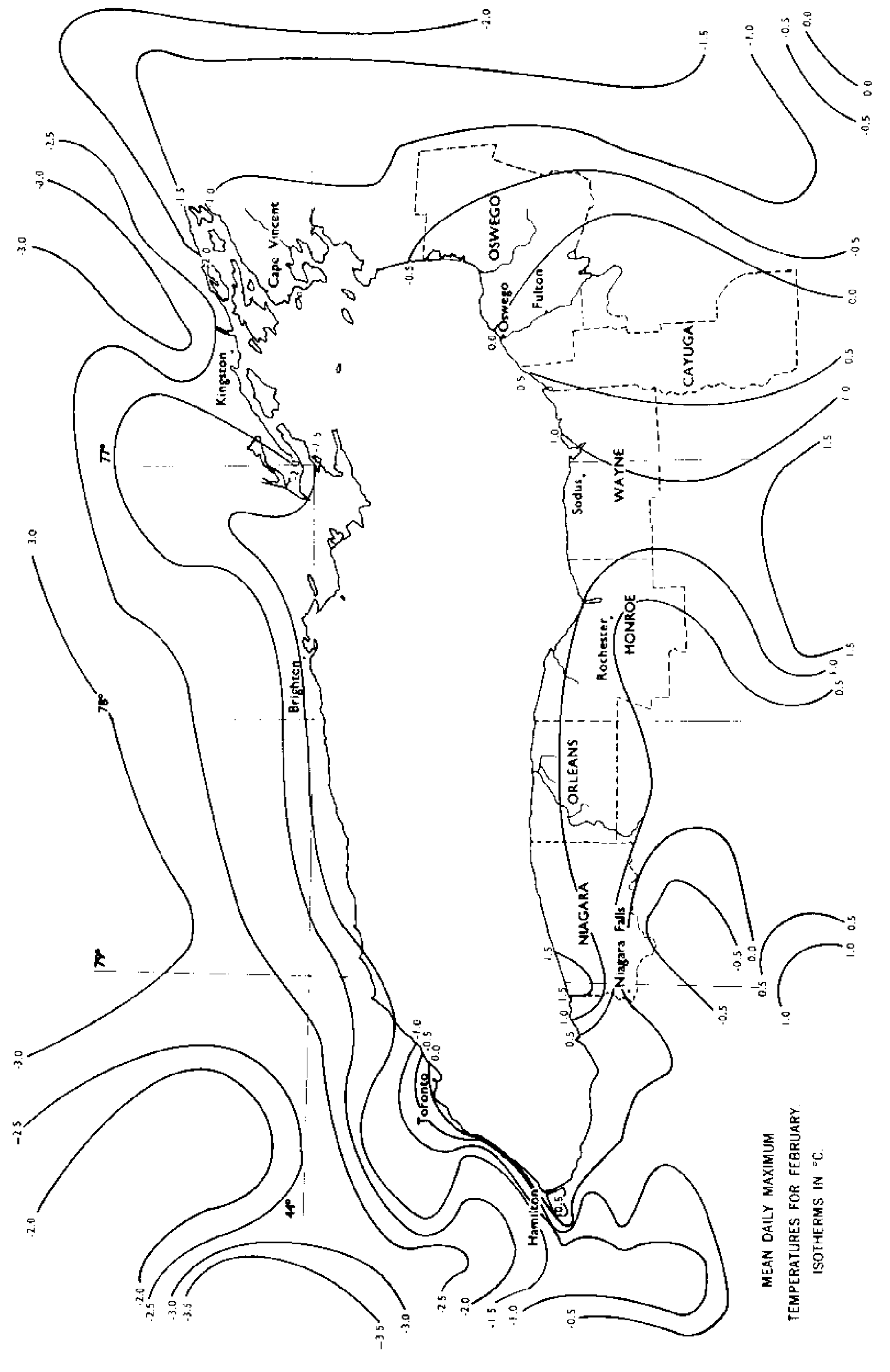
MEAN ANNUAL TEMPERATURES
FOR 1941–1970.
ISOTHERMS IN °C.

Figure 15



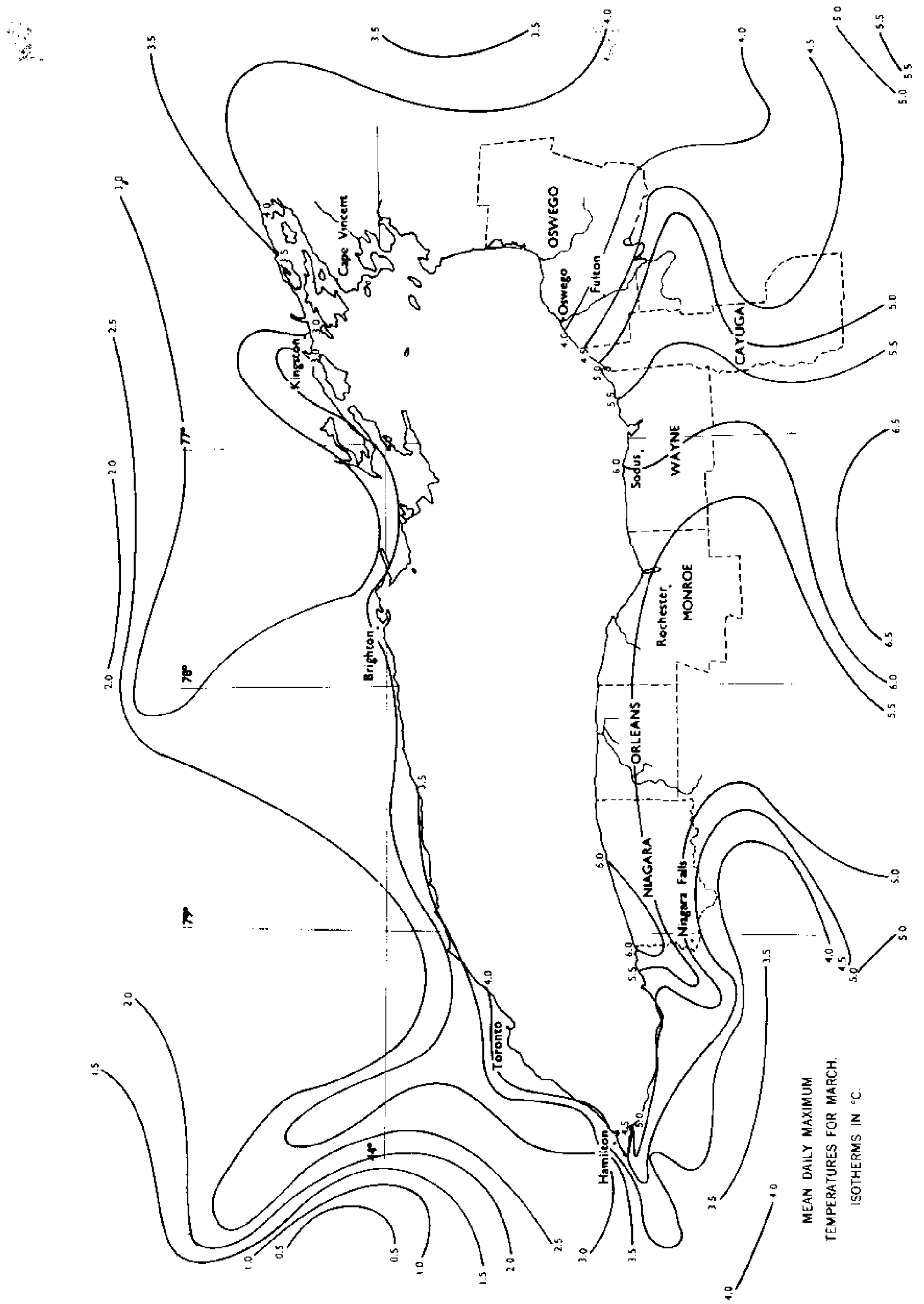
MEAN DAILY MAXIMUM
TEMPERATURES FOR JANUARY.
ISOTHERMS IN °C.

Figure 16



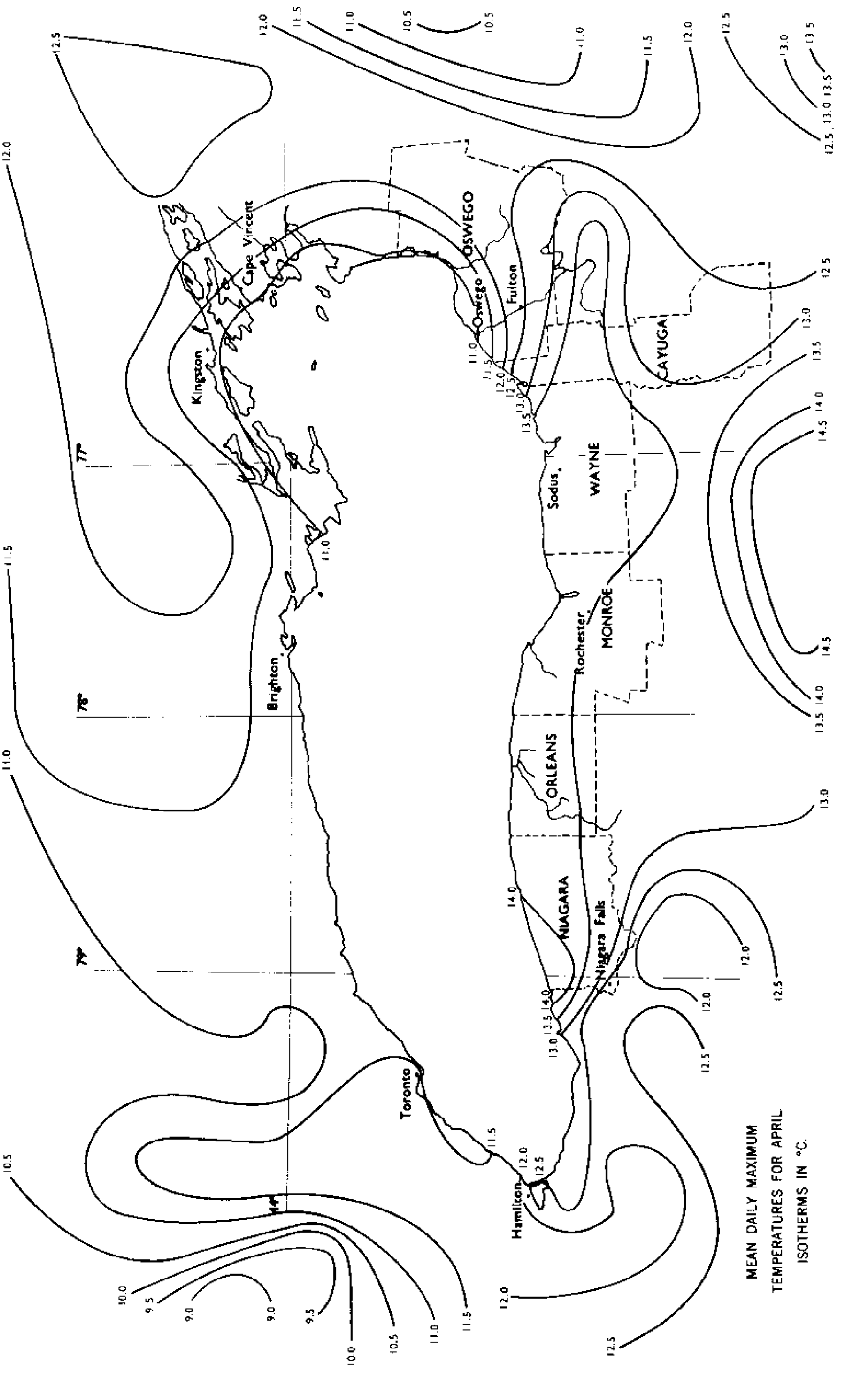
MEAN DAILY MAXIMUM TEMPERATURES FOR FEBRUARY. ISOTHERMS IN °C.

Figure 17



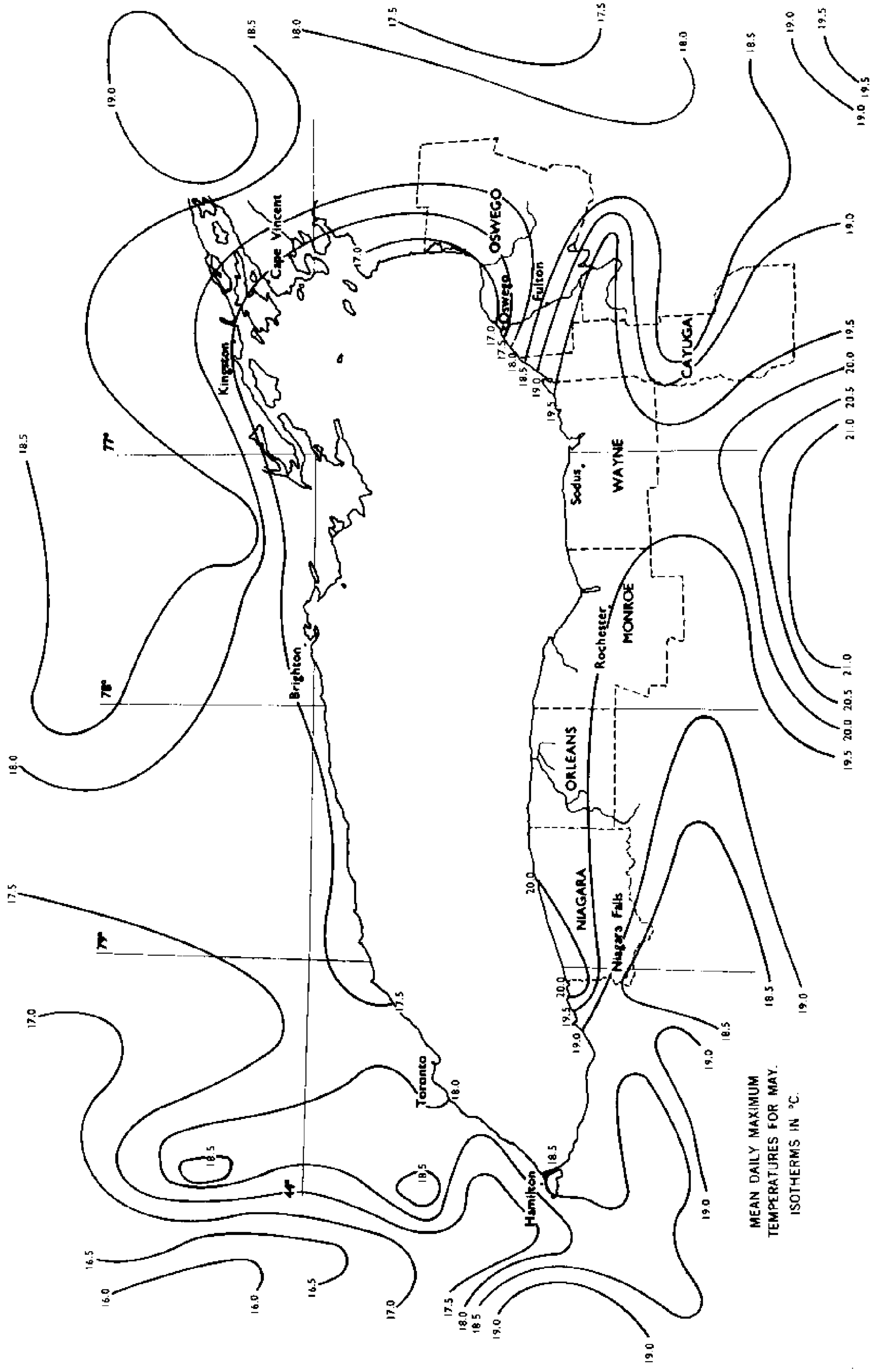
MEAN DAILY MAXIMUM TEMPERATURES FOR MARCH. ISOTHERMS IN °C.

Figure 18



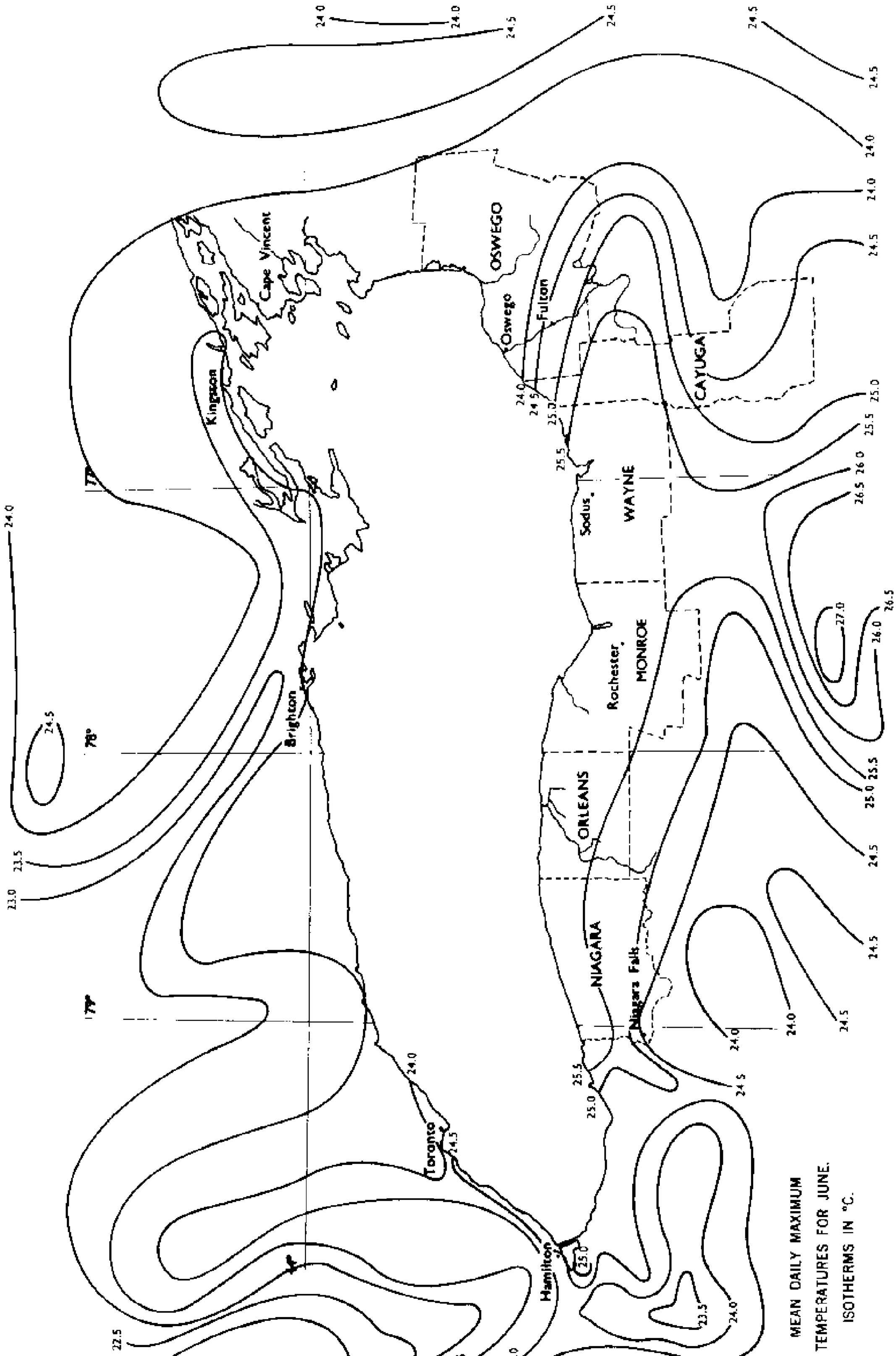
MEAN DAILY MAXIMUM
TEMPERATURES FOR APRIL
ISOTHERMS IN °C.

Figure 19



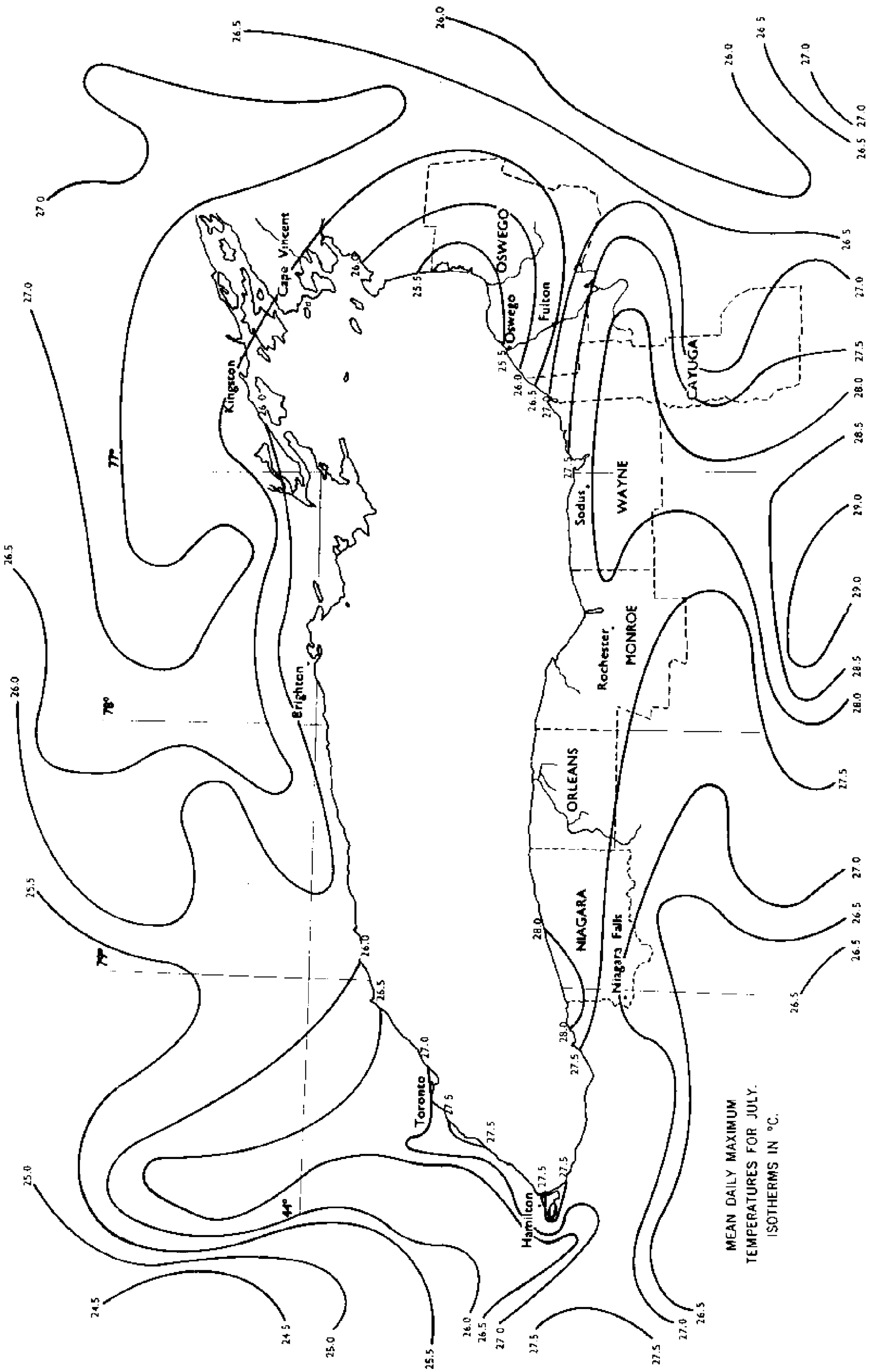
MEAN DAILY MAXIMUM TEMPERATURES FOR MAY. ISOTHERMS IN °C.

Figure 20



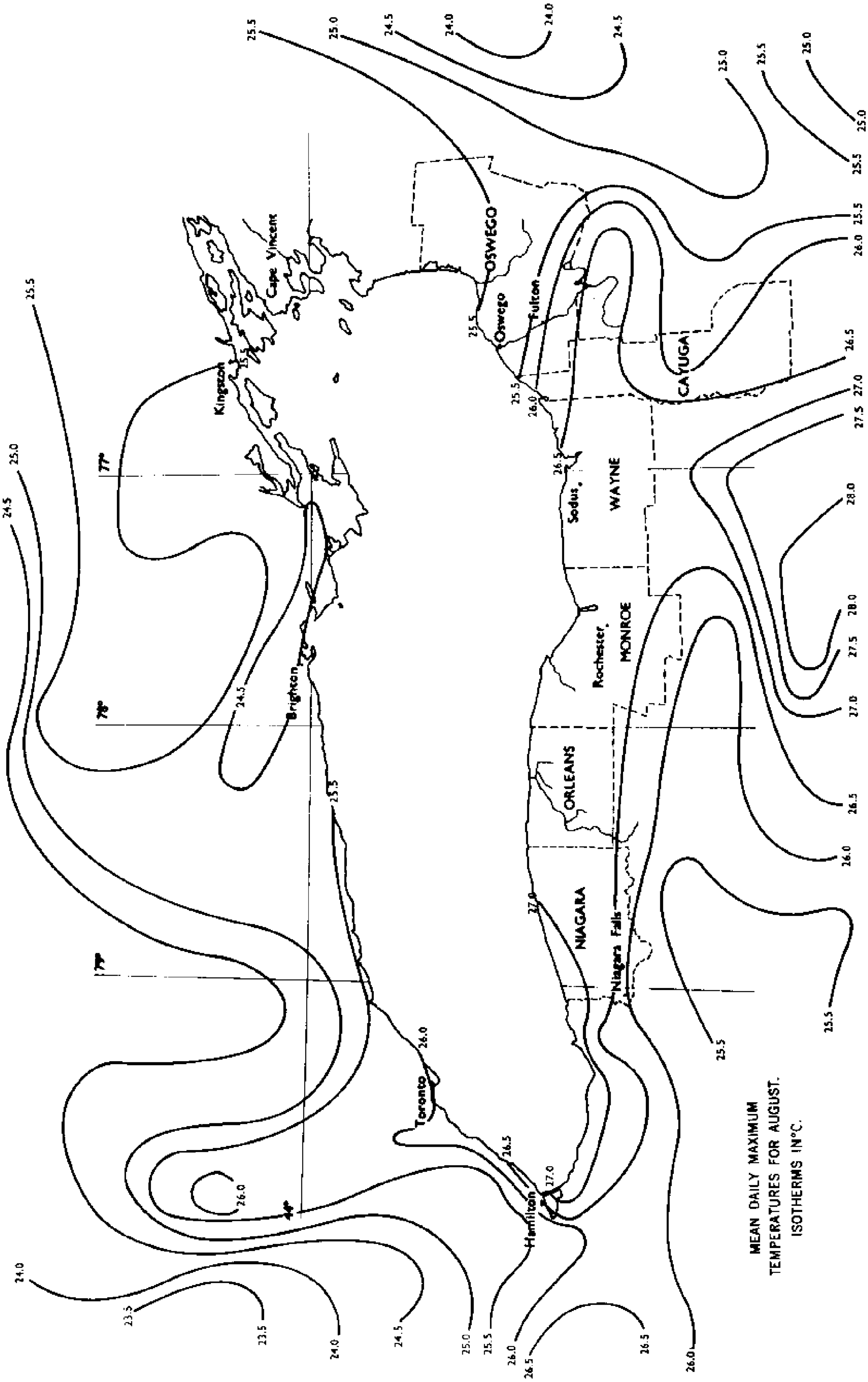
MEAN DAILY MAXIMUM TEMPERATURES FOR JUNE. ISOTHERMS IN °C.

Figure 21



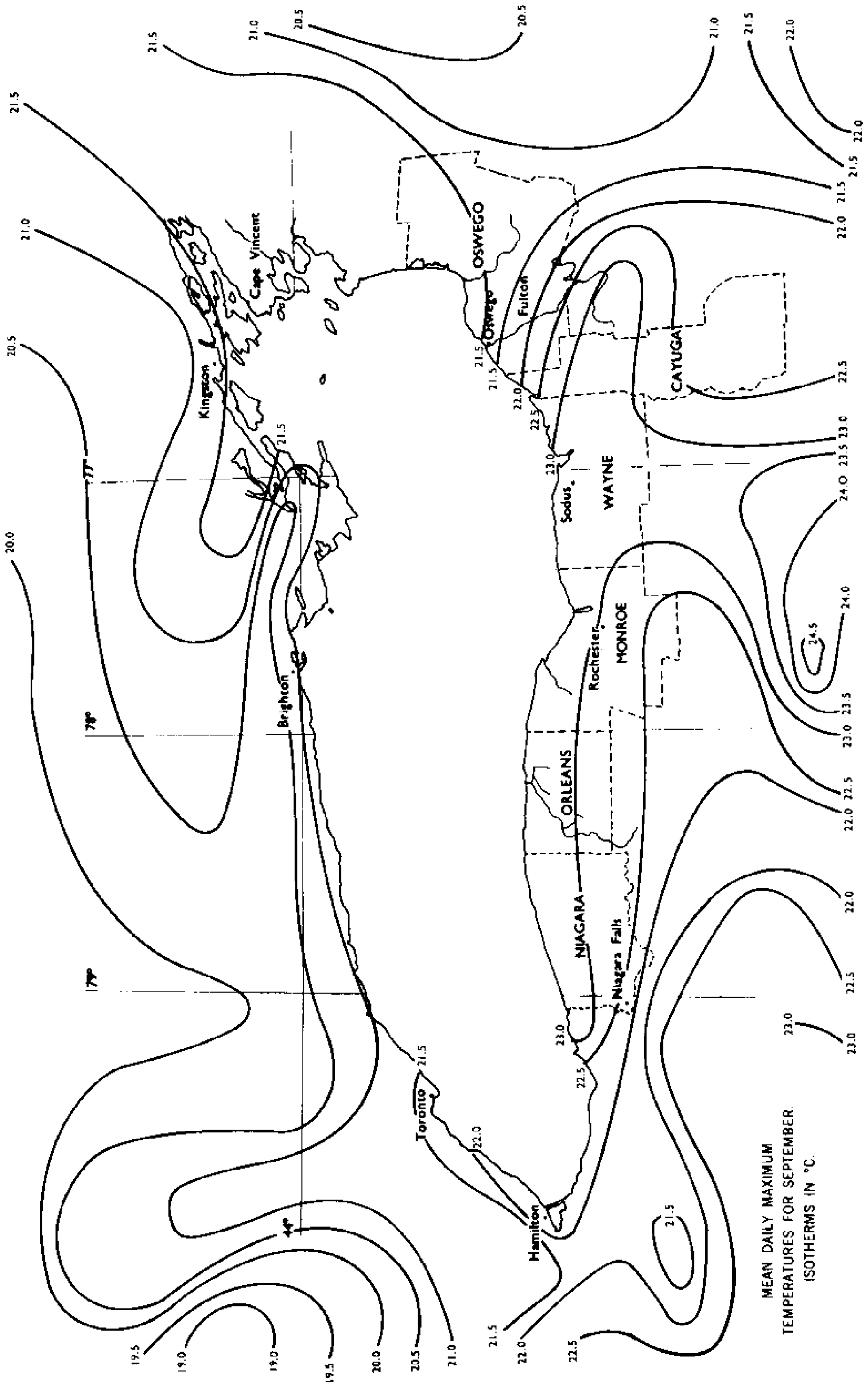
MEAN DAILY MAXIMUM TEMPERATURES FOR JULY. ISOTHERMS IN °C.

Figure 22



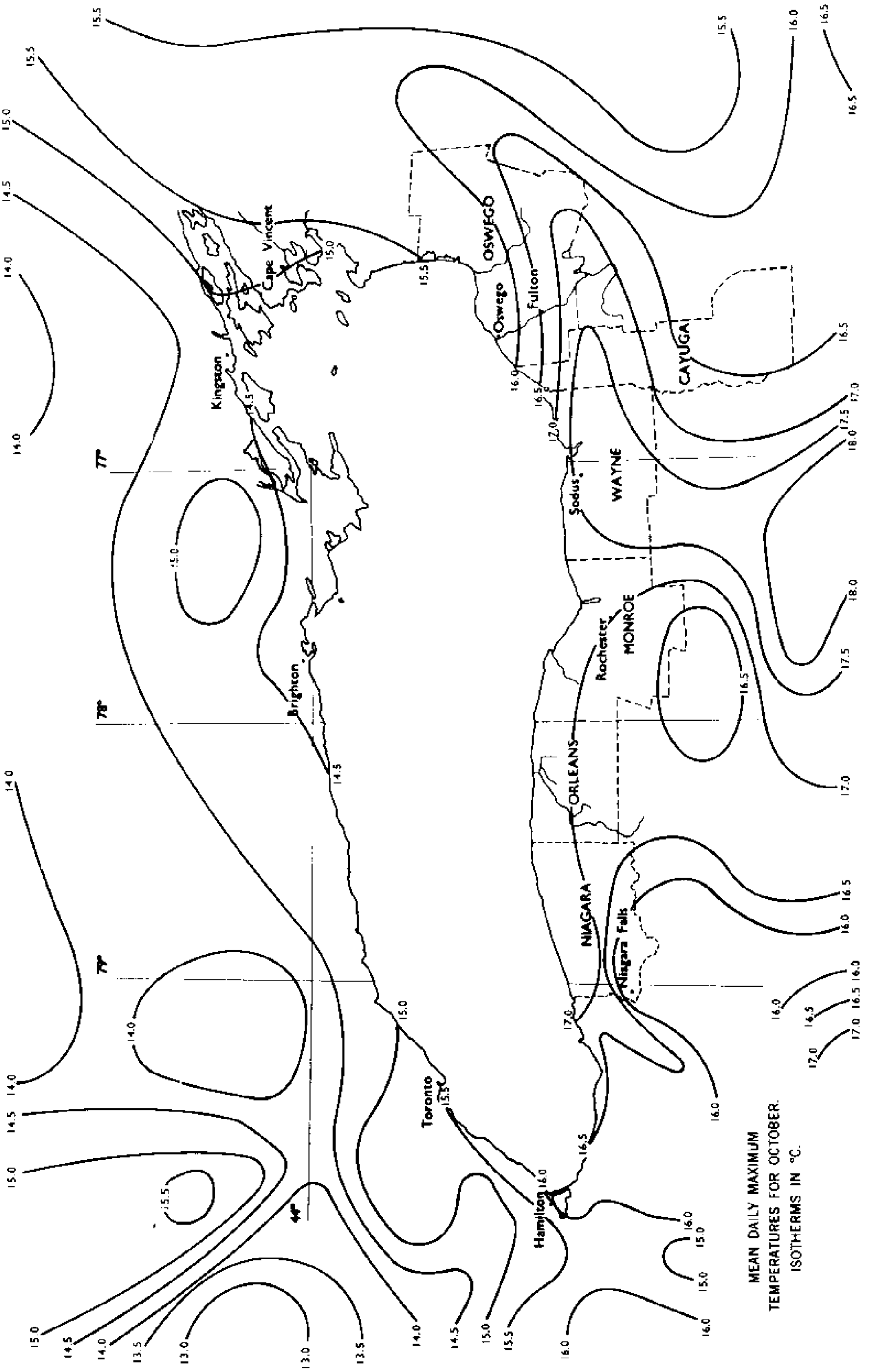
MEAN DAILY MAXIMUM
TEMPERATURES FOR AUGUST.
ISOTHERMS IN°C.

Figure 23



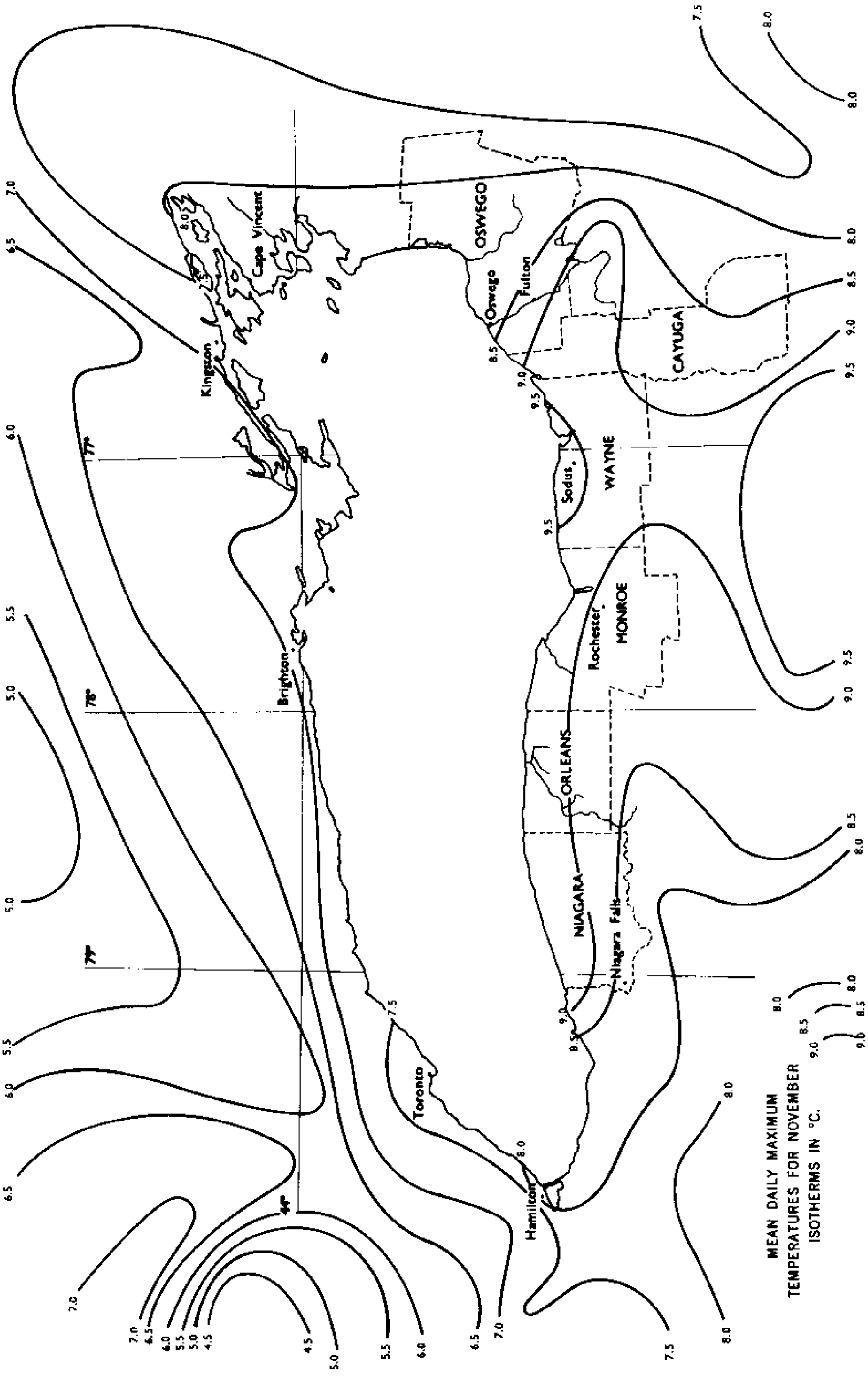
MEAN DAILY MAXIMUM TEMPERATURES FOR SEPTEMBER. ISOTHERMS IN °C.

Figure 24



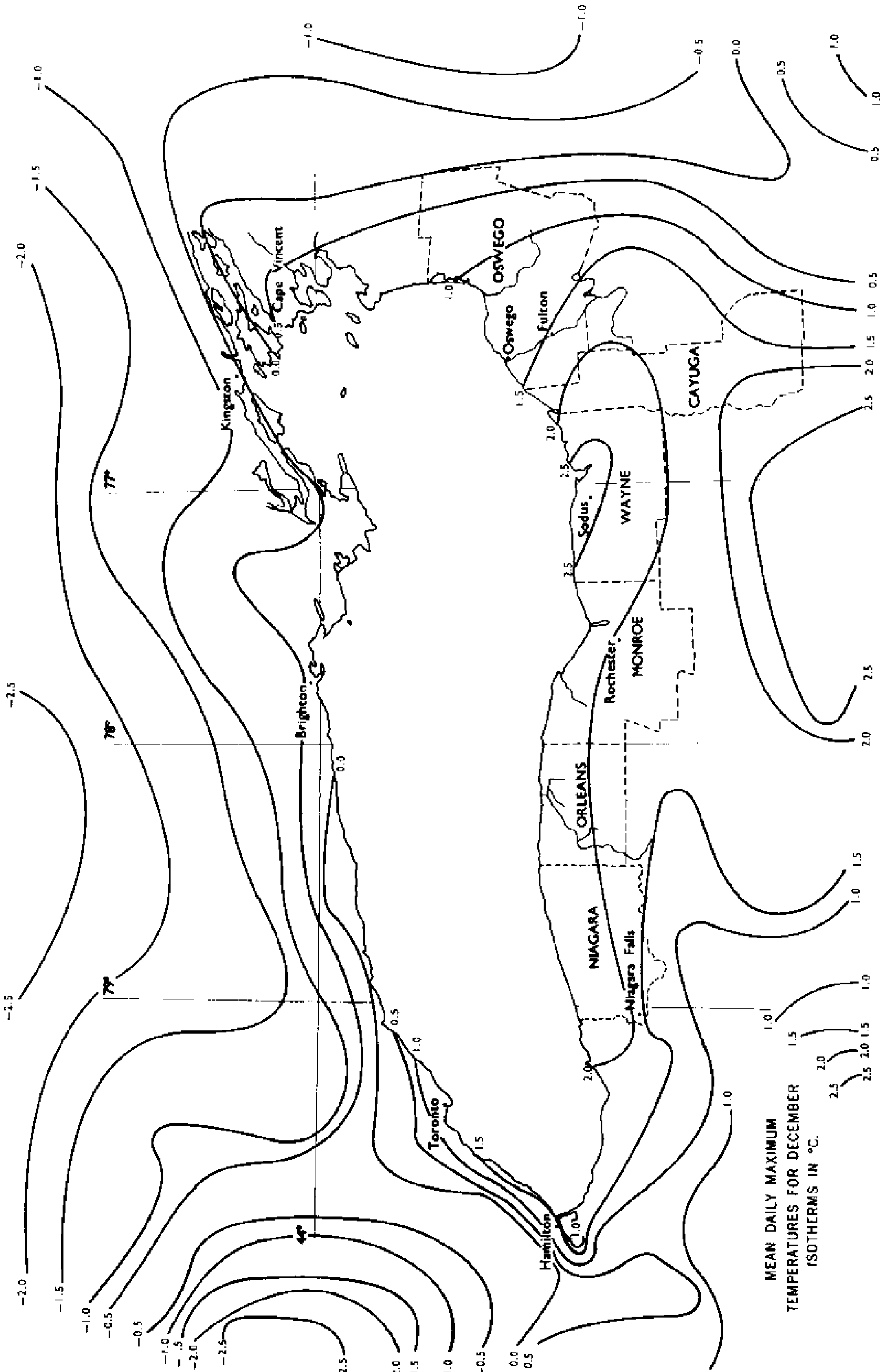
MEAN DAILY MAXIMUM TEMPERATURES FOR OCTOBER. ISOTHERMS IN °C.

Figure 25

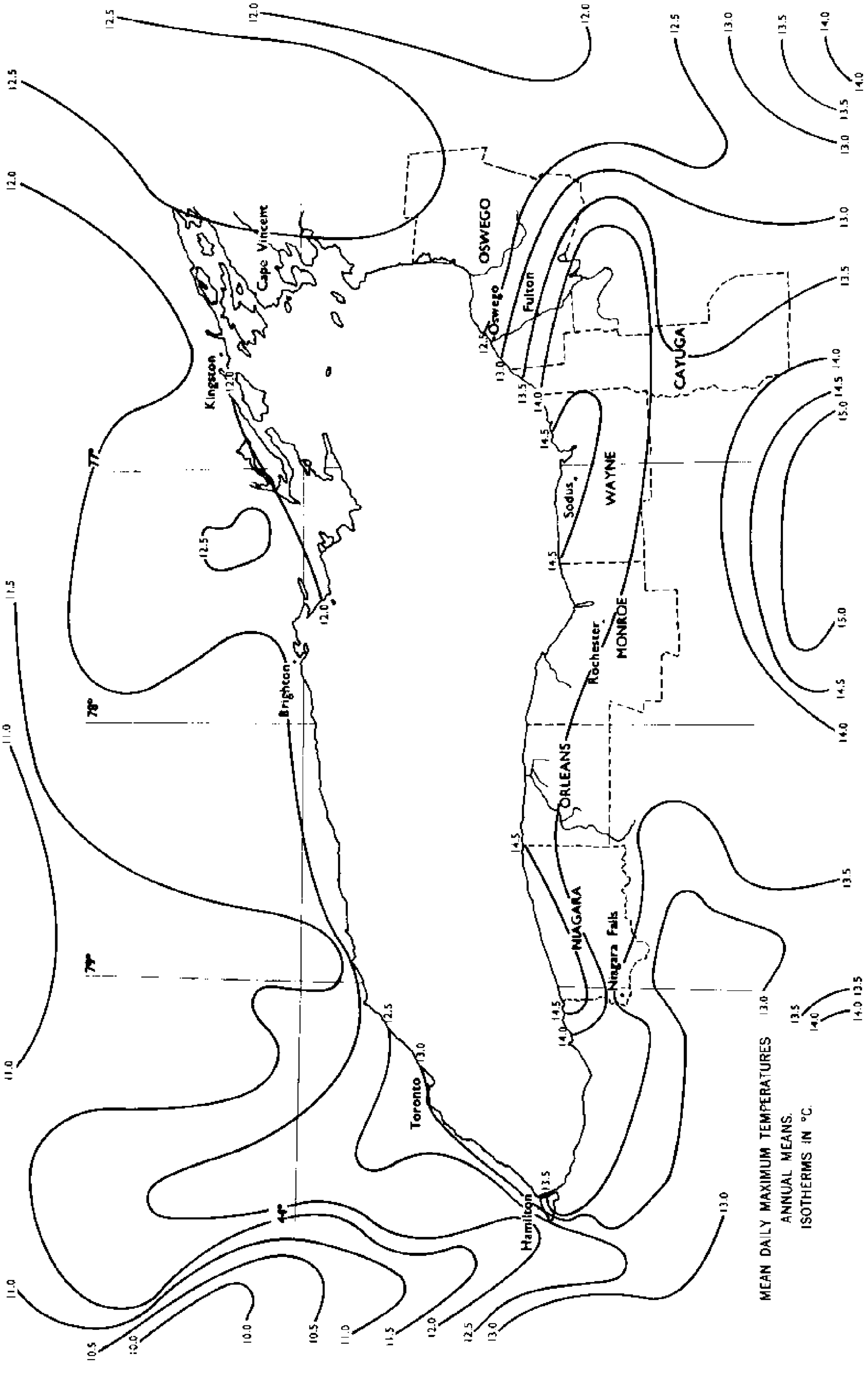


MEAN DAILY MAXIMUM TEMPERATURES FOR NOVEMBER ISOTHERMS IN °C.

Figure 26

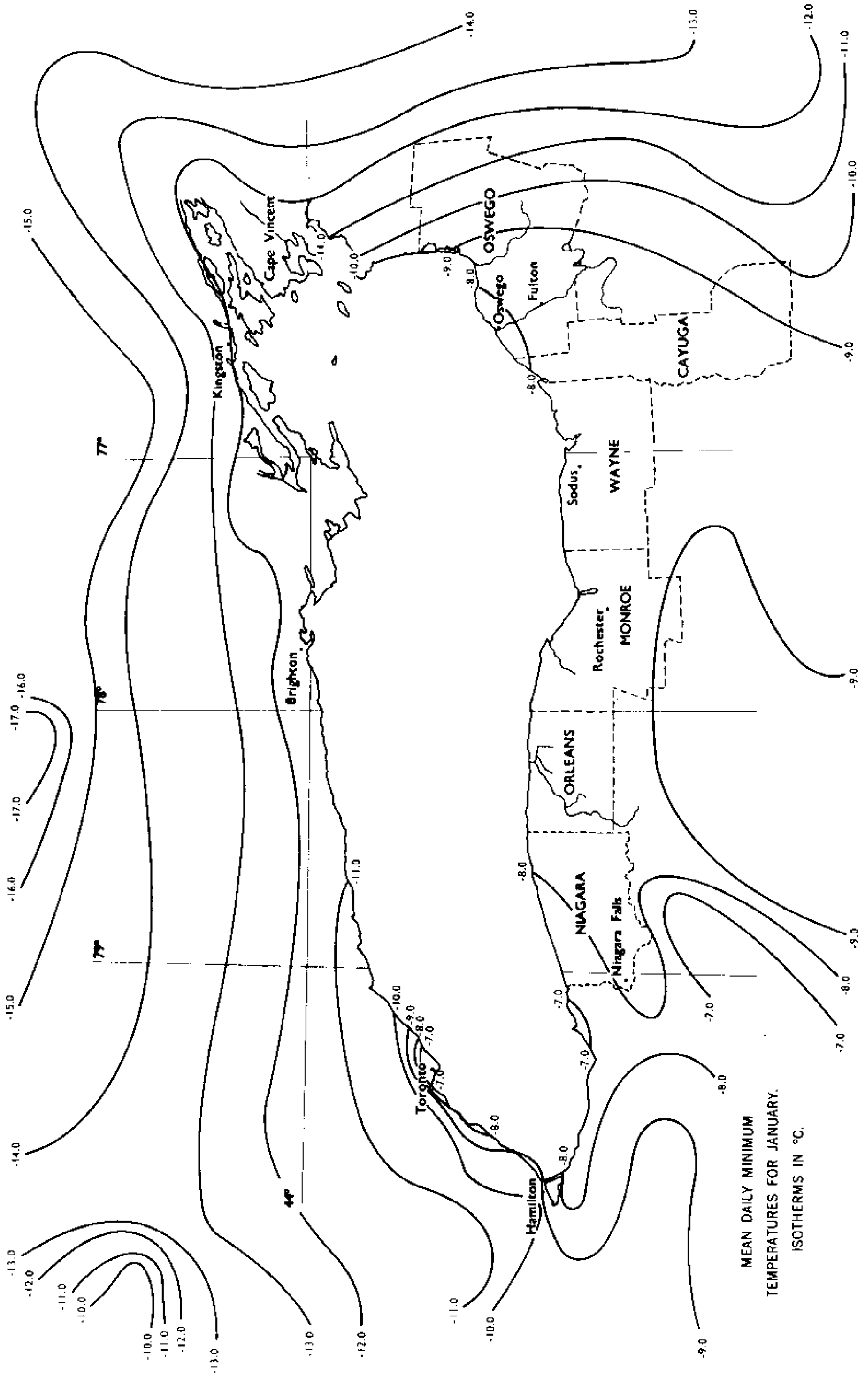


MEAN DAILY MAXIMUM TEMPERATURES FOR DECEMBER ISOTHERMS IN °C.



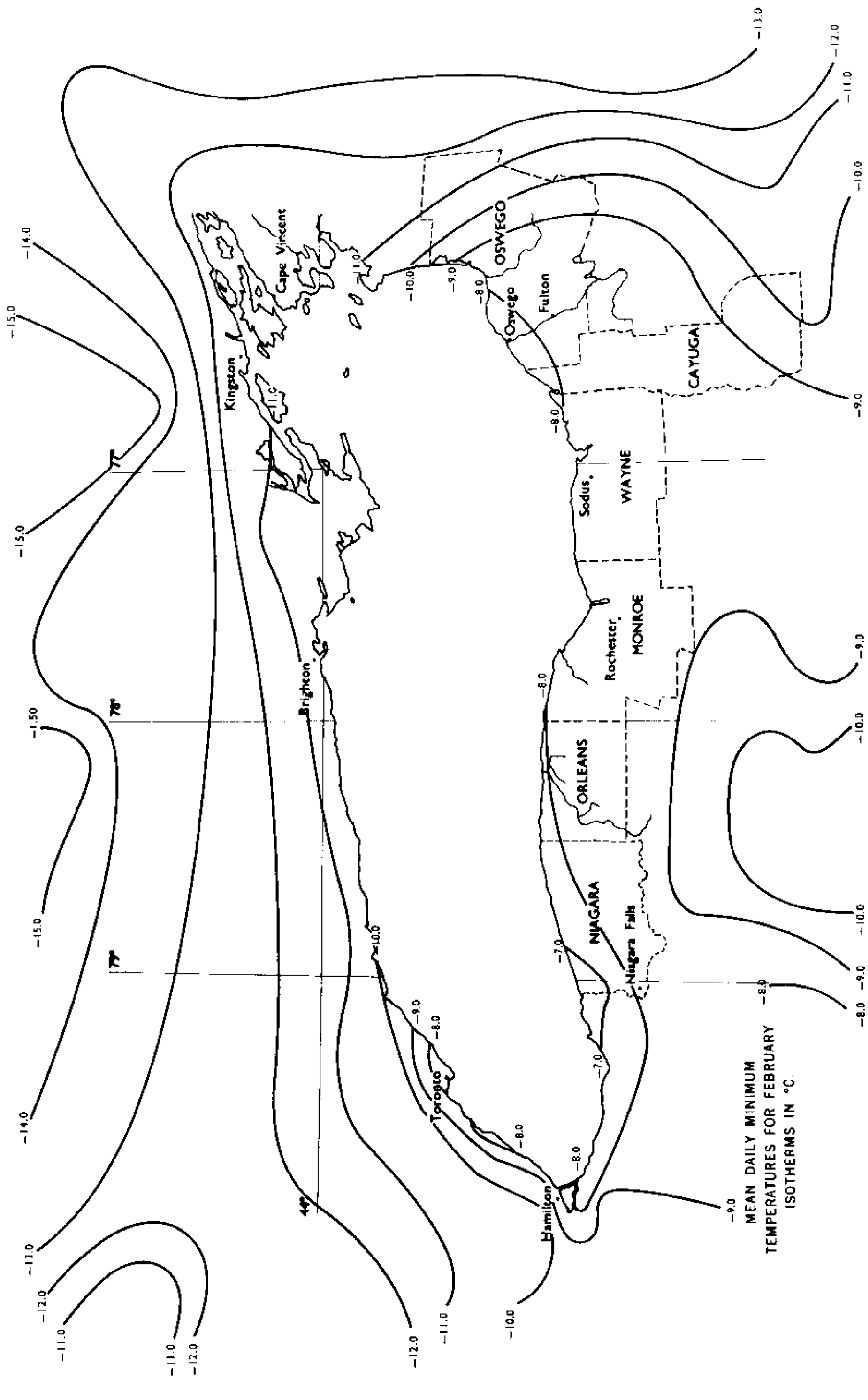
MEAN DAILY MAXIMUM TEMPERATURES
ANNUAL MEANS.
ISOTHERMS IN °C.

Figure 28



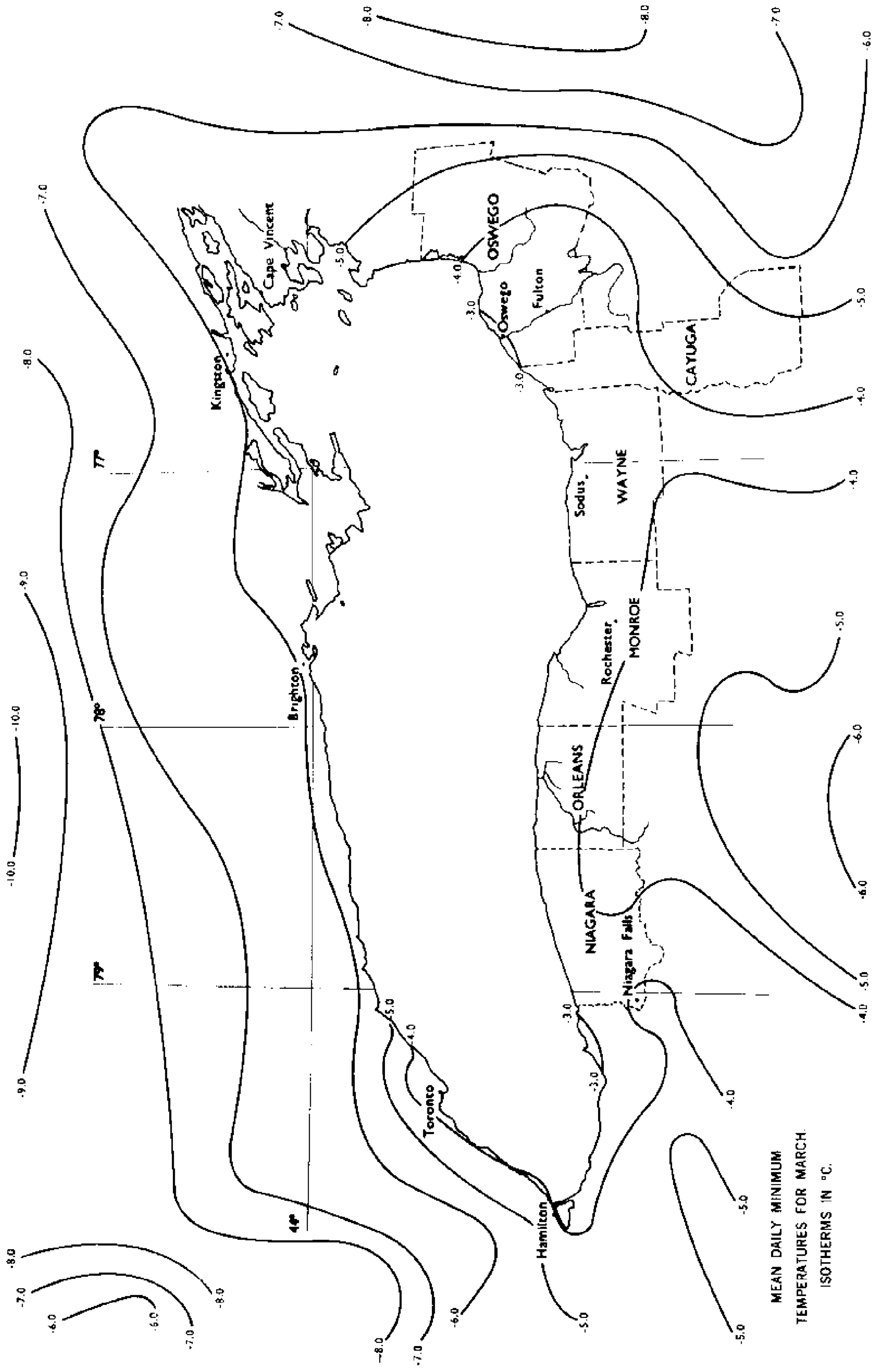
MEAN DAILY MINIMUM TEMPERATURES FOR JANUARY. ISOTHERMS IN °C.

Figure 29



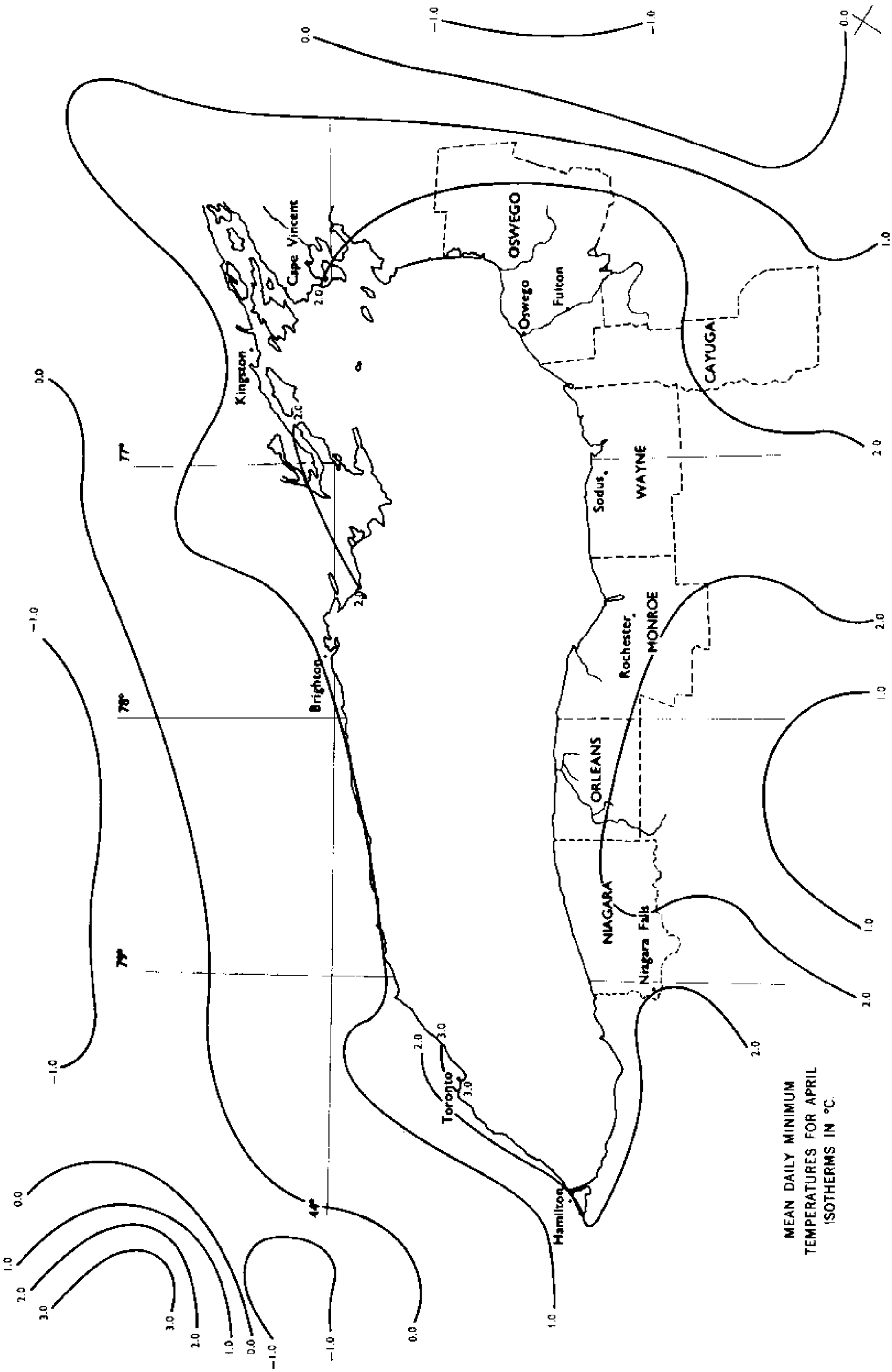
MEAN DAILY MINIMUM TEMPERATURES FOR FEBRUARY ISOTHERMS IN °C.

Figure 30



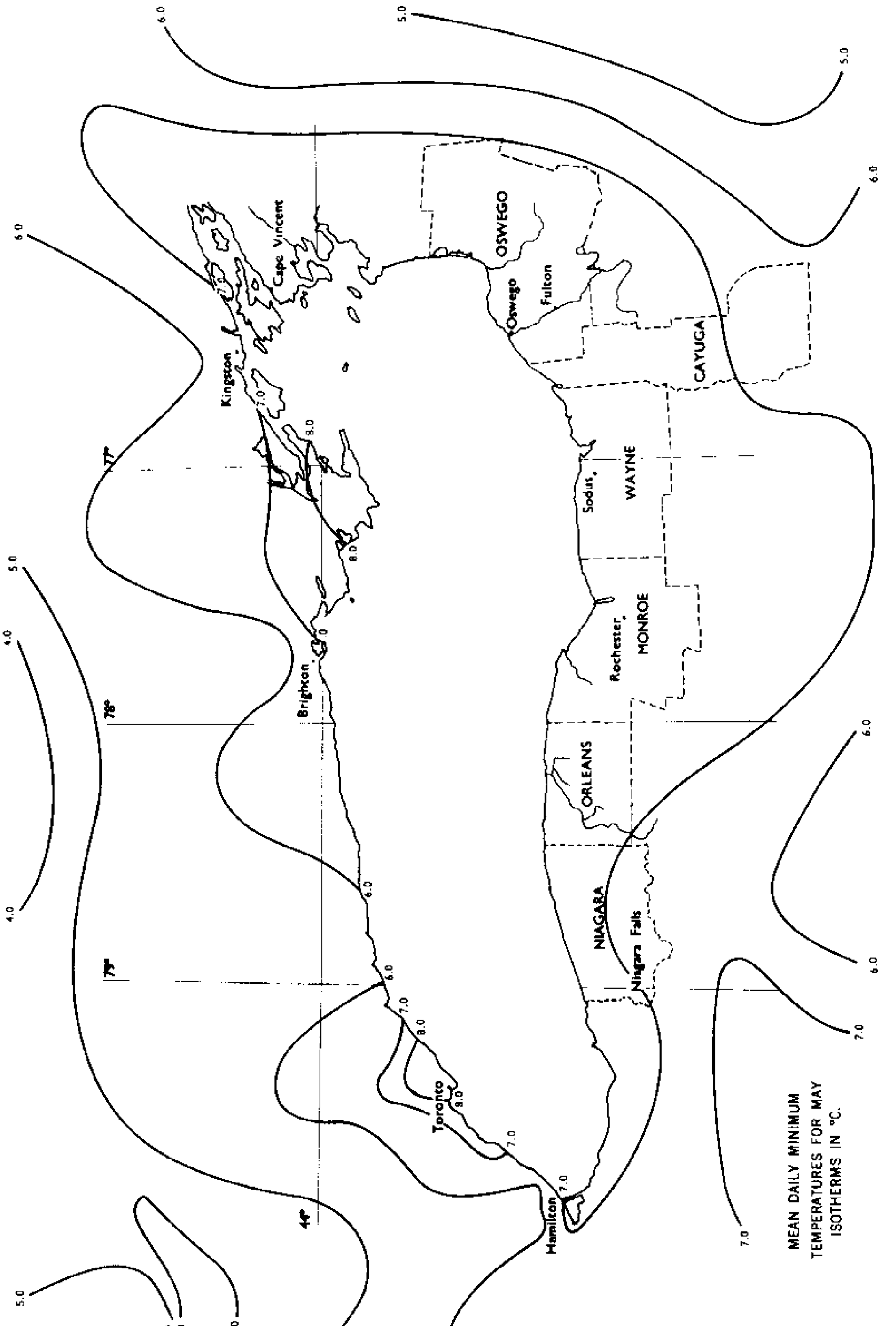
MEAN DAILY MINIMUM TEMPERATURES FOR MARCH. ISOTHERMS IN °C.

Figure 31



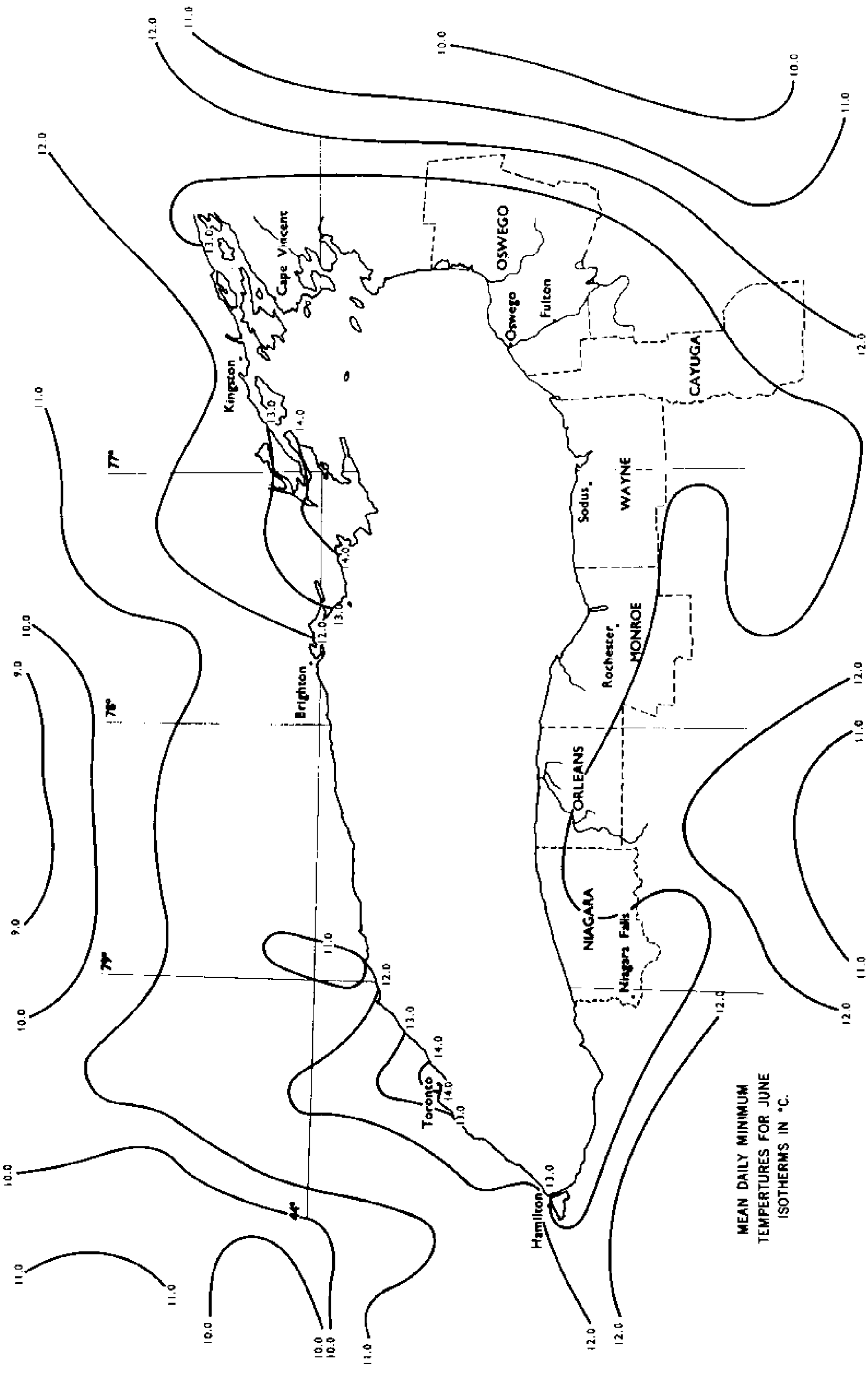
MEAN DAILY MINIMUM
TEMPERATURES FOR APRIL
ISOTHERMS IN °C

Figure 32



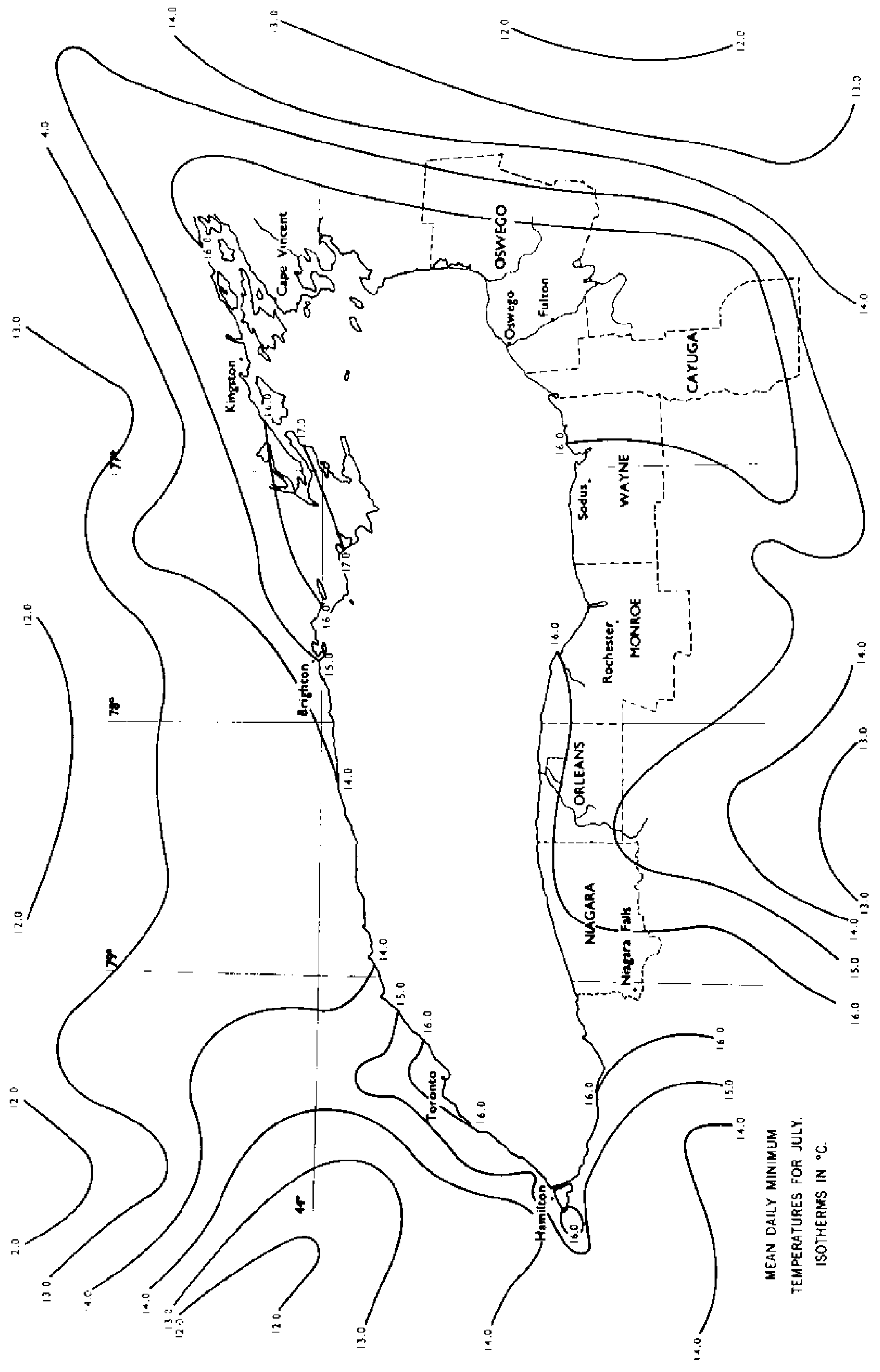
MEAN DAILY MINIMUM TEMPERATURES FOR MAY ISOTHERMS IN °C.

Figure 33



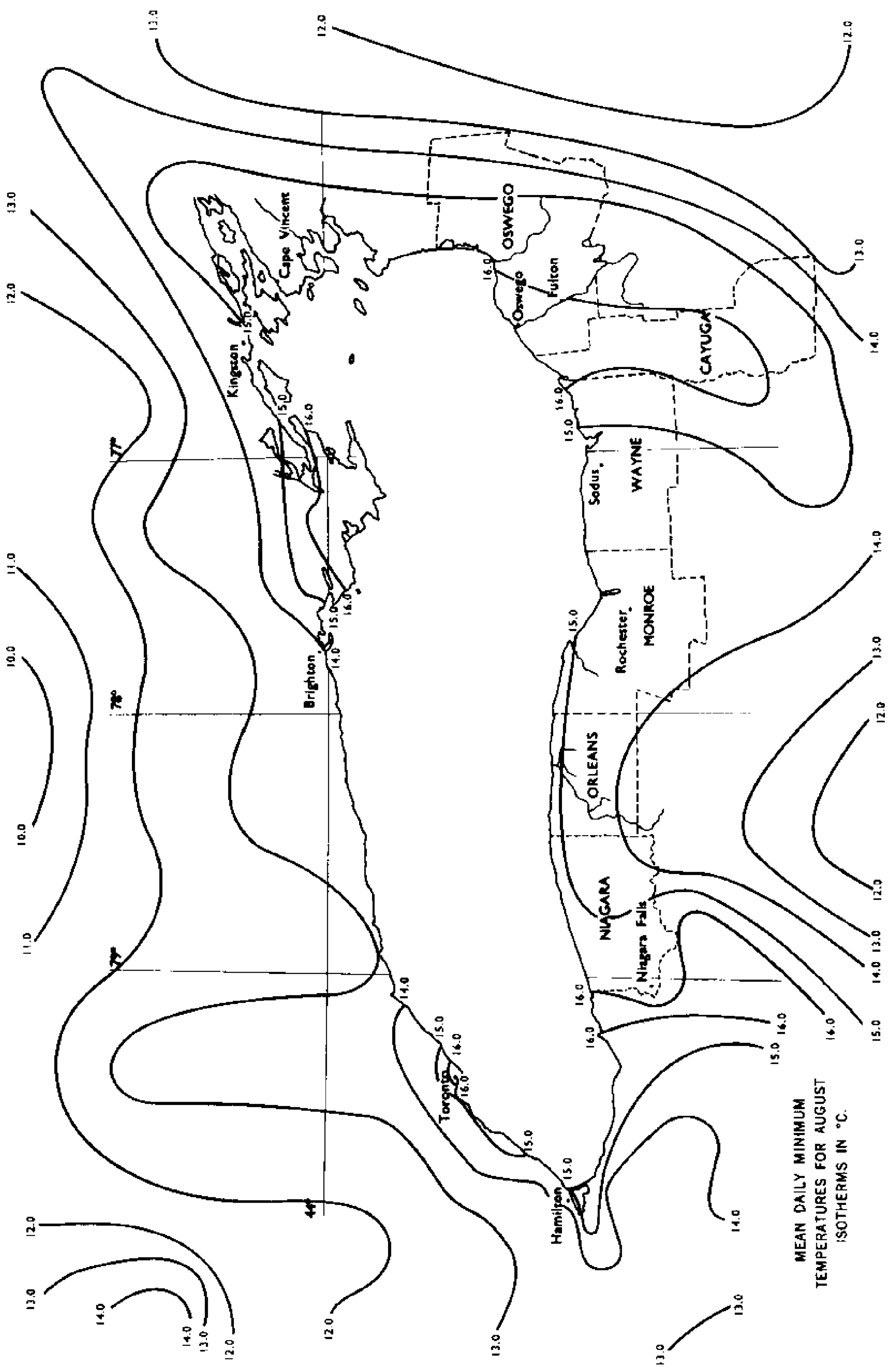
MEAN DAILY MINIMUM TEMPERTURES FOR JUNE ISOTHERMS IN °C.

Figure 34



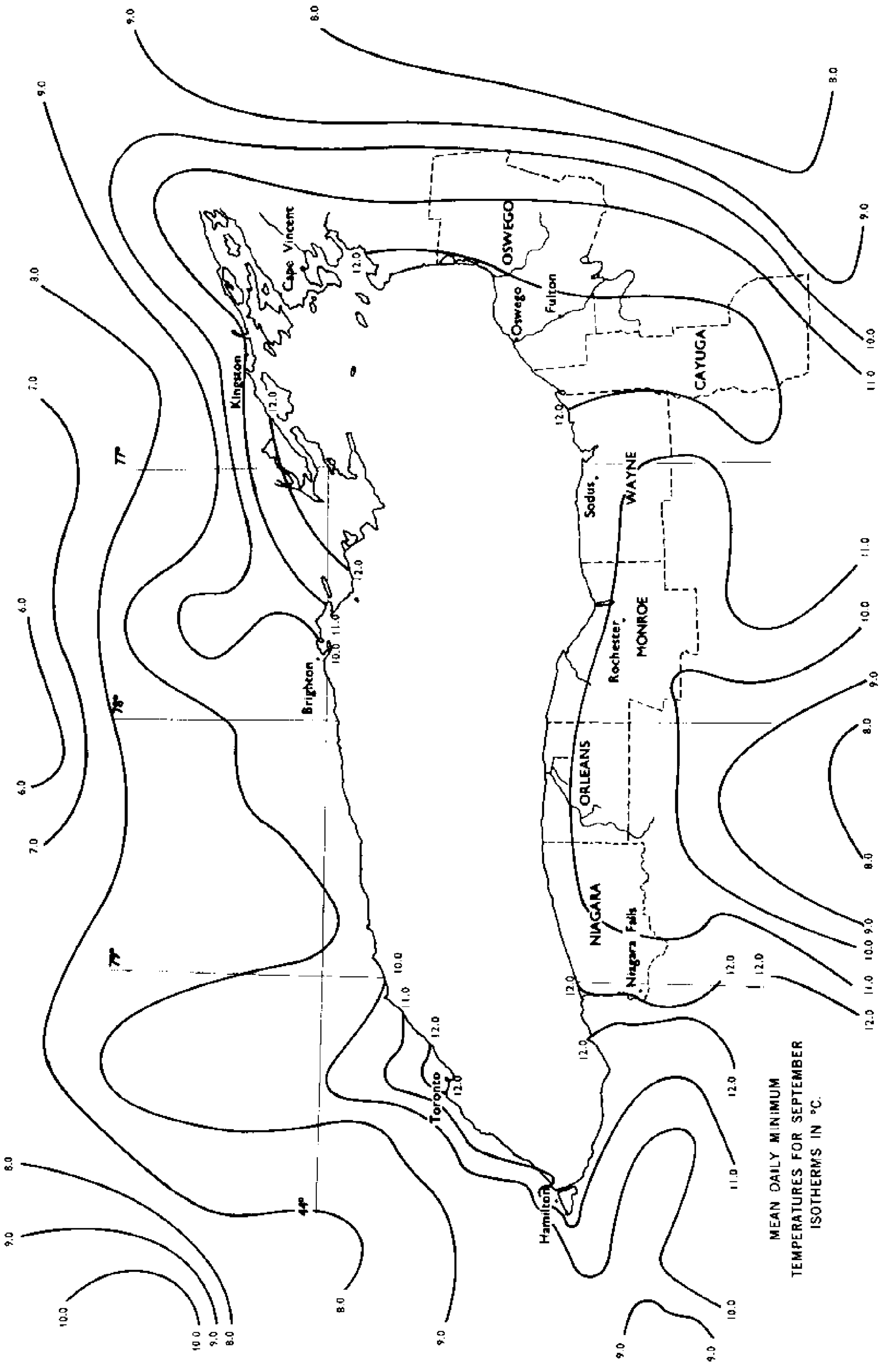
MEAN DAILY MINIMUM TEMPERATURES FOR JULY. ISOTHERMS IN °C.

Figure 35



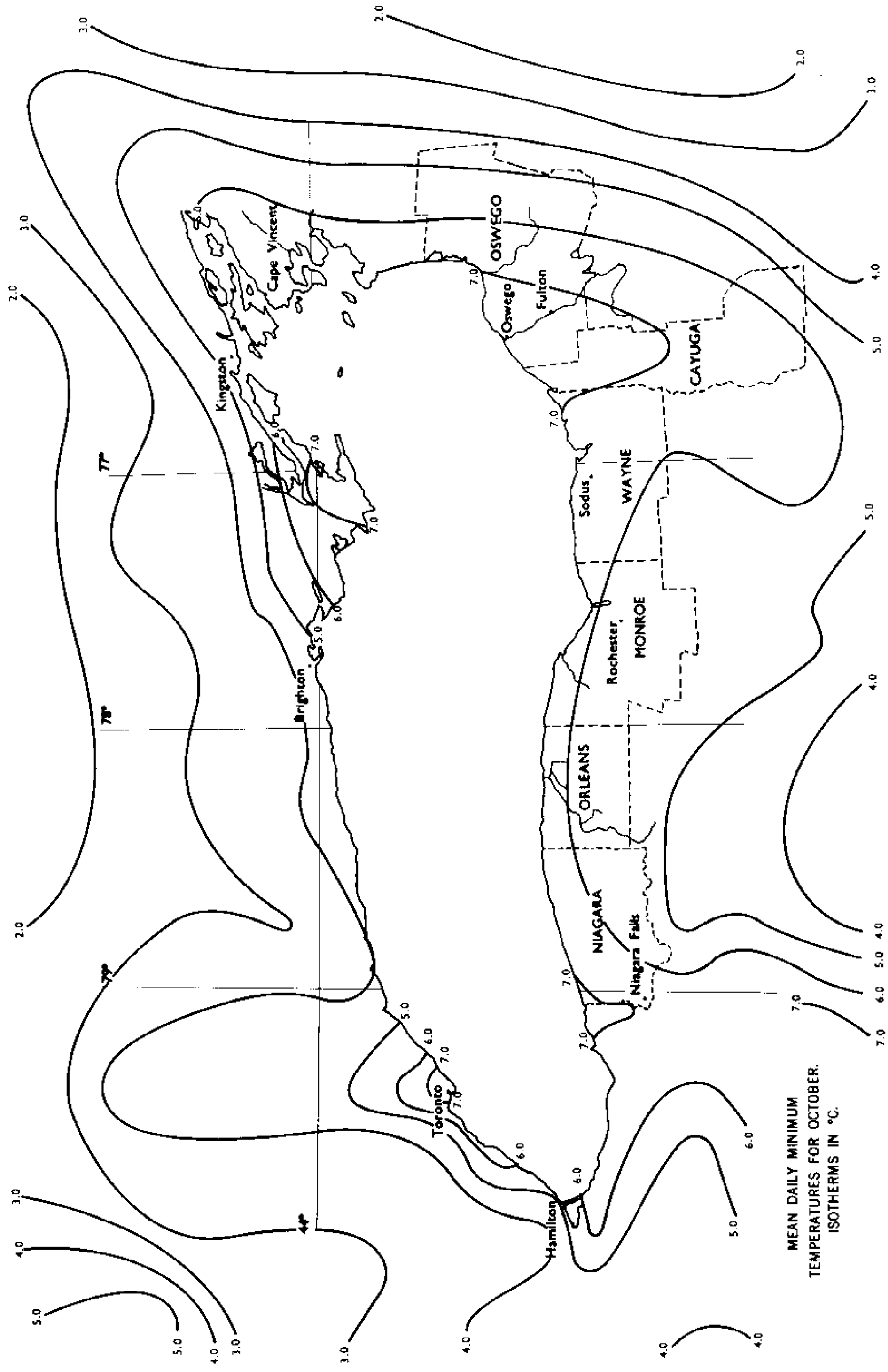
MEAN DAILY MINIMUM TEMPERATURES FOR AUGUST ISOTHERMS IN °C.

Figure 36

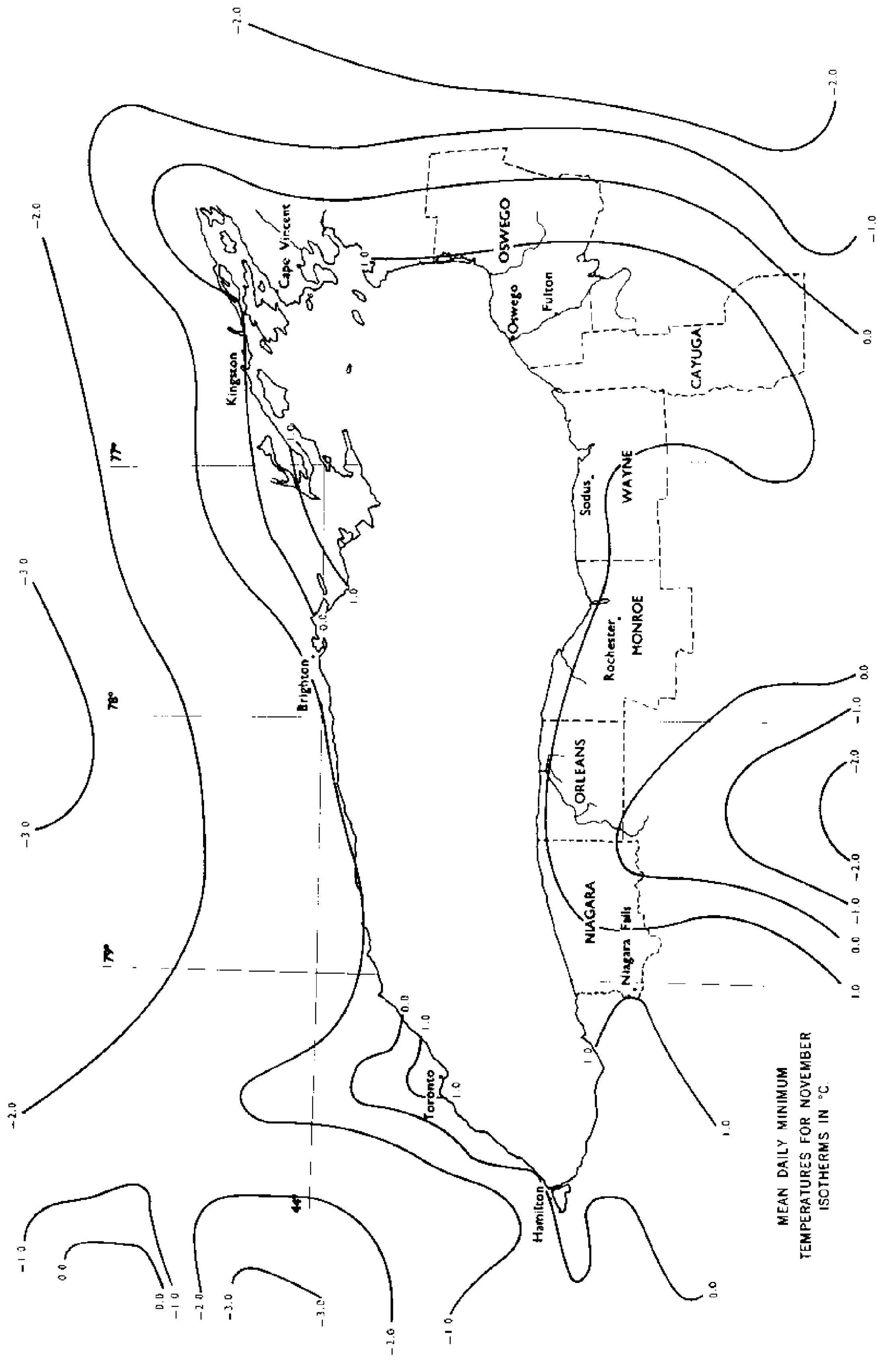


MEAN DAILY MINIMUM
TEMPERATURES FOR SEPTEMBER
ISOTHERMS IN °C.

Figure 37

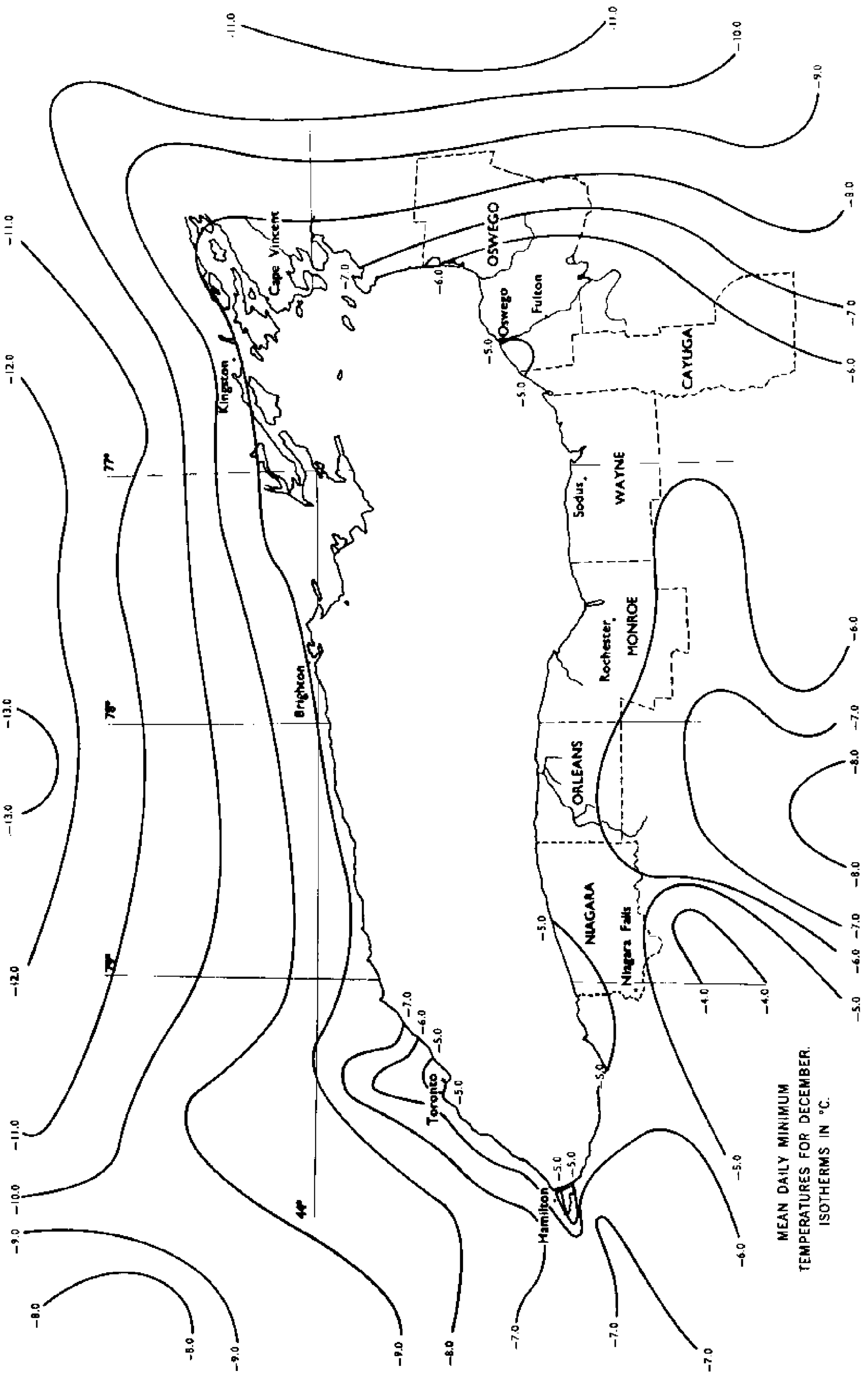


MEAN DAILY MINIMUM TEMPERATURES FOR OCTOBER. ISOTHERMS IN °C.



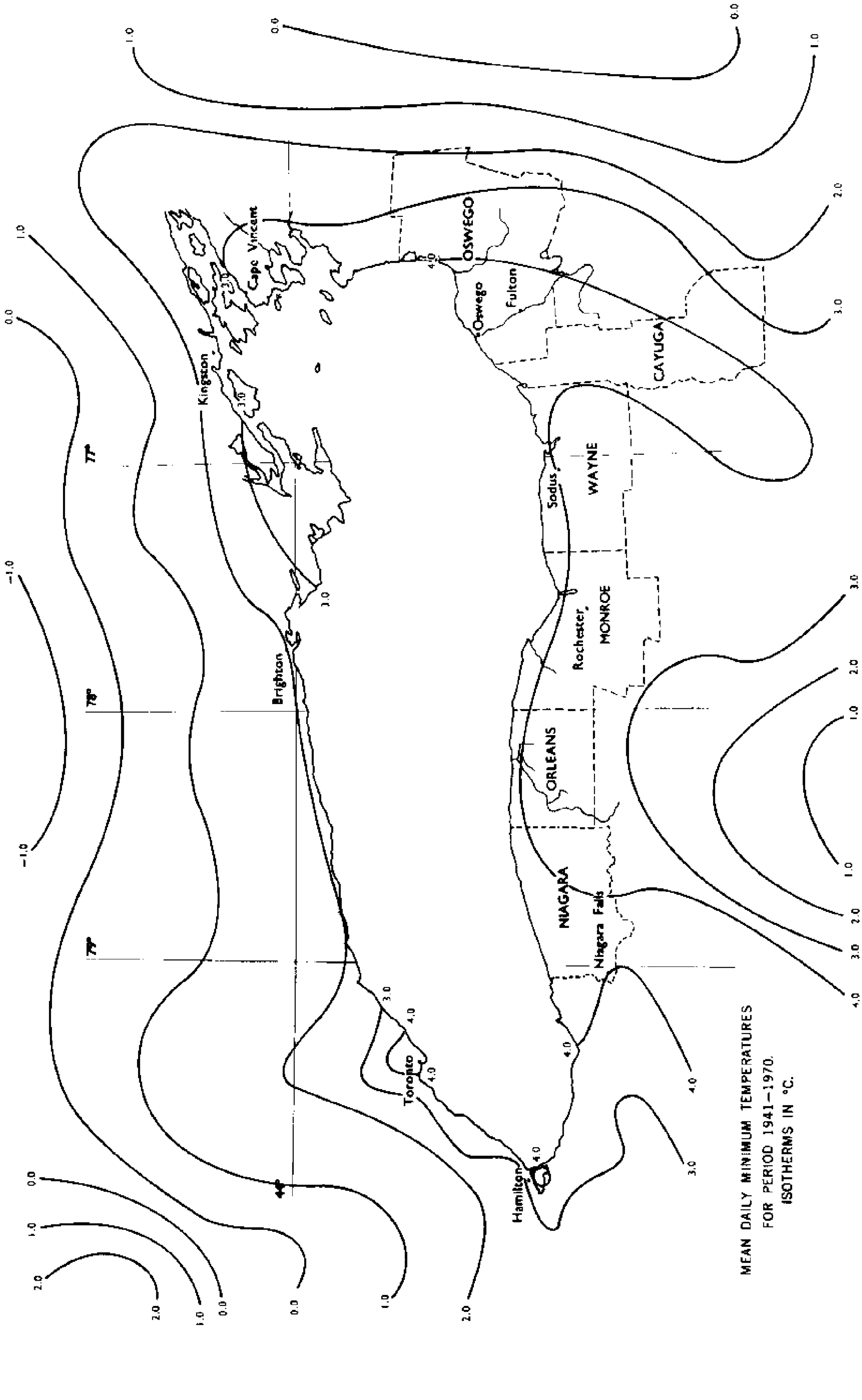
MEAN DAILY MINIMUM
TEMPERATURES FOR NOVEMBER
ISOTHERMS IN °C.

Figure 39



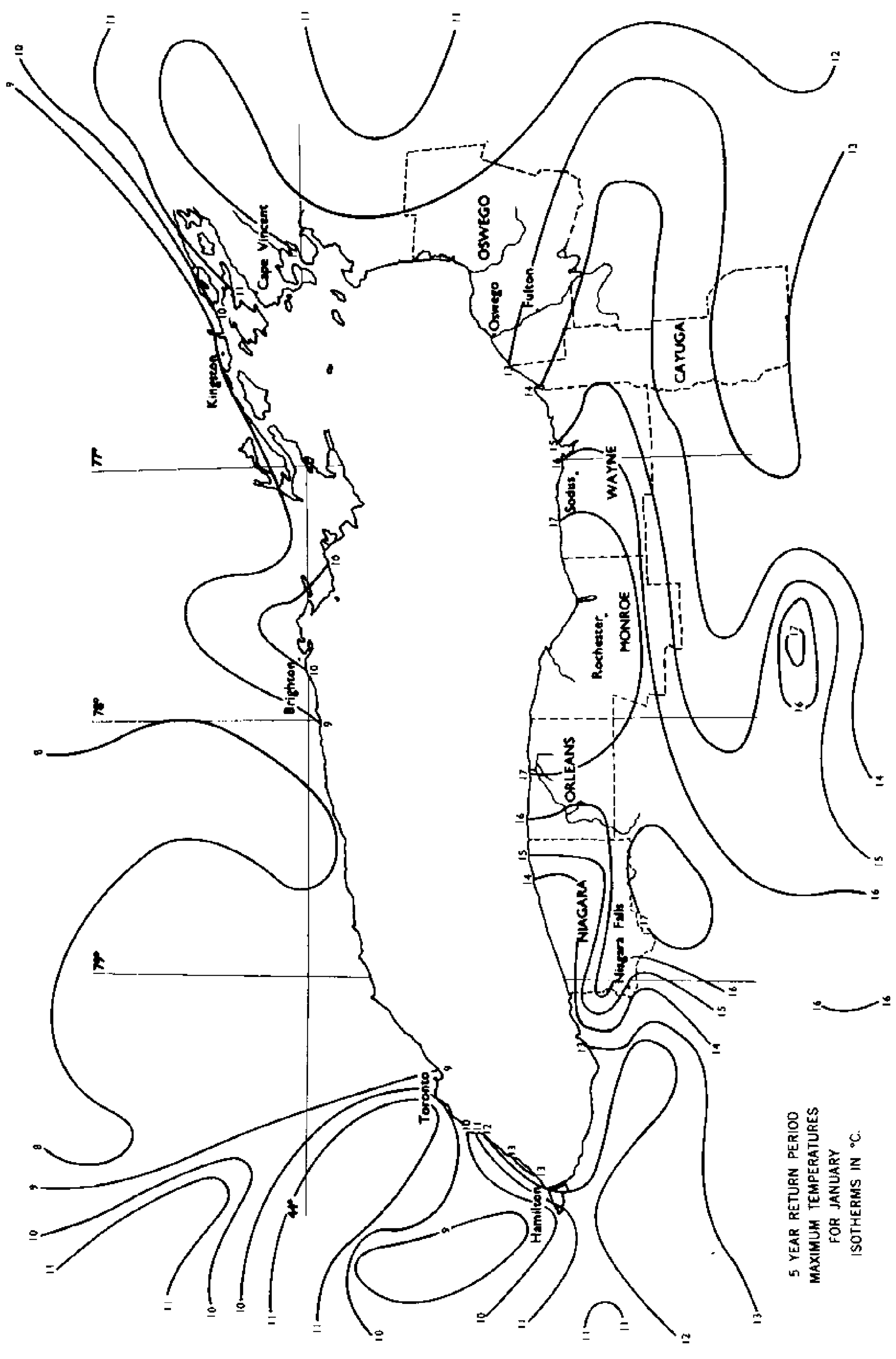
MEAN DAILY MINIMUM
TEMPERATURES FOR DECEMBER.
ISOTHERMS IN °C.

Figure 40



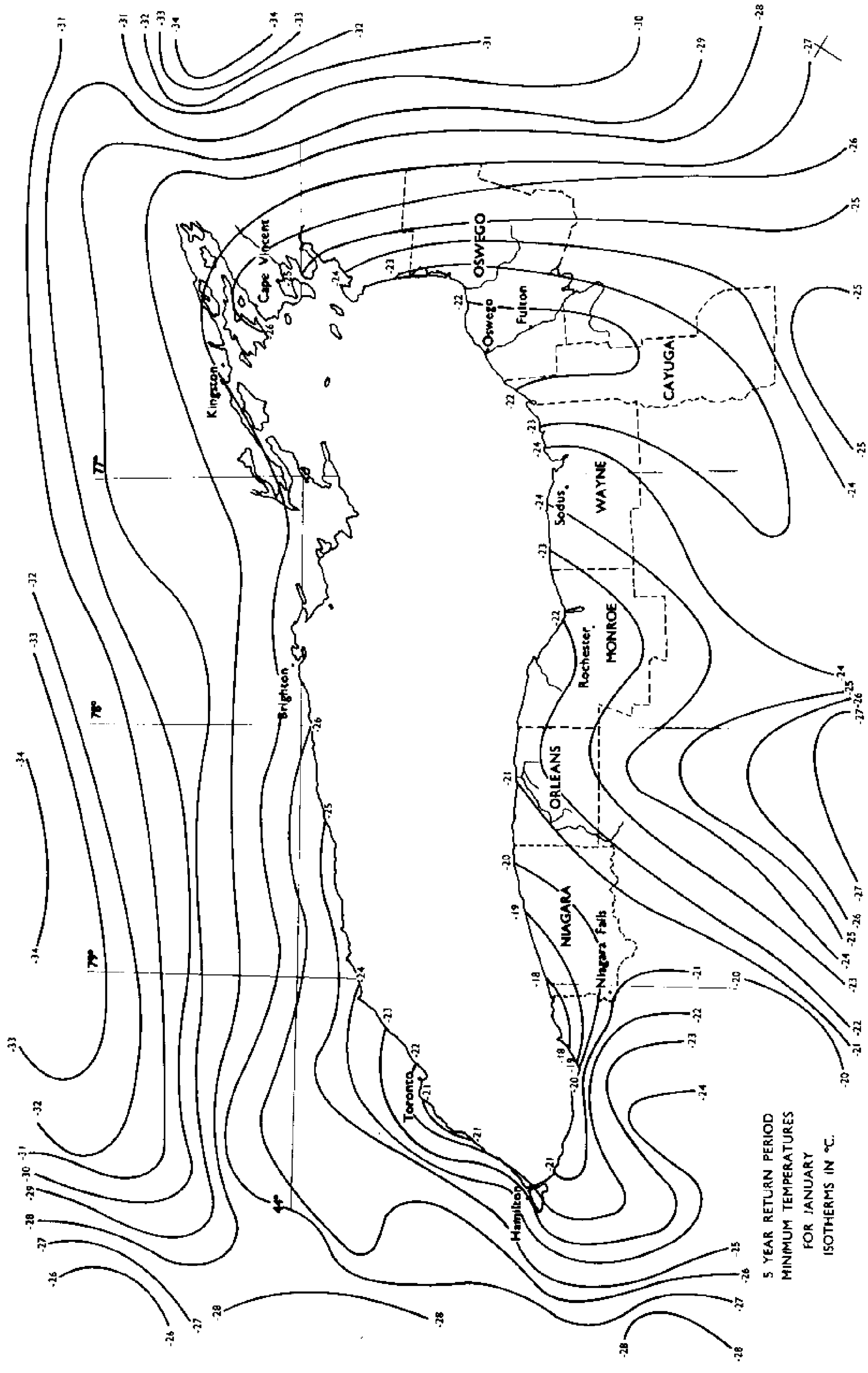
MEAN DAILY MINIMUM TEMPERATURES
FOR PERIOD 1941–1970.
ISOTHERMS IN °C.

Figure 41



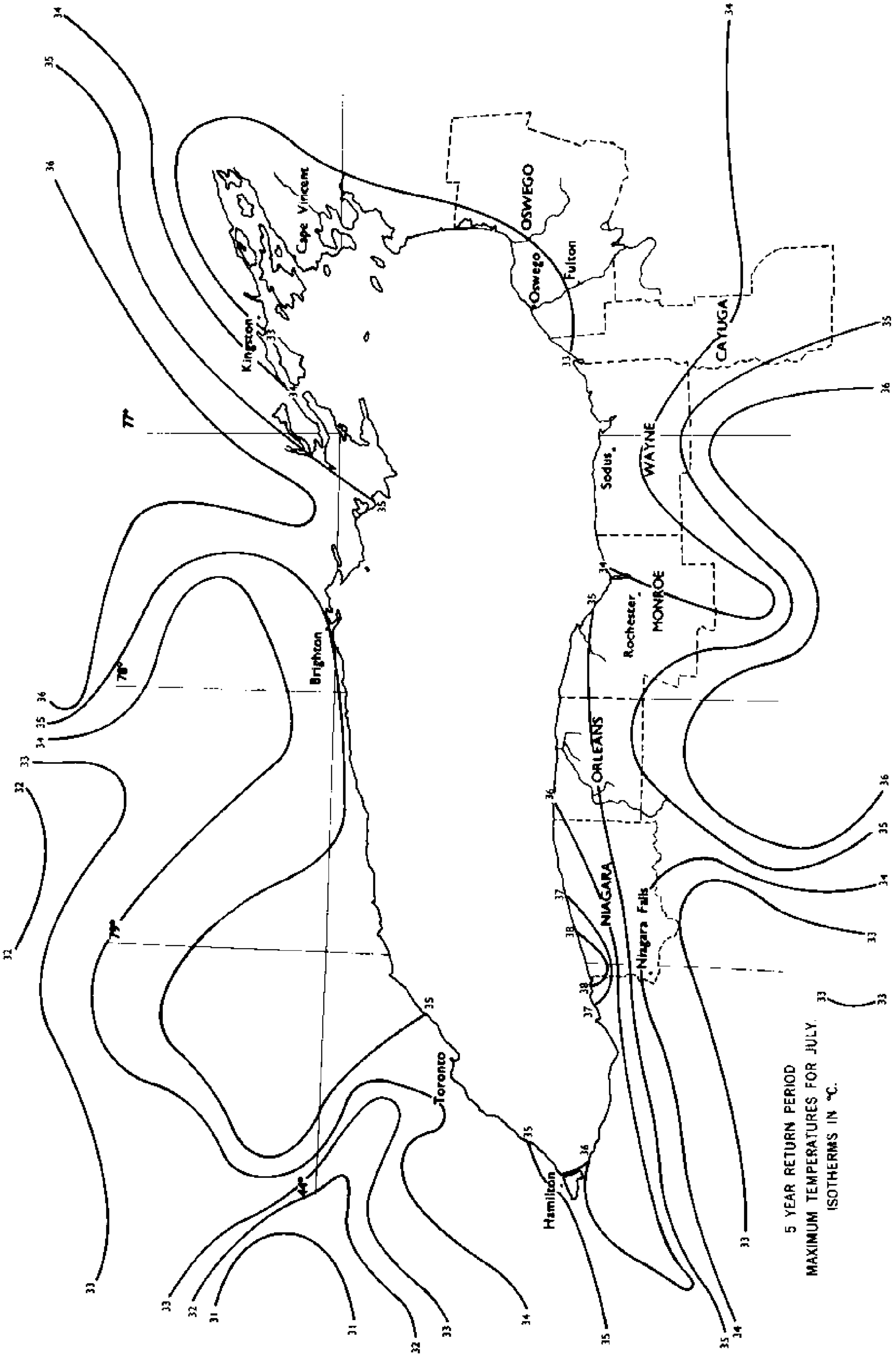
5 YEAR RETURN PERIOD
MAXIMUM TEMPERATURES
FOR JANUARY
ISOTHERMS IN °C.

Figure 42



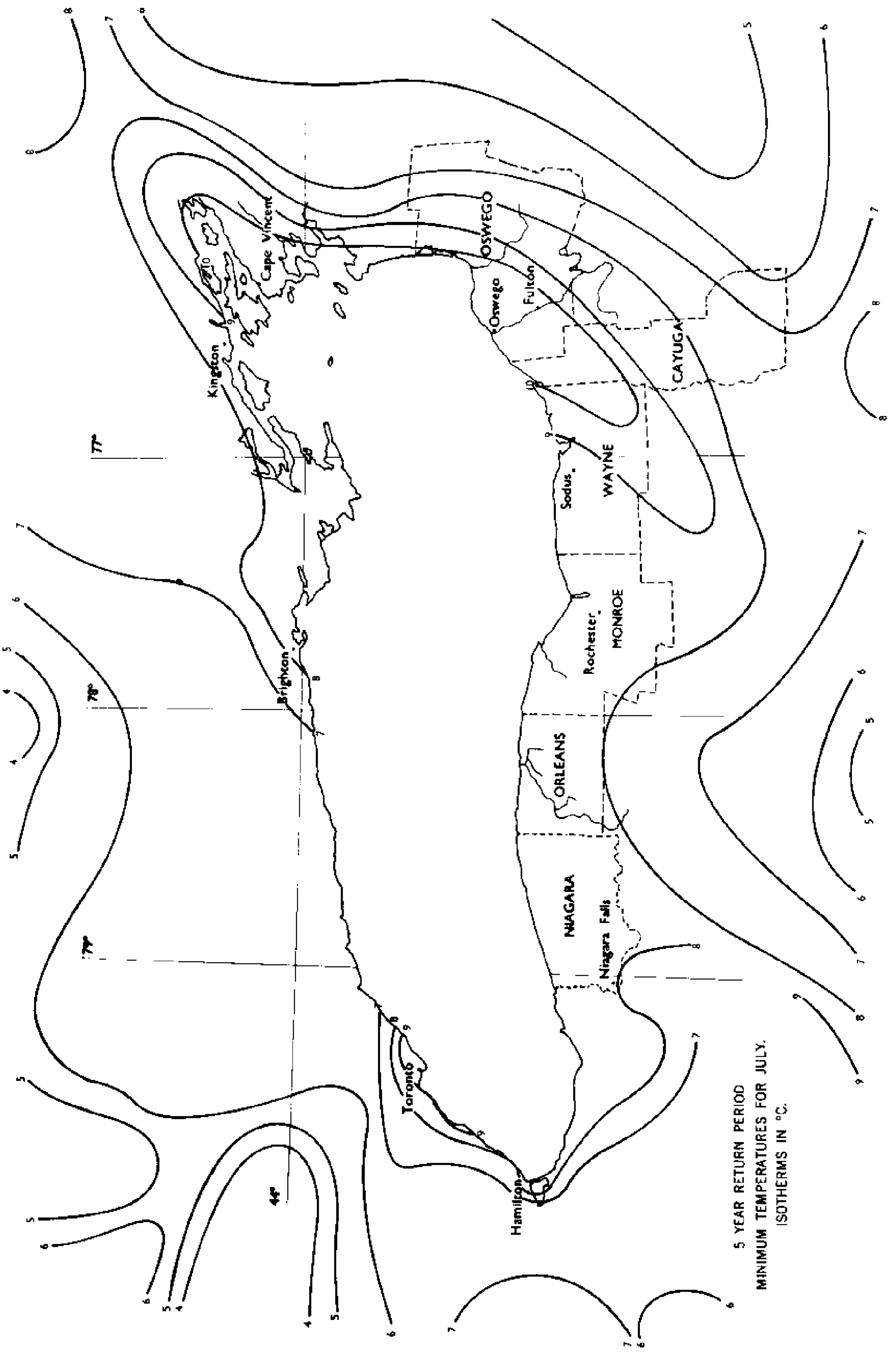
OSWEGO
Cape Vincent
Kingston
Oswego
Fulton
CAYUGA
WAYNE
Sodus
MONROE
Rochester
Brighton
ORLEANS
NIAGARA
Niagara Falls
Toronto
Hamilton
5 YEAR RETURN PERIOD
MINIMUM TEMPERATURES
FOR JANUARY
ISOTHERMS IN °C.

Figure 43



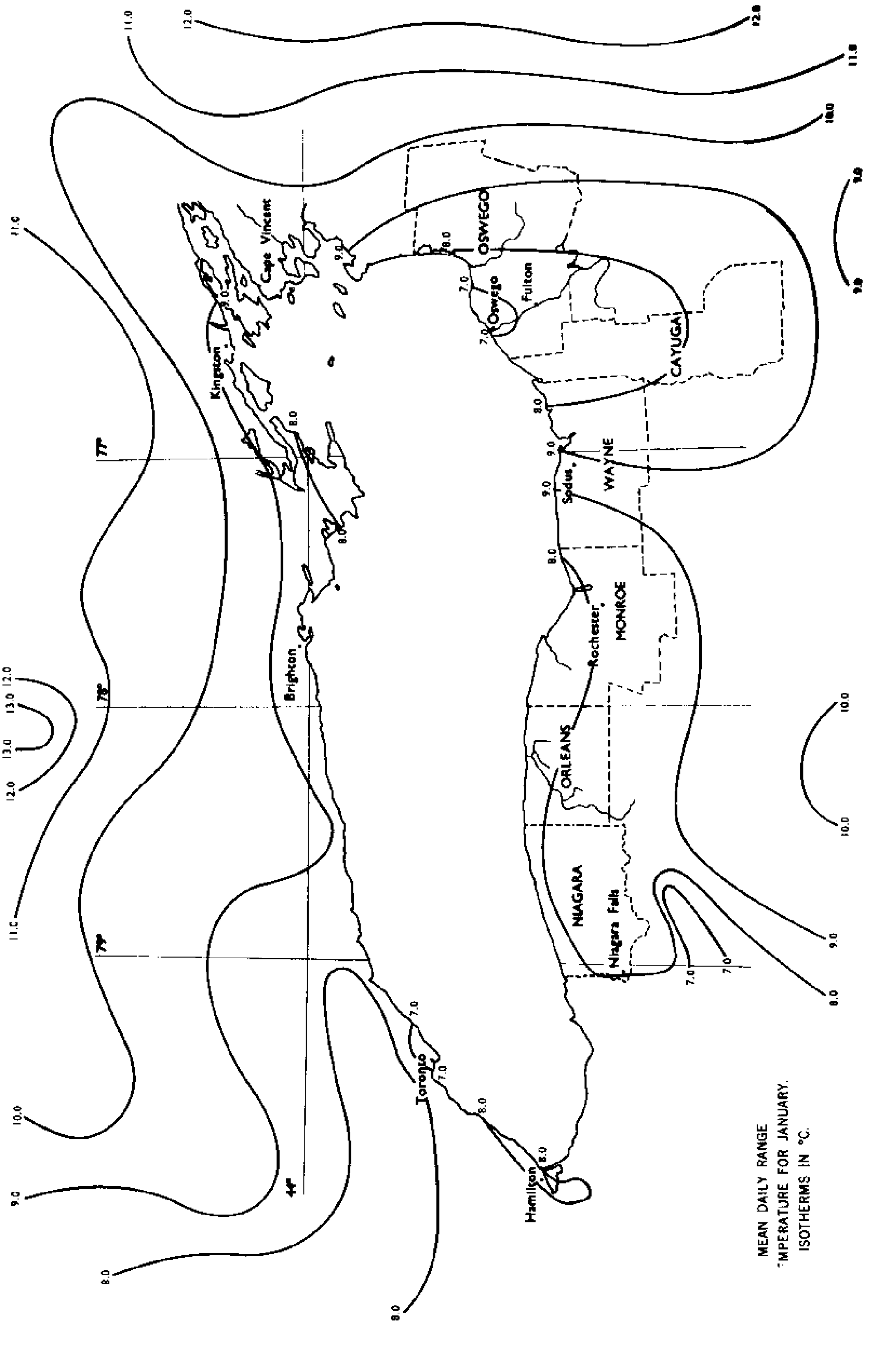
5 YEAR RETURN PERIOD
MAXIMUM TEMPERATURES FOR JULY.
ISOTHERMS IN °C.

Figure 44



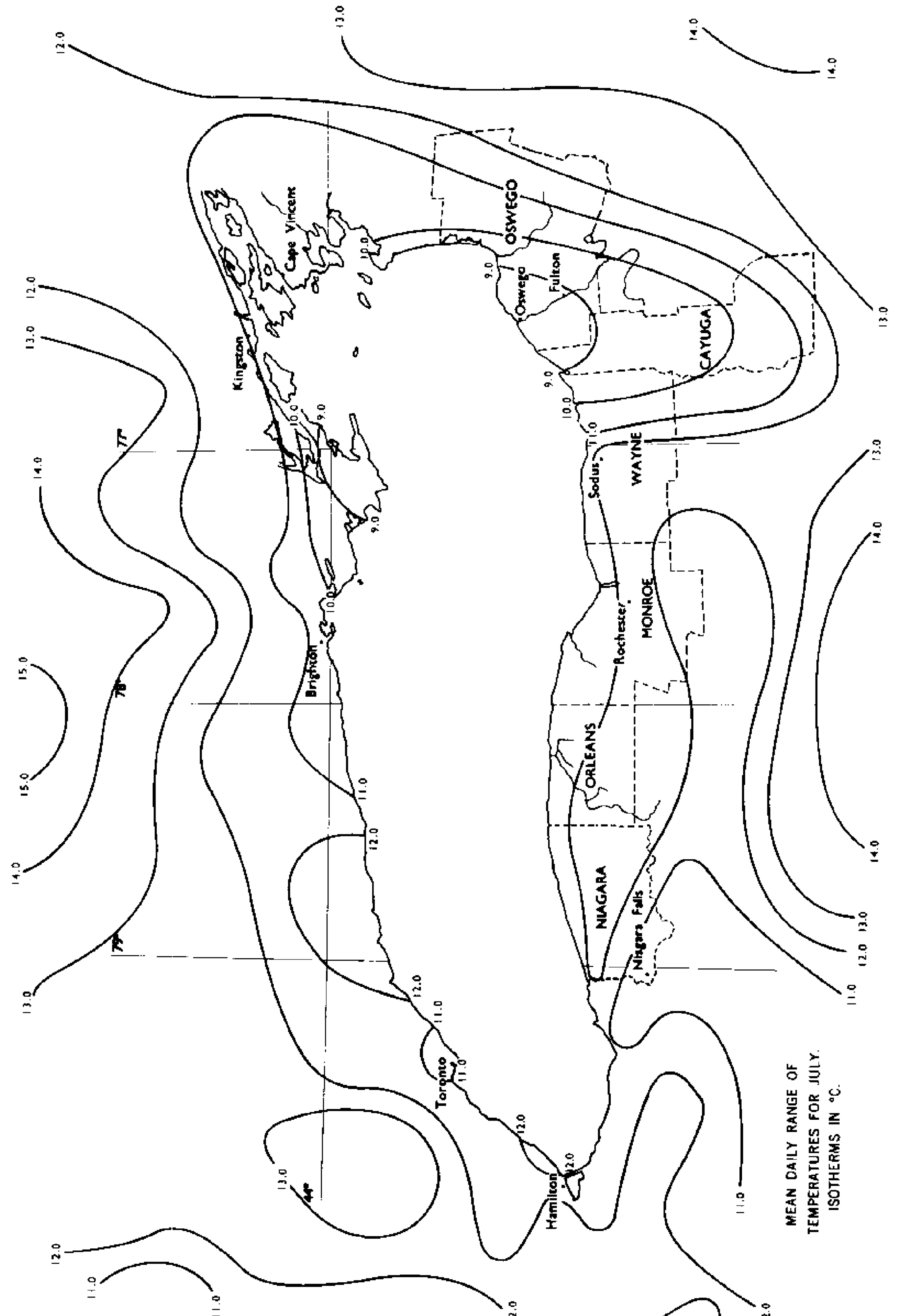
5 YEAR RETURN PERIOD
MINIMUM TEMPERATURES FOR JULY.
ISOTHERMS IN °C.

Figure 45



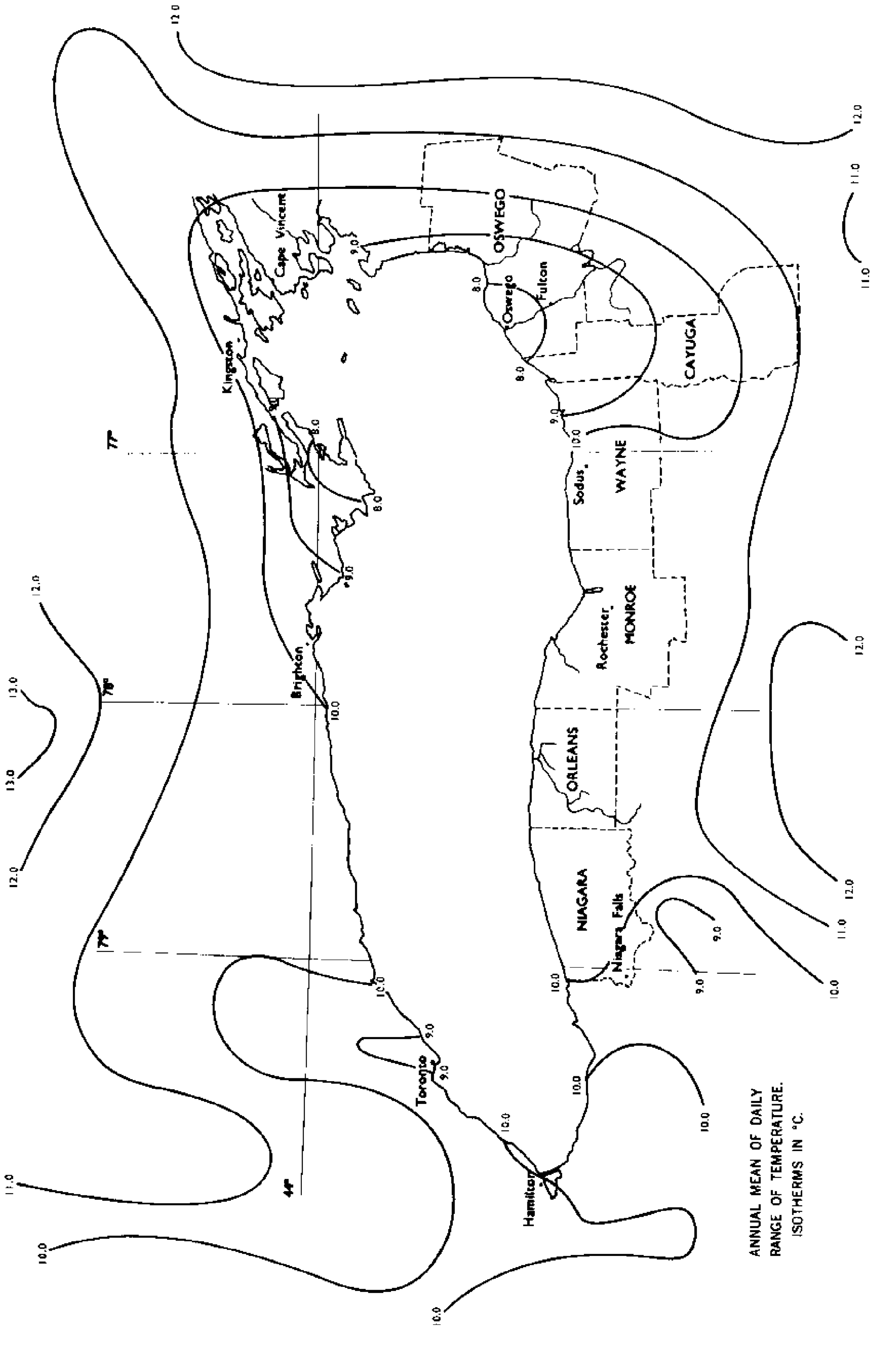
MEAN DAILY RANGE
TEMPERATURE FOR JANUARY.
ISOTHERMS IN °C.

Figure 46



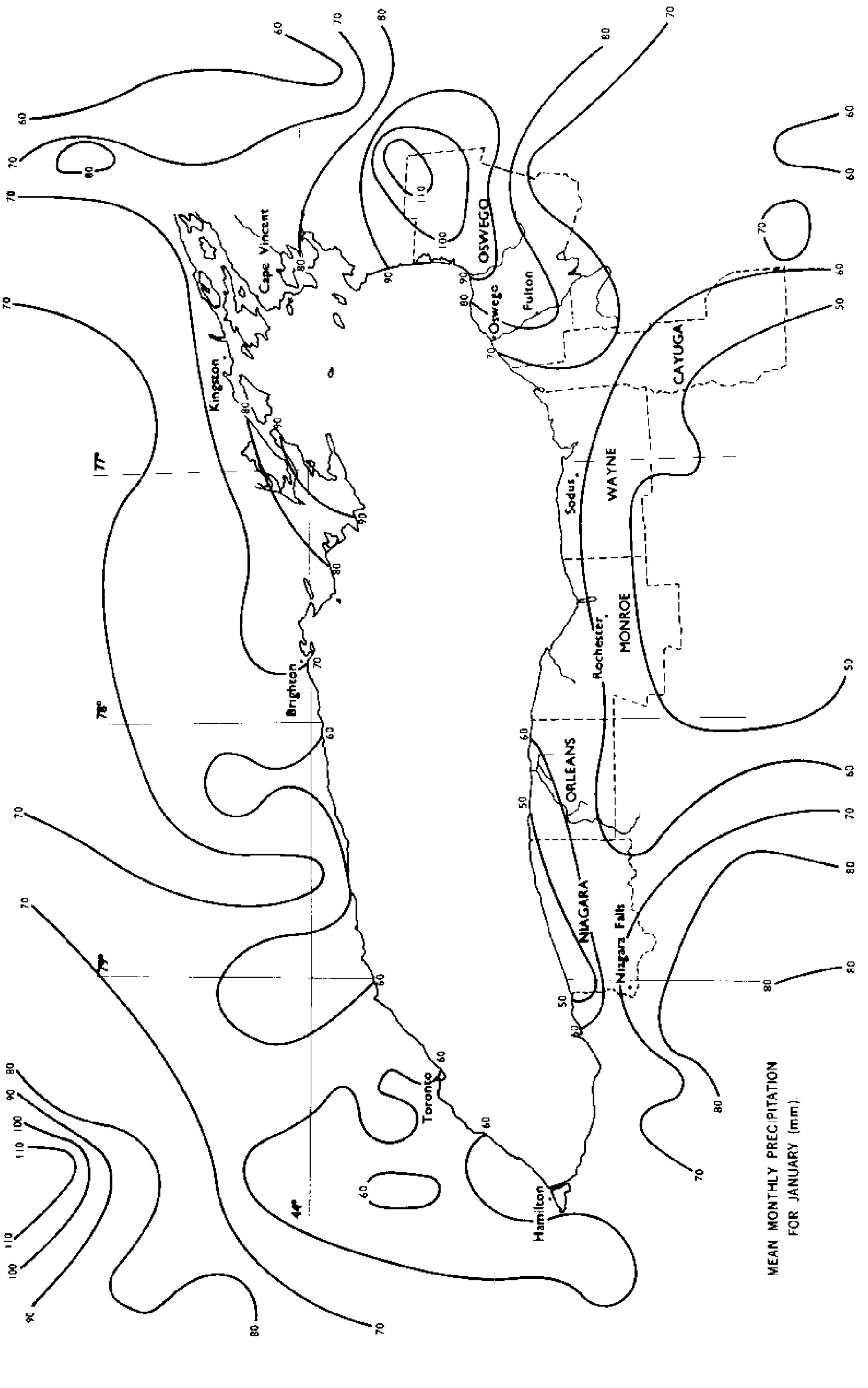
MEAN DAILY RANGE OF TEMPERATURES FOR JULY. ISOTHERMS IN °C.

Figure 47



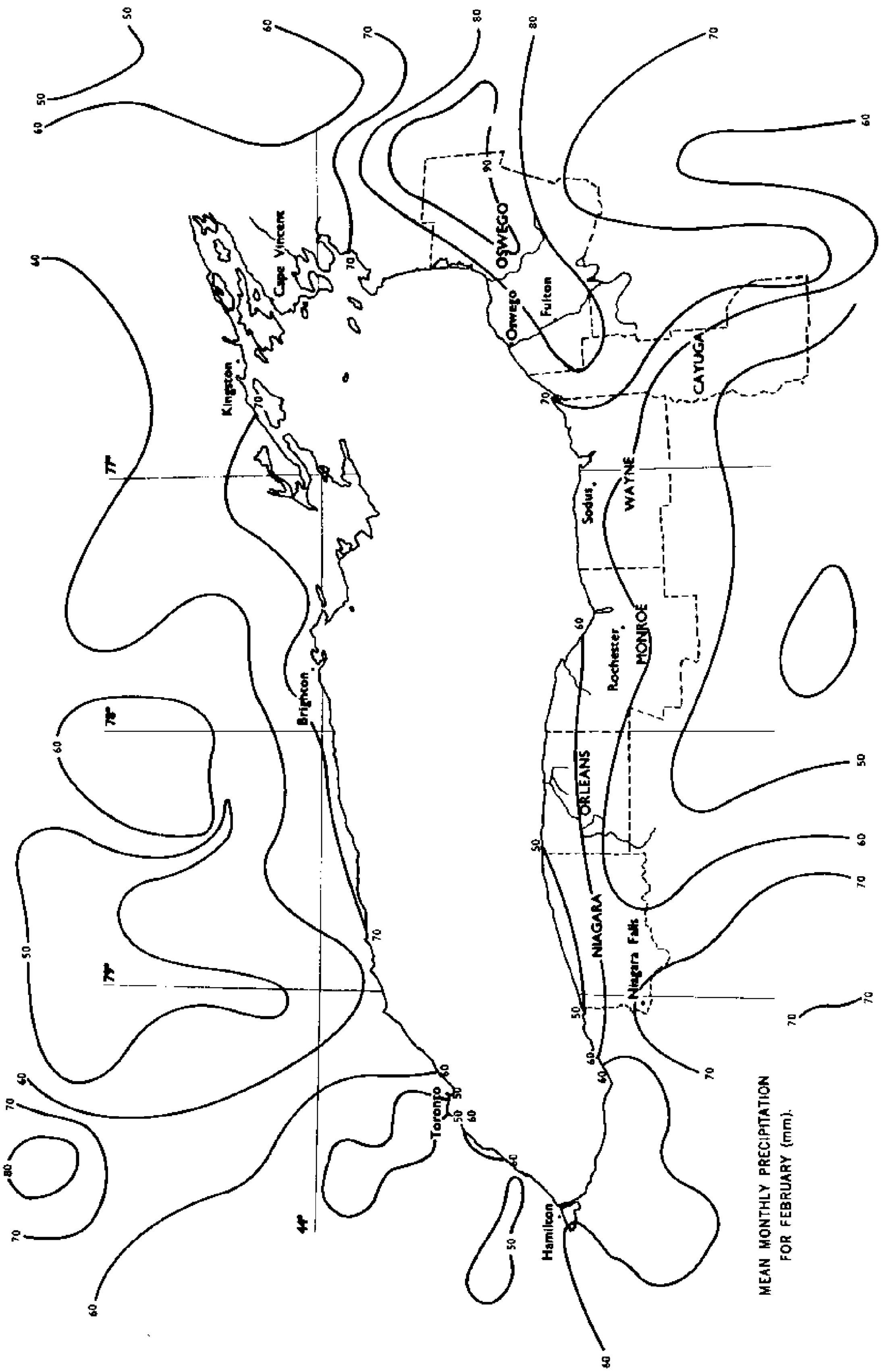
ANNUAL MEAN OF DAILY
RANGE OF TEMPERATURE.
ISOTHERMS IN °C.

Figure 48



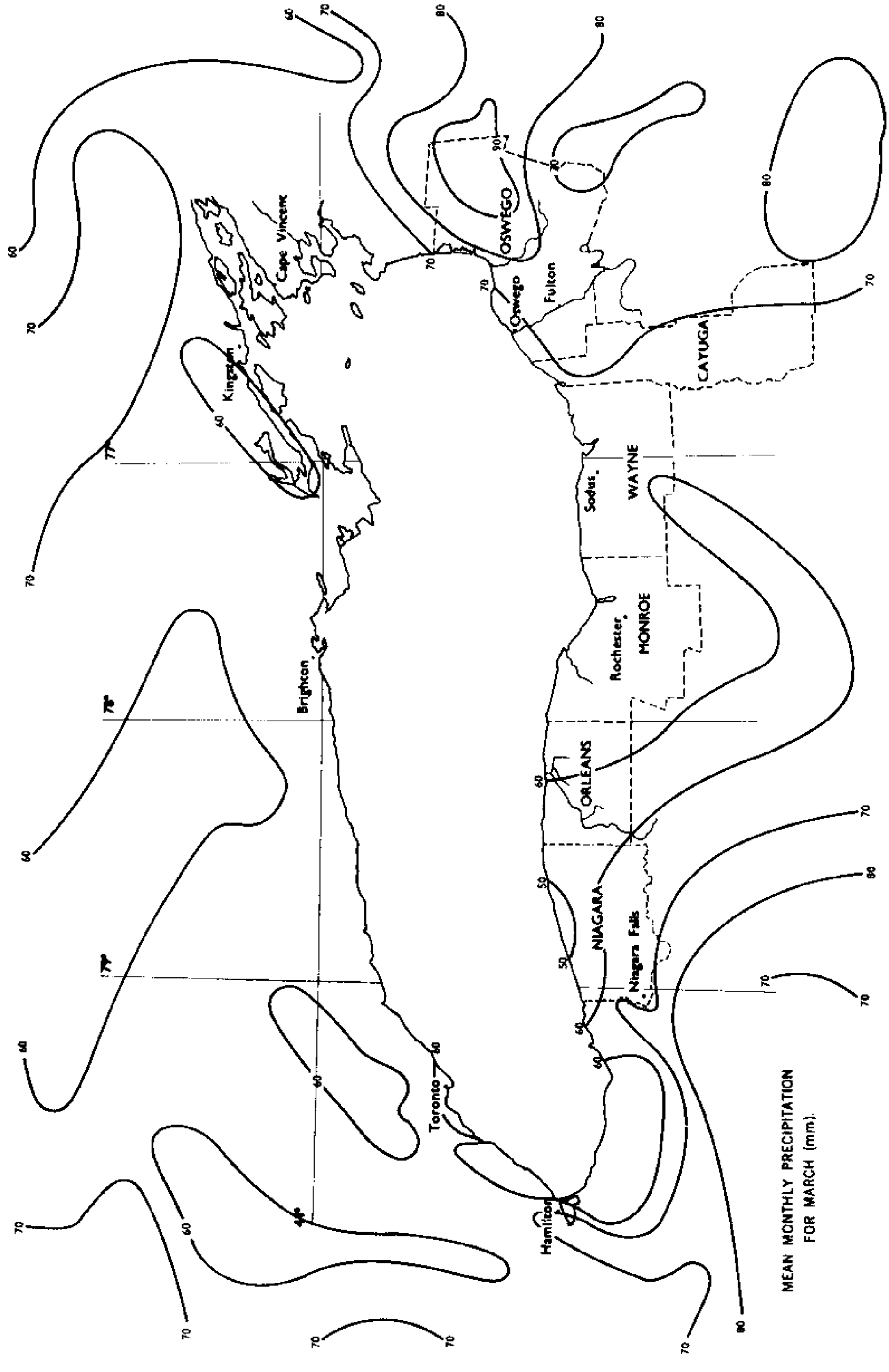
MEAN MONTHLY PRECIPITATION FOR JANUARY (mm)

Figure 49



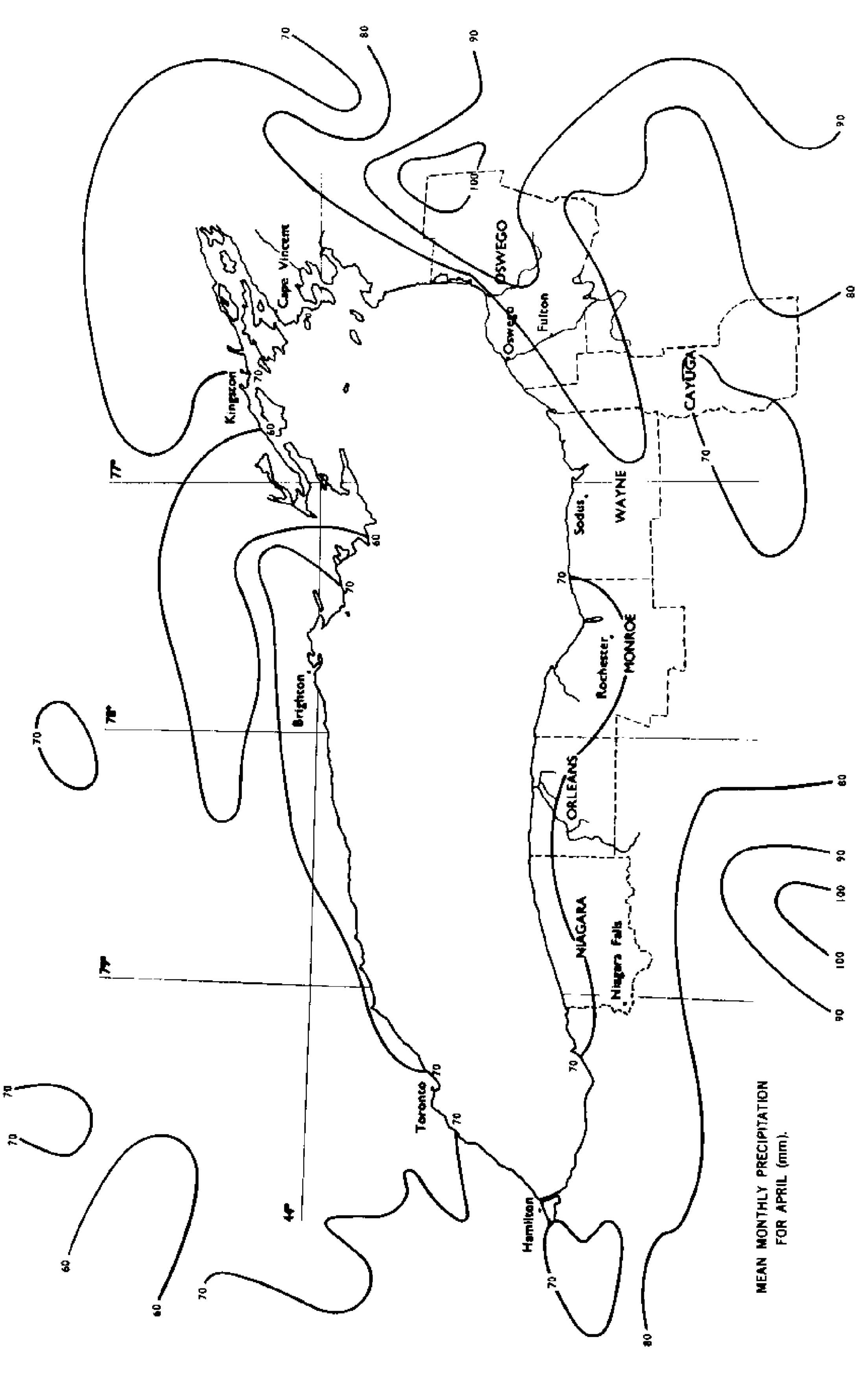
MEAN MONTHLY PRECIPITATION FOR FEBRUARY (mm).

Figure 50



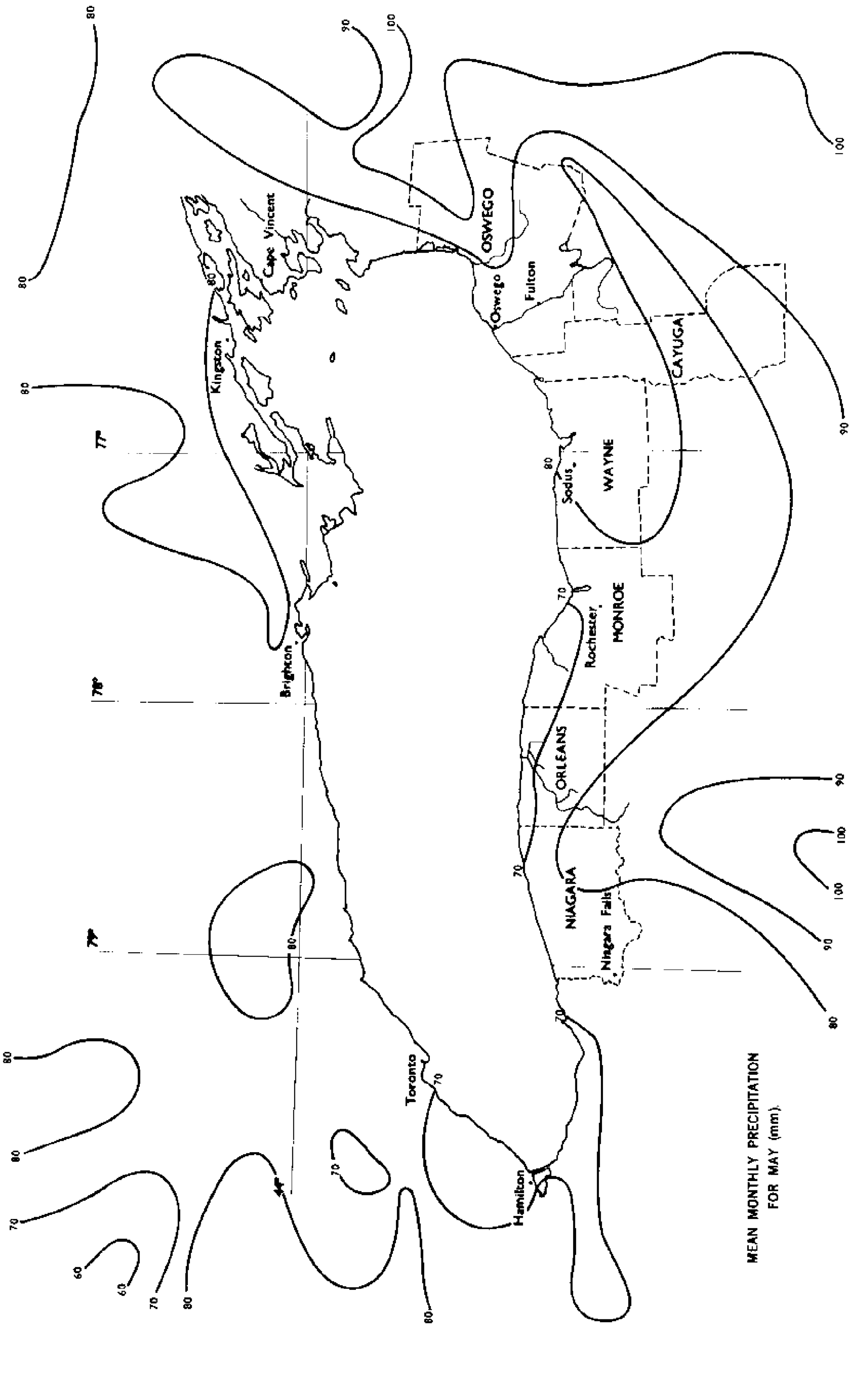
MEAN MONTHLY PRECIPITATION
FOR MARCH (mm).

Figure 51



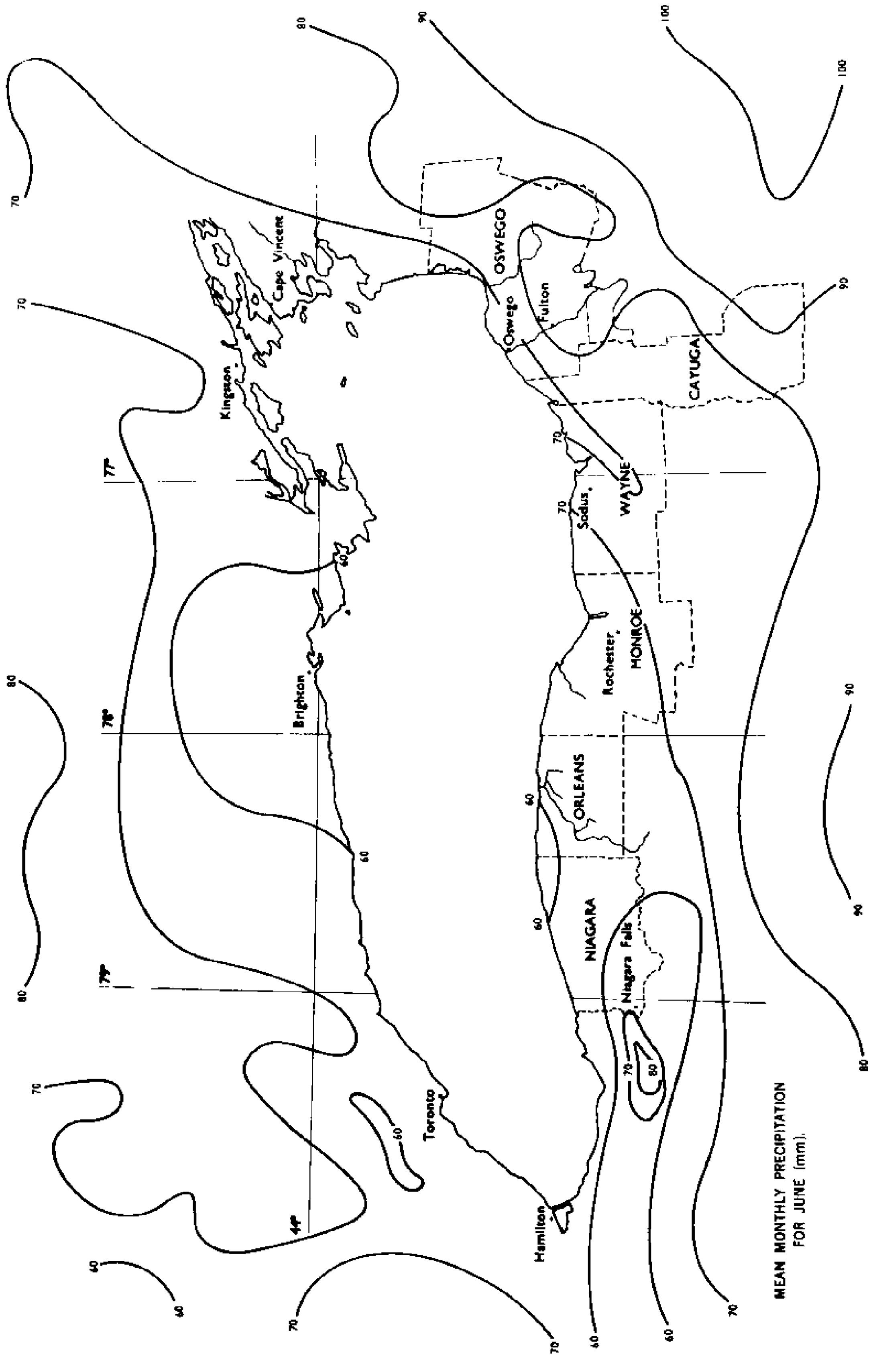
MEAN MONTHLY PRECIPITATION FOR APRIL (mm).

Figure 52



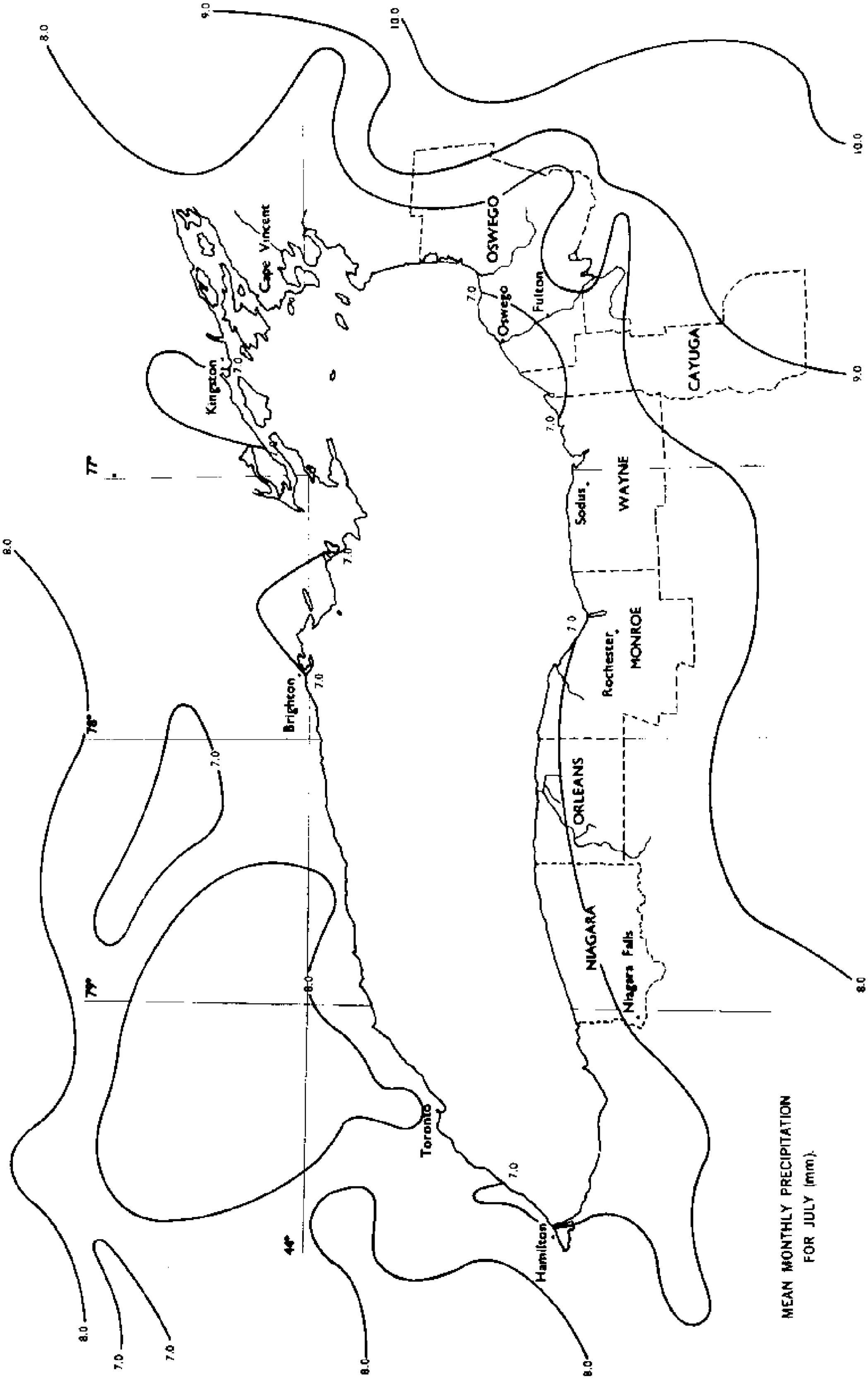
MEAN MONTHLY PRECIPITATION
FOR MAY (mm).

Figure 53



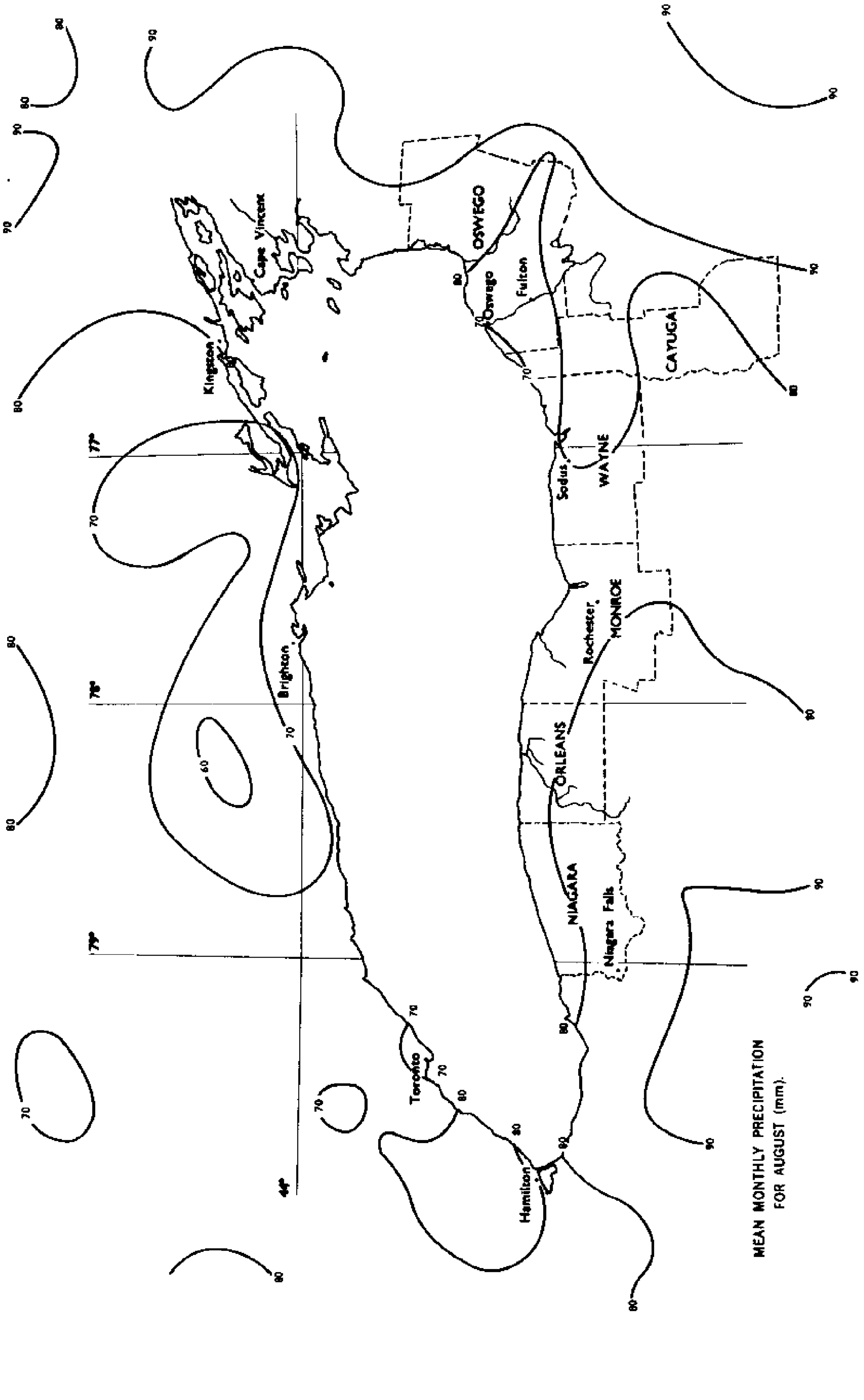
MEAN MONTHLY PRECIPITATION FOR JUNE (mm).

Figure 54



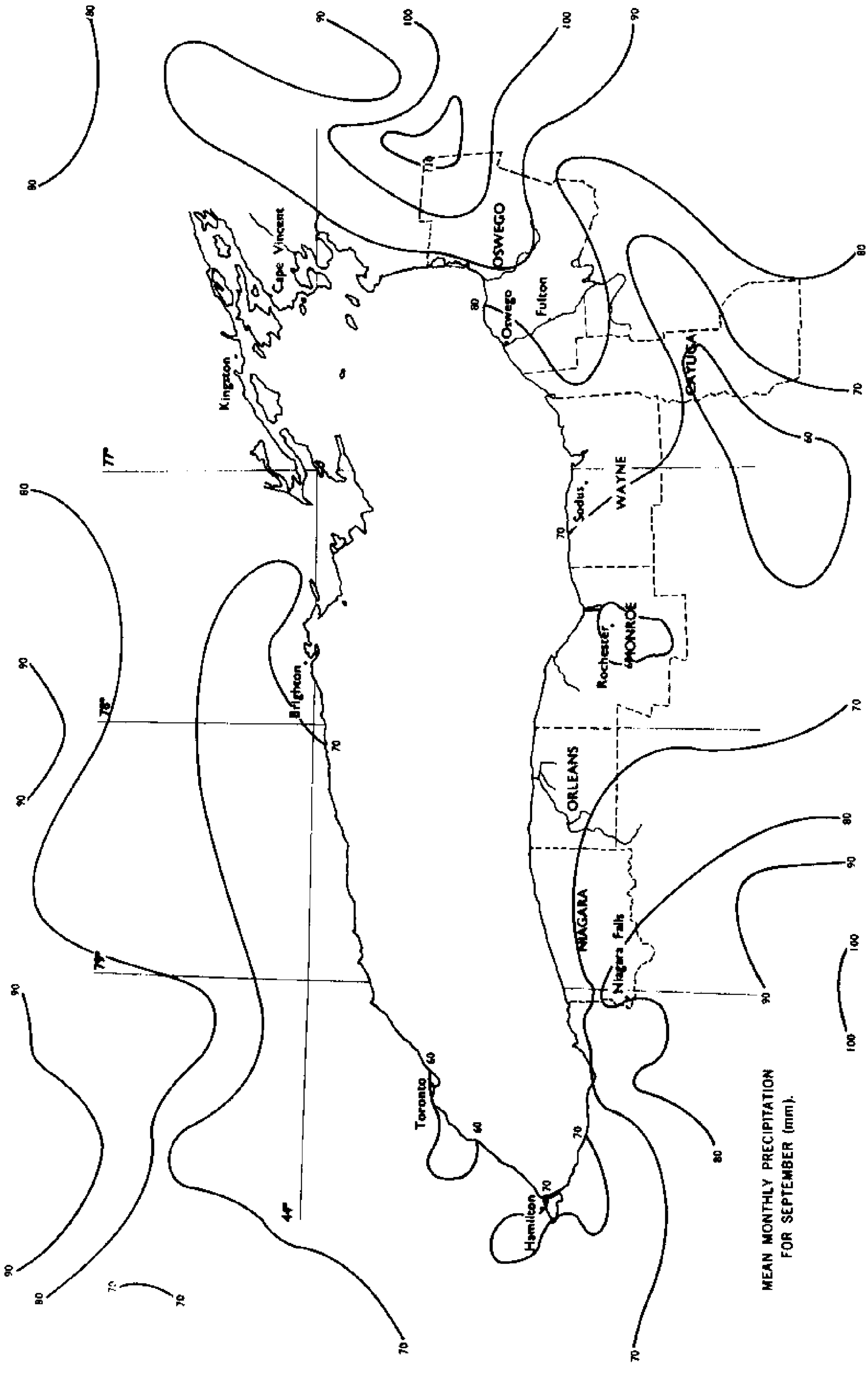
MEAN MONTHLY PRECIPITATION FOR JULY (mm).

Figure 55



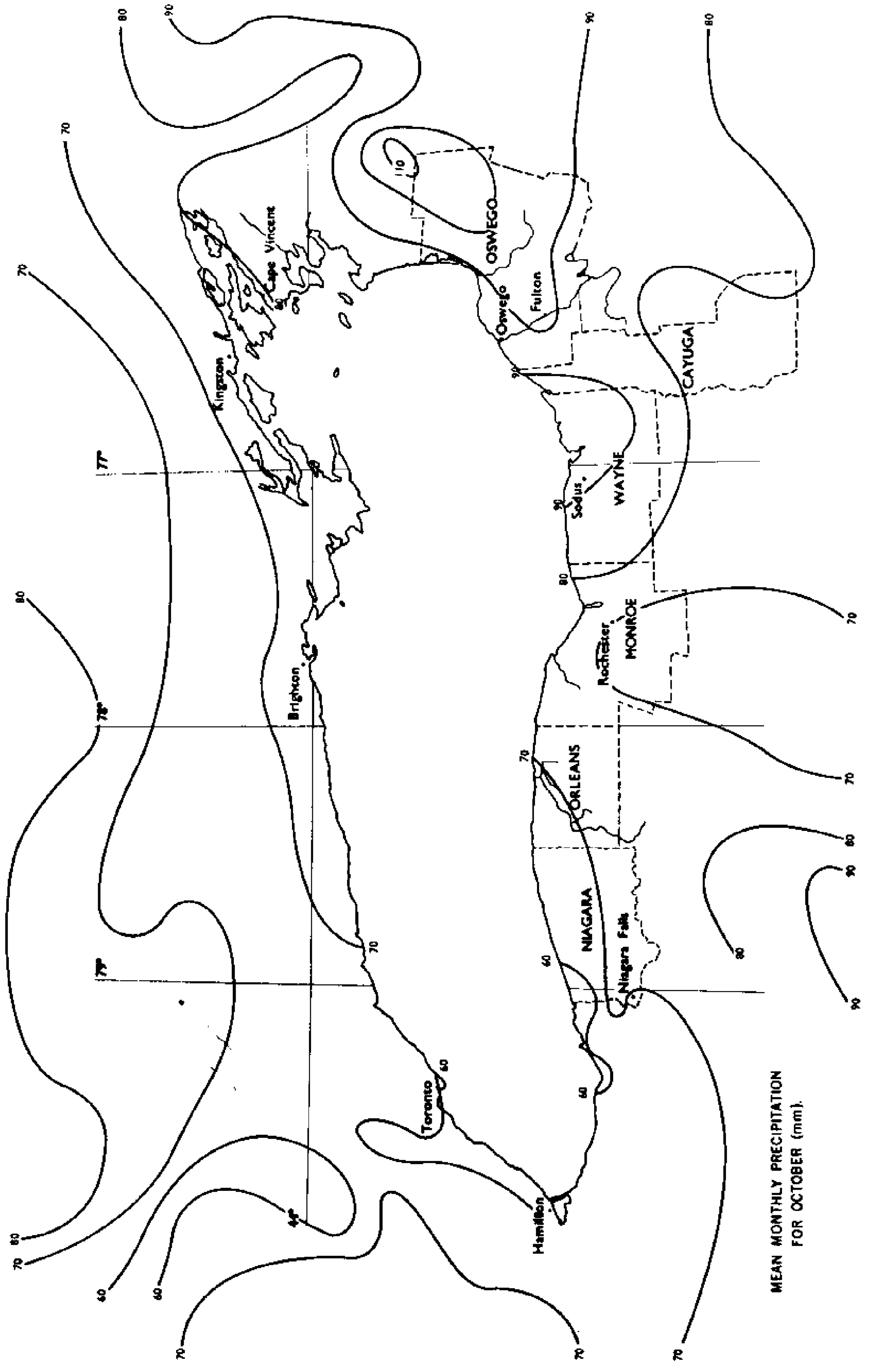
MEAN MONTHLY PRECIPITATION FOR AUGUST (mm).

Figure 56



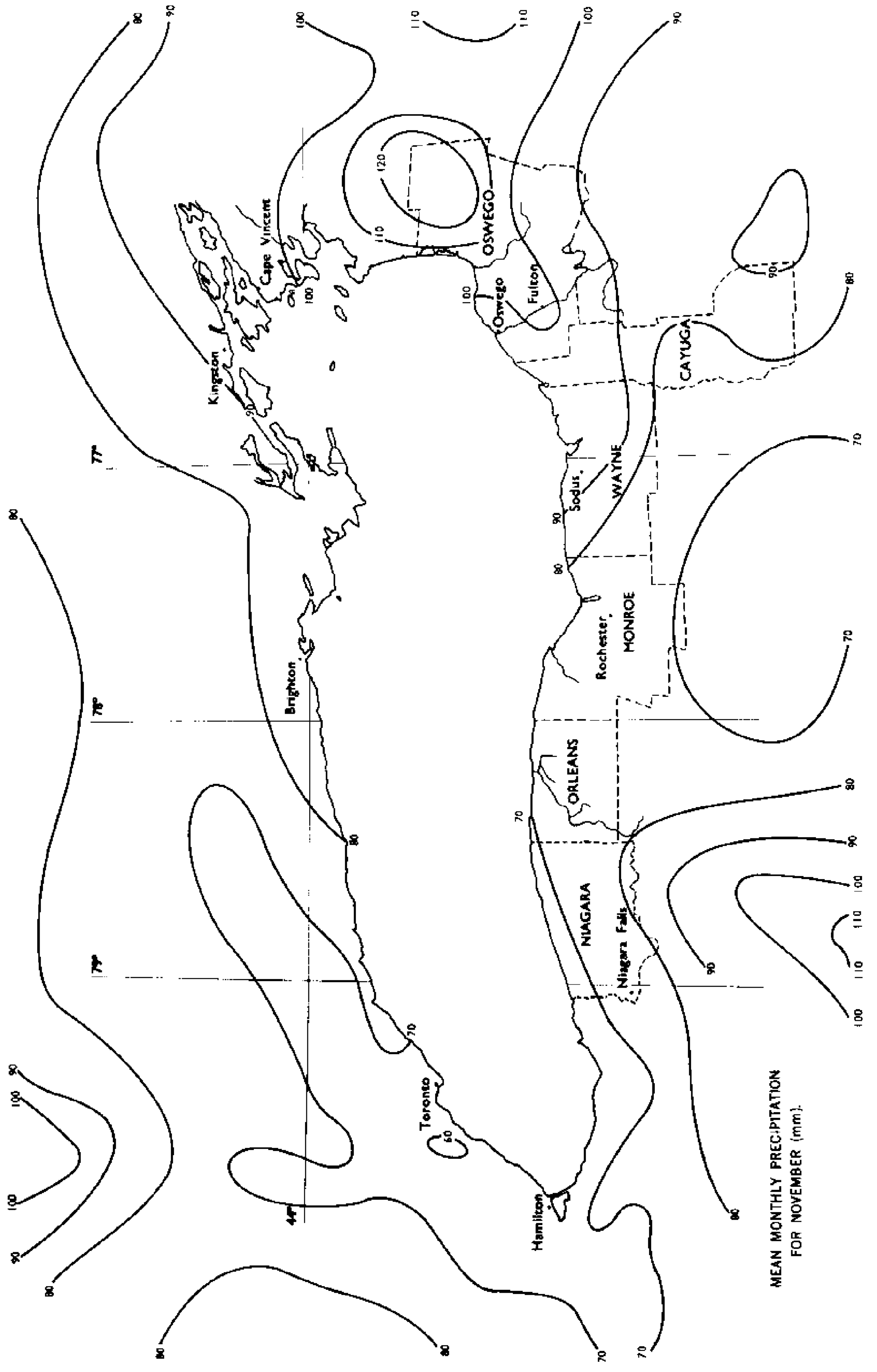
MEAN MONTHLY PRECIPITATION FOR SEPTEMBER (mm).

Figure 57



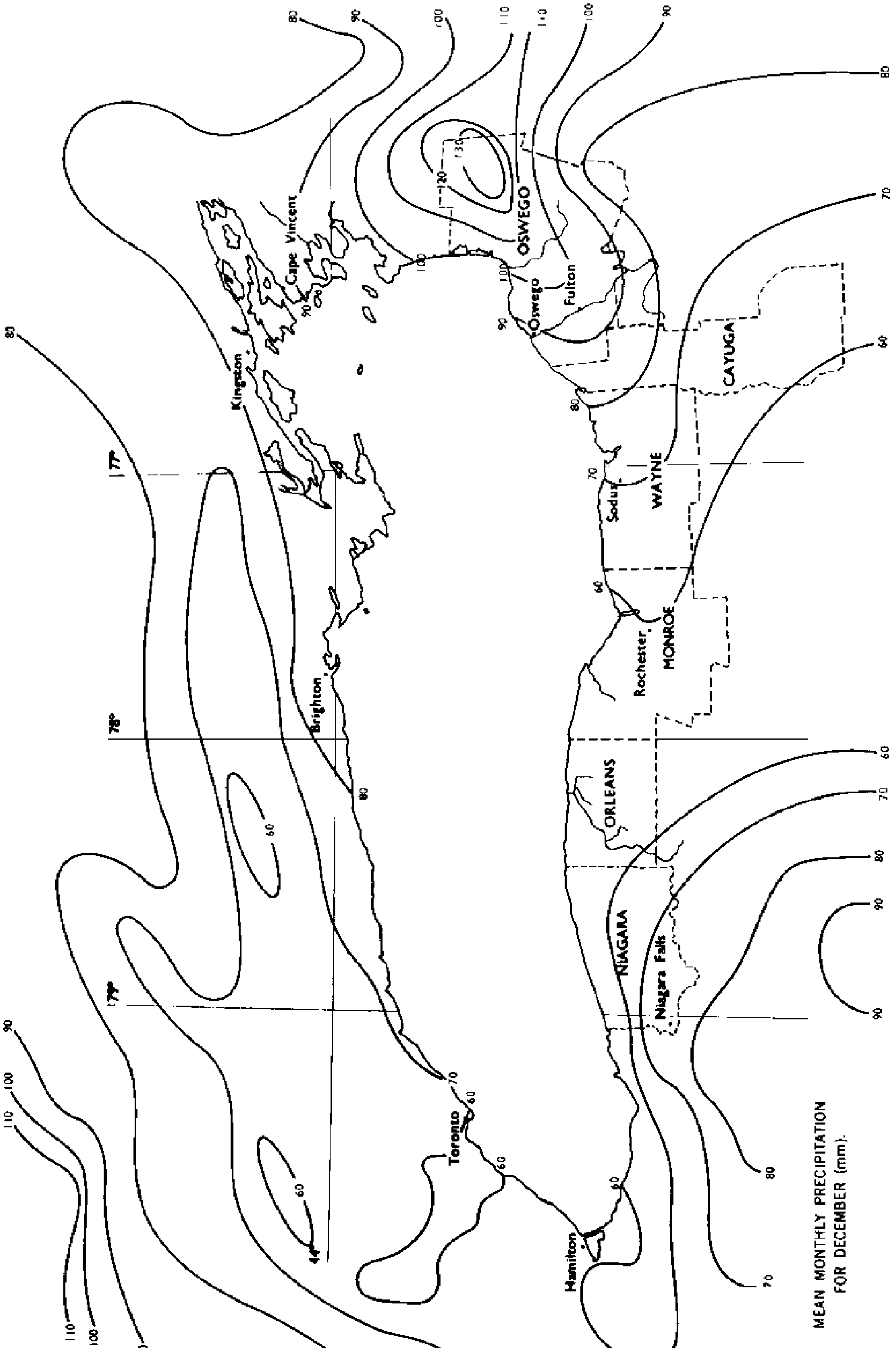
MEAN MONTHLY PRECIPITATION
FOR OCTOBER (mm).

Figure 58



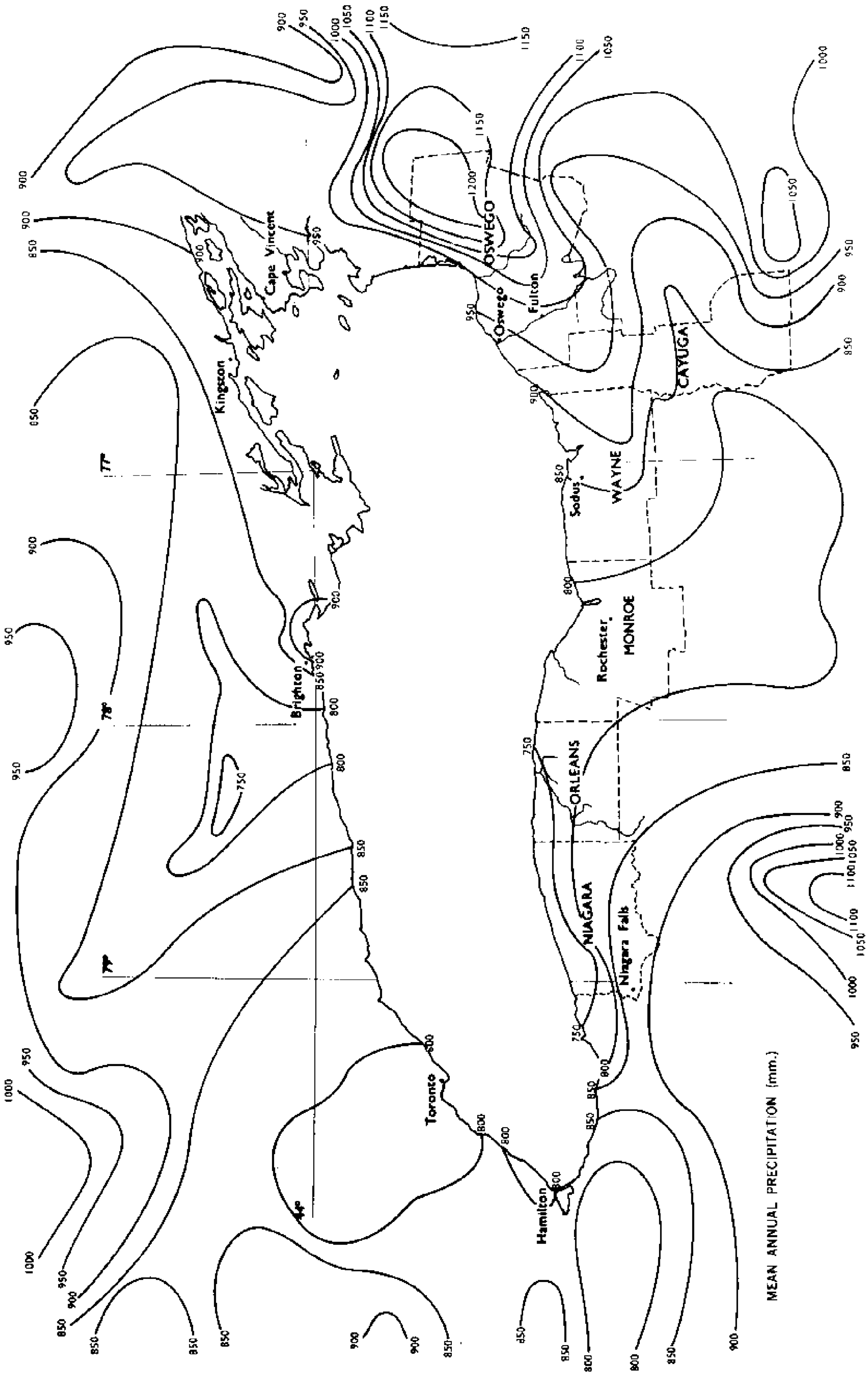
MEAN MONTHLY PRECIPITATION FOR NOVEMBER (mm).

Figure 59



MEAN MONTHLY PRECIPITATION
FOR DECEMBER (mm).

Figure 60



MEAN ANNUAL PRECIPITATION (mm.)

Figure 61

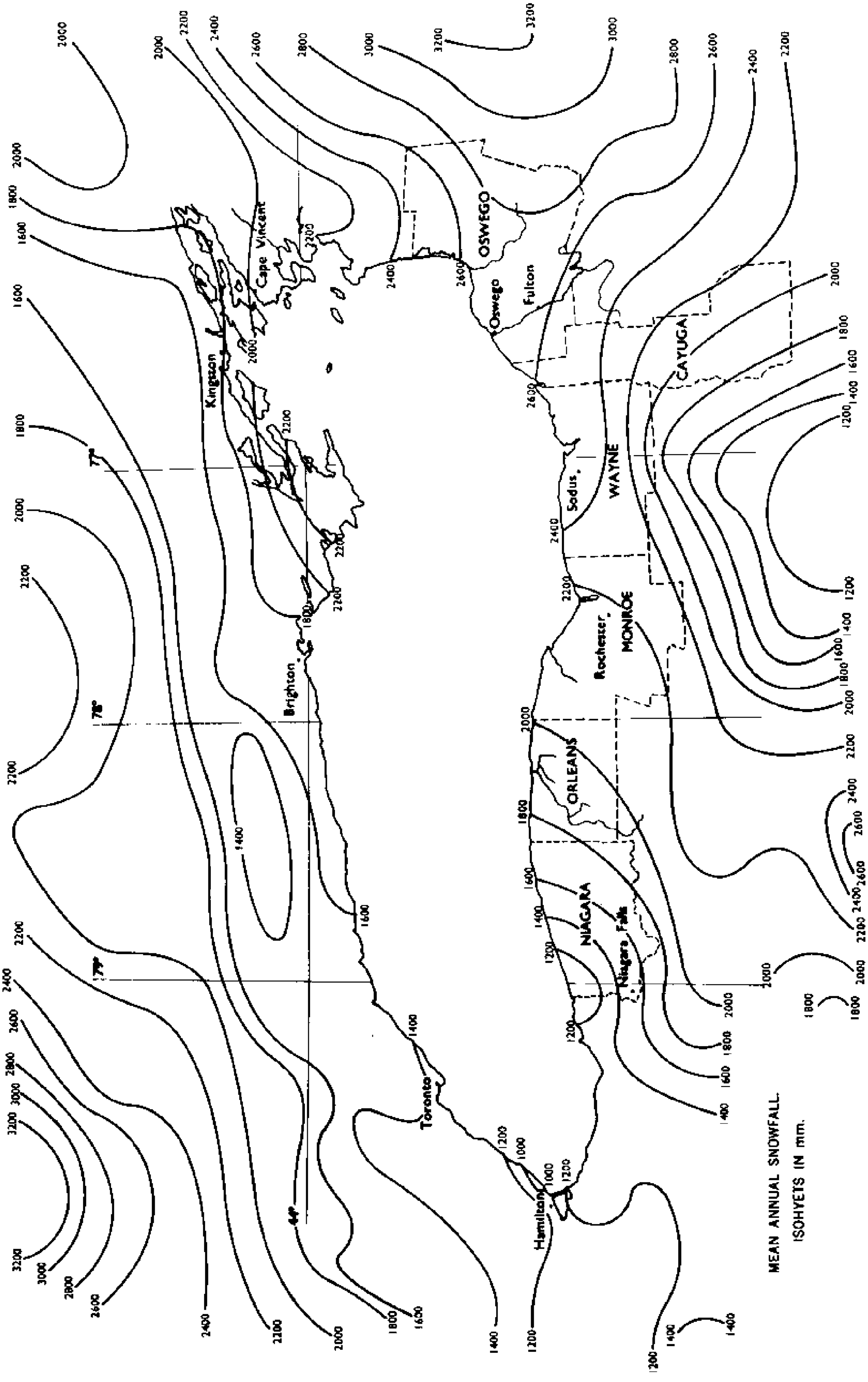
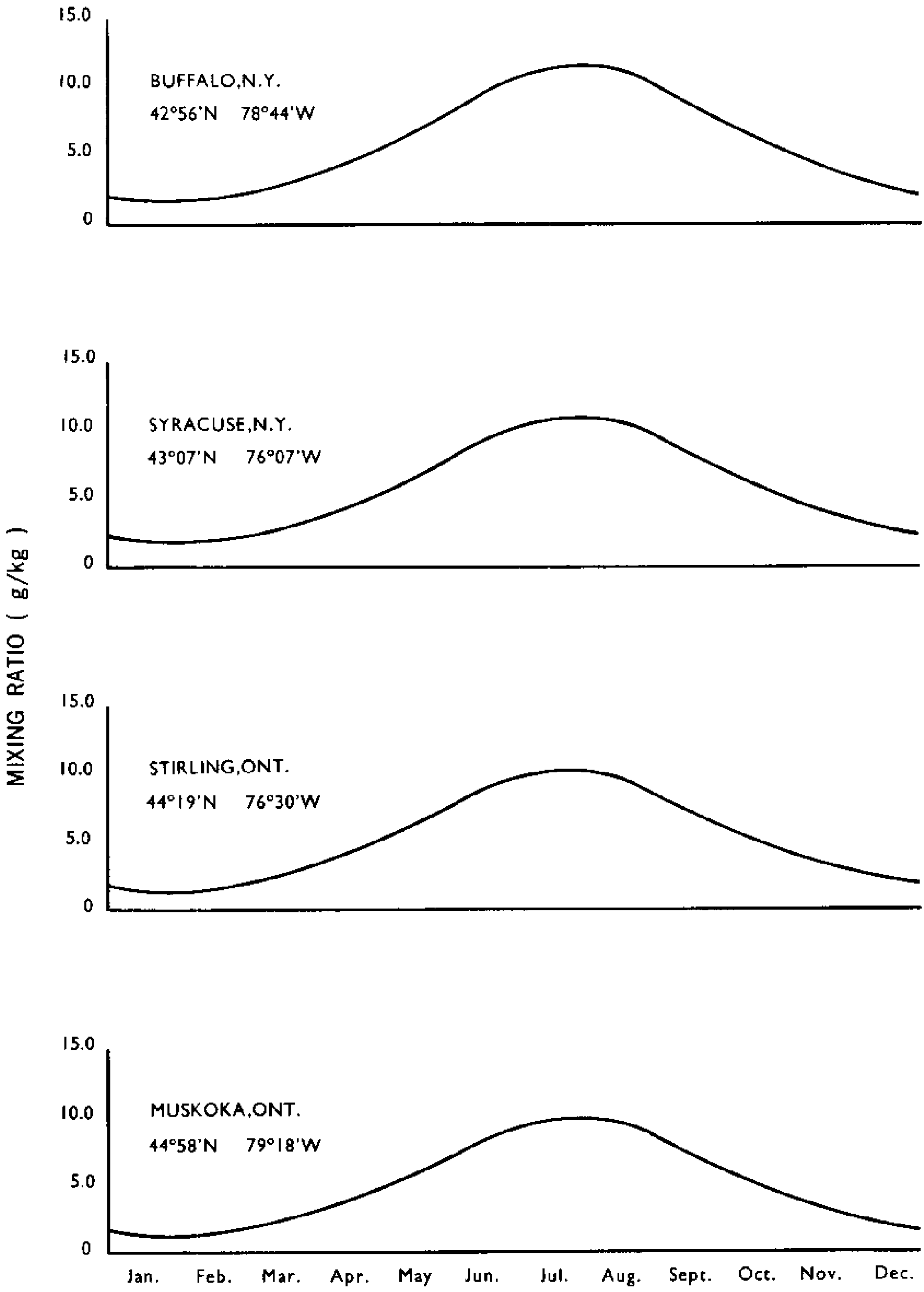

MEAN ANNUAL SNOWFALL.
ISOHYETS IN mm.
OSWEGO
Oswego
Fulton
Cape Vincent
Kingston
CAYUGA
WAYNE
Sodus
MONROE
Rochester
Brighton
ORLEANS
NIAGARA
Niagara Falls
Toronto
Hamilton

Figure 62



MEAN MIXING RATIOS AS A FUNCTION OF TIME OF YEAR

Figure 63

MEAN ANNUAL FREQUENCY OF WIND BY DIRECTION AND SPEED BY DIRECTION