Gordon [illegible] Murray
M.Sc. [illegible]

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COASTAL MAXIMUM AND MINIMUM TEMPERATURES IN AUGUST

# AN INVESTIGATION OF AUGUST MAXIMUM AND MINIMUM TEMPERATURES AT TORBAY, NEWFOUNDLAND

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Gordon Alexander McKay

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TABLE OF CONTENTS

CHAPTER PAGE

## LIST OF TABLES

| TABLE | | PAGE |
|---|---|---|

## LIST OF FIGURES

# CHAPTER I

## THE PROBLEM OF ATLANTIC COAST TEMPERATURE PREDICTION

Forecasts of daily maximum and minimum temperature have become of increasing importance to both agriculture and industry, and reasonable accuracy has been attained in predicting these values. The success in prediction has been largely due to the persistence of either a maritime or continental type of climate. The Canadian Atlantic coast is affected by an unceasing change of both continental and maritime types of air; consequently, a more thorough knowledge of temperature distribution and related weather conditions is required for successful temperature prediction.

### I. THE FORECASTING PROBLEM

Statement of the problem. The object of this study is (1) to indicate the nature of the distribution of the daily maximum and minimum temperatures along the Atlantic coast, and the processes effecting it; (2) to indicate the degree of dependence of the daily maximum and minimum temperatures on other weather conditions more readily predictable.

Importance of the study. The accuracy of present temperature prediction techniques depends on highly idealized weather conditions which may frequently occur over continental areas, and their use is mainly restricted to very short periods of time. Application of these methods to coastal localities is frequently impossible inasmuch as they do not take into account coastal phenomena. A thorough knowledge of the air-mass temperature history and absence of air-mass change are generally required in present forecasting methods; both restrictions make these methods of very limited use in coastal localities.

This study supplements present forecasting methods by providing a thorough knowledge of the temperature distributions of the air-masses and circulation types which affect the western North Atlantic. Such a knowledge of the distributions permits a reasonably accurate estimation of temperature when other methods are inapplicable. By developing the relations between temperature and other predictable weather conditions, with the influence of the sea taken into account, a more efficient and exact method of temperature prediction has been obtained.

The development of the problem. The distribution of maximum and minimum temperature in coastal localities is quite distinct from that of continental observation stations. Two temperature cycles, one continental and one maritime, are superimposed on each other to produce the coastal temperature regime. A clearer insight into the temperature regime may be acquired by separating the continental and maritime effects.

This separation has been accomplished by investigating the maximum and minimum temperatures according to air-mass and to the direction of the air circulation. Both have been considered since each suffers from certain deficiencies. The effect of wind direction is very pronounced and for this reason air-mass alone does not suffice; on the other hand air-mass groupings do introduce such factors as stability and humidity which may be overlooked in a circulation analysis.

The circulations selected for study were based on polar diagrams of the mean maximum and minimum temperature for geostrophic wind direction. Two major arcs of the polar diagram were noted in each instance where there was no appreciable deviation of the mean temperature, and these arcs were selected to represent the circulations.

Conventional air-masses were used with the exception that the maritime air-mass was subdivided according to trajectory.

Once having segregated the maximum and minimum temperatures according to air-mass and circulation, then the frequency distributions, the mean temperatures, and the standard deviations were determined. In each case these values differed considerably from those of the whole temperature distribution. This fact alone would recommend the use of such an analysis in temperature prediction.

The most influential factors to be considered in relating weather conditions and maximum temperature are: (1) reflection of insolation back to space; (2) radiation; (3) eddy diffusion; (4) water vapor content of the atmosphere; and (5) evaporation. These factors were considered and investigated either directly or through their associations. A degree of association of the daily maximum temperature with cloud albedo, wind speed, and thickness of the air stratum near the ground was observed.

The relations between the nocturnal minimum temperature and the following weather conditions were investigated: (1) cloud type and amount; (2) wind speed; (3) dew point; and (4) thickness of the air stratum near the ground. Through these relations such processes as radiation, eddy diffusion, and dew formation were introduced. Favourable associations of minimum temperature with dew point, thickness, and wind speed were observed.

The relation of water vapor content, cloud albedo, and thickness of the air stratum near the ground to temperature may be treated roughly as linear, and on this basis partial regression equations were developed for both the maximum and minimum temperatures. These equations permit a useful forecast of temperature, but they do not include the full effect of the wind which is non-linear.

Wind speed has been partially incorporated into the regression equations through its association with thickness in some circumstances. To obtain a prediction which incorporates the full influence of wind speed, the bias of the regression equation prediction for ranges of wind speed was determined. Applying a correction for this bias to the predicted value, a reasonably accurate forecast of the maximum or minimum temperature may be obtained.

The frequency of maritime circulations decreases markedly westward from Newfoundland. It was desirable to obtain as much data as possible for the maritime air-masses and circulations, and Torbay, situated in the extreme southeast of Newfoundland, permits the best study in this regard.

August has been selected since it is representative of the summer conditions. An investigation of the other seasons is planned for a further study.

The study, therefore, provides a clearer insight into the temperature regime and indicates a method of more accurate prediction of maximum and minimum temperature. The temperature distributions of the air-masses and circulations allow a reasonable forecast under most difficult conditions while the regression equations permit accurate prediction when more data are available.

## II. DEFINITION OF TERMS USED

Maximum and minimum temperature. Throughout this study maximum and minimum temperature refers to the daily value of these quantities as measured at Torbay unless otherwise stated. The daily maximum temperature referred to is that used for climatological purposes, and is the highest temperature recorded within the twenty-four hour period beginning at 12.30 G.M.T.. The daily minimum temperature is also that used for climatological purposes, and is the lowest temperature recorded in the twenty-four hour period commencing at 03.30 G.M.T..

The temperatures were obtained and the dew points determined according to procedures recommended by the International Meteorological

Organization.[1] The thermometers were housed in a louvered screen which is located four feet above an area of short grass. Temperatures are given in the Fahrenheit scale unless stated otherwise.

Air-mass. An air-mass is broadly defined as an expanse of air of large horizontal dimension which is relatively homogeneous with regard to temperature and humidity in the horizontal direction.[2] The source region of the air was also referred to in this investigation. It is frequently impossible to distinguish one oceanic air-mass from another from their surface features since all air-masses quickly assume the temperature characteristic of the immediate sea surface.

Air-masses are classified according to latitude and the nature of the surface over which they are travelling. Factors such as stability or humidity may also be included in the classification, but have not been used in this study. The following nomenclature has been adopted to describe the air-masses considered in this investigation:

(1) Polar continental, abbreviated as PC, is air of fresh polar origin, usually arriving directly from Labrador or northern Quebec.

(2) Modified polar continental, abbreviated as MPC, is air arriving from the maritime provinces or southern Quebec.

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[1] Provisional Guide to International Meteorological Instrument and Observing Practice, p. 39.

[2] The Meteorological Glossary, p. 9.

(3) Polar maritime, abbreviated as PM, is air arriving at Torbay after a trajectory across the strong gradient of sea surface temperature to the southeast of Newfoundland, or from the sector 100° to 220°.

(4) Polar maritime 1, abbreviated PM1, denotes air arriving from the oceanic areas to the north of the sector prescribed for PM.

(5) Polar maritime 2, abbreviated as PM2, is air arriving from the southwest after a lengthy sea trajectory off the continental coast.

(6) Tropical, abbreviated as T, is air which has acquired its character through a lengthy trajectory over the southern United States or over southern portions of the North Atlantic; air arriving from the west is given this classification when history indicates that it has similar characteristics.

(7) Modified polar maritime, abbreviated as MPM, is maritime air which has had a lengthy land trajectory over sections of eastern Canada.

The abbreviation, rather than the full air-mass name, has been used throughout this study to permit greater facility in reading.

Circulation. The direction of the geostrophic wind is considered to be the direction of the circulation; a grouping of wind directions from which similar temperatures are experienced, expressed as an arc or sector of a circle, is classified as a circulation for the purposes of this study. The sectors are given in a clockwise direction. Primarily they represent offshore and onshore winds, but it is apparent that instability is also a factor in the minimum temperature circulations.

Throughout this study, with the exception of the discussion of land and sea breezes, the geostrophic wind direction and speed has been used.

Stability and instability. Whenever the vertical temperature lapse rate exceeds the adiabatic, an air-mass may be described as unstable; whenever the vertical temperature lapse rate does not exceed the adiabatic lapse rate, an air-mass may be considered as stable.[3] In this study the terms have been used in a relative sense to indicate the tendency toward stability or the tendency toward instability. Most summer air-masses are stable, but some are much more so than others; this relative degree of stability is generally referred to whenever these terms are employed.

Albedo. Albedo is defined as "The proportion of radiation falling on a non-luminous body which it diffusely reflects."[4] Throughout this study albedo is used in a loose sense and refers to the percentage of the solar radiation which is prevented from reaching the ground through the presence of clouds. Sunlight is partly absorbed, partly reflected, and partly transmitted through clouds; therefore, the adopted definition of albedo refers not only to the

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[3] The Meteorological Glossary, p. 118.

[4] Ibid., p. 11.

reflected sunlight, but also to the absorbed portion.

Thickness. Thickness is used throughout this study in reference to the vertical thickness of the air stratum between the 1,000 and 850 millibar pressure levels. It is expressed in tens of geopotential feet.

## CHAPTER II

## REVIEW OF THE LITERATURE

Literature on temperature distribution. The frequency polygons of daily maximum and minimum temperature at Torbay show multiple maxima which are due to the distinct difference in the averages of the temperatures for the onshore and offshore circulations.

McIntyre has obtained frequency polygons of the temperature at 700 and 500 millibars for a selection of Canadian, British, and American observing stations. Some of these give evidence of two maxima which are produced by an effect similar to that observed along the Atlantic coast. For Tatoosh Island in the state of Washington, McIntyre observed that, at 700 millibars, there existed on the average a strongly baroclinic zone which separates two barotropic zones. The baroclinic zone migrates to the north and south of Tatoosh; therefore, the temperature distribution at this level shows a preponderance of values representative of each barotropic zone and a lesser frequency of those temperatures representative of the baroclinic zone.[5]

Literature on processes affecting the maximum and minimum temperature. The earth and its atmosphere absorb solar radiation which they, in turn, radiate in a spectrum which is largely infra-red. The warming of the ground and the atmosphere on the receipt of the solar radiation and the cooling of these by the energy losses through their

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[5] McIntyre, D.P., "On the Air-Mass Temperature Distribution in the Middle and High Troposphere in Winter," Journal of Meteorology, 7:101-07.

own radiation at night, are the processes which give rise to the diurnal temperature cycle.

A thorough discussion of the solar radiation and its effects on the earth and atmosphere has been given by Fritz. He points out that (1) far the greatest portion of the solar radiation is absorbed by the earth; (2) when there are extensive cloud systems, indications are that about 20 per cent of the solar radiation incident upon the clouds is absorbed by them; (3) 7 to 8 per cent of solar radiation is scattered back to space by the pure cloudless atmosphere; (4) most of the solar radiation reflected back to space is reflected by clouds. Fritz has determined the albedos of several cloud types.[6]

Haurwitz has determined the ratio of the solar radiation reaching the ground with overcast skies to that reaching the ground when skies are clear for the major cloud types. Depending on the cloud type, these ratios vary from 85 to 15 per cent. They have been determined for different values of the optical air-mass.[7]

Gold made use of the total solar radiation received at the ground in his method of predicting the daytime maximum temperature with the tephigram. His method is applicable when there are clear skies and little advective change in the type of air.[8]

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[6]Fritz, Sigmund, "Solar Radiant Energy and Its Modification by the Earth and Its Atmosphere," Compendium of Meteorology, pp. 13-33.

[7]Haurwitz, B., "Insolation in Relation to Cloud Type," Journal of Meteorology, 5:110-13.

[8]Gold, E., "Maximum Day Temperatures and the Tephigram," Professional Notes, Meteorological Office, London, Vol.5, No.3, pp.4f., cited by Bungaard, Robert C., "A Procedure in Short-Range Weather Forecasting," Compendium of Meteorology, p. 788.

Brunt, in discussing the radiative transfer of heat in the troposphere, proffers the following conditions to favor nocturnal cooling of the ground: (1) clear skies or only high cloud; (2) absence of wind; (3) low atmospheric vapor pressure; (4) low thermal conductivity and specific heat of the ground. Using values representative of these conditions and the radiating temperature of the ground, Brunt has developed an equation to determine the minimum temperature under ideal conditions. He has also shown that the net radiation loss at the ground on a clear night may be expressed by the formula $R/\sigma T^4 = a + b\sqrt{e}$; where $\sigma T^4$ is the black body radiation as determined by the Stefan-Boltzmann law, e is the atmospheric vapor pressure, and a and b are coefficients which may be determined experimentally. The radiation loss may be reduced by the presence of cloud which radiates in all directions as a black body. The intensity of the radiation from the cloud base depends on its temperature; therefore, it is a function of the cloud height. The net radiation loss at the ground increases as the height of the cloud increases.[9]

Attempts have been made to improve on Brunt's equation for minimum temperature forecasting since it does not allow for the flow of heat to the ground from the air above it,[10,11] or for the heat gain due to the deposition of dew.

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[9] Brunt, David, Physical and Dynamical Meteorology, pp. 124-46.

[10] Jaeger, J.C., "Note on the Effect of Wind on Nocturnal Cooling," Quarterly Journal of the Royal Meteorological Society, 71:388-90.

[11] Knighting, E., "A Note on Nocturnal Cooling," Quarterly Journal of the Royal Meteorological Society, 76:173-81.

Elsasser[12] and Möller have both developed radiation charts which permit the computation of the radiative exchanges between the ground and the atmosphere. Of the radiation returning to the ground from the atmosphere, Möller claims that 37 per cent proceeds from the lowest one hundred metres and 88 per cent from the lowest five hundred metres, under normal atmospheric conditions. Möller also claims that the effect of the ground inversion is such that it may reduce the ground radiation loss to four fifths, or even as low as one half of its possible value.[13]

The temperature gradient near the ground and the effect of the numerous processes affecting maximum and minimum temperature are discussed in great detail by Geiger. Geiger's work is in reference to the micro-climate, but it has much bearing on the temperature at the screen level which is governed by the radiating temperature of the ground.[14]

Saunders has developed a method of predicting the minimum temperature which is based on the rate of cooling of the ground during the night. The cooling temperature curve is discontinuous and is characterized by a steep decline followed by a more gradual decline. The change

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[12] Elsasser, W.M., "An Atmospheric Radiation Chart and Its Use," Quarterly Journal of the Royal Meteorological Society, Supplement 66:41-56.

[13] Möller, F., "Long-Wave Radiation," Compendium of Meteorology, pp. 34-49.

[14] Geiger, Rudolph, The Climate Near the Ground, 482 pp.

in cooling rate is due to the formation of dew, and Saunders has noted that the time at which the discontinuity occurs is independent of wind speed, but does vary with the season. The lack of relationship between time and wind speed is attributed to the effect of friction; the cooling within the grass and at the ground surface is apparently relatively unaffected by the mixing of the air above the ground. The use of Saunders' method is restricted to nights when there are clear skies, no advective change of humidity, and no sea effects.[15]

Present day forecasting techniques have been briefly discussed by Bungaard who states:

> The local diurnal temperature minimum can be predicted quantitatively by means of formulas and nomograms which relate empirically the sunset observation of temperature, humidity, and wind at the place of prediction and auxiliary stations some distance upwind to the heat loss during the ensuing night for synoptic situations in which no new air-masses are to be expected.[16]

Referring to present day methods of predicting maximum temperature, he states that the methods are applicable for at least the half day period from one hour after sunrise to the time of the temperature maximum when skies are clear and there are no changes of air-mass. Bungaard also outlines how temperatures may be determined by a method of graphical integration.[17]

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[15] Saunders, W.E., "Some Further Aspects of Night Cooling Under Clear Skies," Quarterly Journal of the Royal Meteorological Society, 78:603-12.

[16] Bungaard, loc. cit.

[17] Ibid., p. 787-88.

Deficiencies of previous studies. The theoretical aspects of energy interchange between the sun, earth, and atmosphere have been well developed generally, while temperature forecasting methods have been well developed for very specific circumstances and for very limited periods of time.

Both maximum and minimum temperature may be successfully forecast by methods indicated in the current literature, but these methods are applicable only under very restricted conditions. Clear skies and absence of air-mass change are required in most instances. Techniques using auxiliary stations and historical temperature data for the air-mass are not generally applicable in coastal localities.

The generally accepted methods of temperature prediction are unsatisfactory along the Canadian Atlantic coast for the following reasons:

(1) There is a high incidence of air-mass change in this region.

(2) The variation in length of land trajectory must be considered in the use of the tephigram.

(3) Sea breezes may alter the expected distribution of solar energy.

(4) Land breezes and humidity gradients are frequent in coastal areas.

(5) It is impossible to consider auxiliary upwind stations for onshore circulations.

(6) Coastal localities experience a much higher percentage of cloudiness than inland localities.

CHAPTER III

# SOURCES OF DATA AND METHODS OF PROCEDURE

## I. SOURCES OF DATA

The data used in this study have been obtained from the official records and charts of the Meteorological Division of the Department of Transport. The records and charts consulted were those of the Meteorological Office at Torbay Airport and of the Dominion Public Weather Office at Gander, Newfoundland.

Geostrophic winds, dew points, cloud type and amount, precipitation type and intensity, isobaric curvature, and air-mass were all determined or obtained from synoptic charts. Aerological data were extracted from the 850 millibar charts and tephigrams prepared at Gander. Tephigrams were available for the years 1949-52.

The daily maximum and minimum temperature records were obtained from the Monthly Record[18] and from a monthly climatological summary prepared by the Meteorological Office at Torbay Airport.

Temperature data for St. John's were obtained from the station abstract which was available at Gander. The Climatic Summaries were consulted for the temperature data for the city of Quebec and Chatham,[19]

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[18] Monthly Record of Meteorological Observations in Canada and Newfoundland, 1942-51.

[19] Climatic Summaries for Selected Meteorological Stations in the Dominion of Canada, I,16-27.

and for the wind frequencies at Torbay[20].

A study of the diurnal variation of the surface wind was made possible through the use of the microfilm copy of the Airways Weather Record[21]. This record was available for the years 1942-44, 1947-48, 1950-51. In the intervening years occurrences of a sea breeze or land breeze were evident in some instances in the synoptic charts.

## II. METHODS OF PROCEDURE

Preparation of data. During the month of August the maximum temperature at Torbay occurs generally at 18.30 G.M.T. and the minimum temperature at 08.30 G.M.T.. Throughout this study it has been assumed that the conditions indicated on the 06.30 G.M.T. chart and the 03.00 G.M.T. radiosonde were representative of the conditions which gave rise to the minimum temperature, while the conditions indicated on the 18.30 G.M.T. synoptic chart and the 15.00 G.M.T. radiosonde were typical of the conditions which gave rise to the maximum temperature.

In the determination of the temperature distribution for the air-masses, instances were rejected where air-mass change would have rendered the observed maximum or minimum temperature unrepresentative.

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[20] Climatic Summaries for Selected Meteorological Stations in Canada, Newfoundland and Labrador, II, 88.

[21] Airways Weather Record, an official record of the Department of Transport of weather observations taken for aviation purposes.

The aerological information used throughout this study was obtained from observations made at St. John's and Argentia, both located in the Avalon Peninsula.

The thickness of the air stratum between 850 and 1,000 millibars obtained from these observations has been used extensively. In some instances errors in the original reports were in evidence, and these were corrected by a recomputation of the thickness from basic data.

The aerological data were of use only for the years 1946-52 when the reports were made with reference to the constant pressure levels. For this reason and because of occasional deficiencies in other observations, the number of data available for each section of the investigation vary, and values given in the various tables show slight differences.

The procedure in analysis. The analysis of the temperature data has been based on elementary statistics. The annual temperature regime has been studied on the basis of frequency polygons of temperature. The temperature distributions of the air-masses and circulations have been investigated through frequency polygons, arithmetic means, and standard deviations. The relations of various weather conditions with temperature have been generally investigated on the basis of a linear relationship for which correlation coefficients and useful regression equations were determined.

Smoothing has been applied to the frequency polygons and the polar diagrams of mean temperature by averaging each value with the two terms adjacent to it. This has been done in order to eliminate the effect of spurious groupings or values.

Wherever the standard deviation is given, the value used is the best estimate. The data available for most relations investigated were few, and, under these circumstances, the calculated standard deviation tends to be an underestimate. The best estimate of the standard deviation was determined by applying Bessel's correction.[22]

Linear relations have been assumed to exist between the maximum and minimum temperature and the effects of the cloud, dew point, and thickness of the air stratum near the ground. While dew point and thickness have been used directly, albedos have been used in determining the effect of cloud on temperature.

The ratios of the solar radiation received with overcast skies to that received with clear skies, as determined by Haurwitz, have been used extensively in determining the albedo.[24] For conditions which were complex or intermediate between overcast and clear, the values of the albedo were interpolated with reference being made to the albedos determined by Fritz[25].

All correlation coefficients have been determined by the product-moment method[26]. The number of data in many instances is small; the

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[22] Moroney, M.J., Facts From Figures, p. 226.

[23] Haurwitz, B., "Insolation in Relation to Cloud Type," Journal of Meteorology, 5:111.

[24] Cf. Albedo, p. 9.

[25] Fritz, Sigmund, "Solar Radiant Energy and Its Modification by the Earth and Its Atmosphere," Compendium of Meteorology, p. 26.

[26] Hodgman, Charles D., compiler, Mathematical Tables from Handbook of Chemistry and Physics, p. 288.

least value of the correlation coefficient that is significant at the .01 probability level[27] has been used as a significance test, and is referred to as the one per cent or .01 significance level. Further, the range has been calculated within which there is a 95 per cent probability that the true value of the correlation coefficient will lie. This range was calculated by using Fisher's "z" transformation[28].

The effect of wind speed on temperature is non-linear, but through its association with thickness it has been partially accounted for in the various regression equations which have been calculated. The relationship between thickness and wind velocity prevents the use of a simple correction for wind speed in the prediction of the maximum or minimum temperature. In order that wind might be fully accounted for, the bias of the regression equation predictions have been determined for ranges of geostrophic wind speed. A correction for this bias allows the effect of wind to be taken into account over the entire range of wind speed.

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[27] Moroney, op. cit., p. 218.

[28] Weatherburn, C.E., A First Course in Mathematical Statistics, p. 200.

## CHAPTER IV

## TOPOGRAPHICAL CONSIDERATIONS

Newfoundland. Newfoundland may be described as an equilateral triangle with sides some 300 miles in length and the base lying along the 47°31' N. latitude. Hare describes it as a tilted plateau rising northwestwards from the east coast; the height of the western half of this plateau rises in places to over two thousand feet.[29]

Air passing over this plateau from the west has had a brief trajectory over the Gulf of St. Lawrence. Its continental character is generally restored by daytime passage over the island or by the effects of the initial lift and subsequent subsidence of about two thousand feet as it reaches the east coast.

The Avalon Peninsula. The Avalon Peninsula is the most easterly extension of Newfoundland. It has the shape of a letter "H" with its arms rotated about 30 degrees to the right of true north. The arms are about seventy-five miles in length, and land extends for a distance of eighty-five miles diagonally across the "H".

The meteorological observation station at Torbay is located on the northeast arm of the Avalon Peninsula at 47°37' N. latitude and 52°44' W. longitude, three miles inland from the Atlantic Ocean. A line of rolling hills, extending in a north to south direction, is

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[29] Hare, F. Kenneth, "The Climate of the Island of Newfoundland: A Geographical Analysis," Geographical Bulletin, No. 2, p. 36.

crested one to two miles west of Torbay. These hills rise to seven hundred feet near the airport and to one thousand feet in the centre of the Peninsula. Another series of rugged hills, five to seven hundred feet in height, form the east coast southward from a point four miles to the northeast of the observation station. The arm of the "H" at Torbay is nine miles wide, and it tapers to a point some thirteen miles to the north. From the northeast the land slopes gradually upward from sea level, attaining a height of 375 feet at the observation station and 600 to 700 feet within one to two miles to the southwest.

Air arriving at Torbay from the arc 250° to 330° has been subjected to the influence of the island proper; air arriving from any other direction, if it has a straight trajectory, has passed over at least five hundred miles of ocean. Once having passed over the island, the air must still pass over the cold waters of Trinity and Conception Bays; each about fourteen miles wide. The eastern shore of Conception Bay is six miles west of the observation station; that of Trinity Bay is thirty-five miles west.

Windsor Lake, a cold spring-fed lake four miles in length and three quarters to one and one half miles wide, lies one and one half miles to the southwest of the observation station. It is so orientated that winds arriving from the southwest have swept its full length, but its influence is limited since the normal water level is over one hundred feet higher than the observation station.

## CHAPTER V

## THE INFLUENCE OF THE SEA ON AIR TEMPERATURE

Air in contact with the sea quickly acquires the temperature of the sea surface. The changes experienced by the air depend on its original temperature, the time in transit, and the sea temperature. The distribution of mean sea surface temperature in the western North Atlantic is complex and subject to small scale changes. The effect of the sea on the air is equally complex, and the small scale deviations of sea temperature may result in monthly or seasonal deviations in the mean air temperature.

The distribution of mean sea temperature. The normal latitudinal gradient of mean sea temperature is distorted in the western North Atlantic by the influence of the Labrador Current and the Gulf Stream. The Labrador Current produces a southward displacement of the sea isotherms about Newfoundland. The northward advection of very warm water by the Gulf Stream and the effects of the Labrador Current combine to give an intense gradient of mean sea surface temperature to the southeast of Newfoundland. The effects of the two are indicated in the chart of the mean sea surface temperature for August presented in Figure 1.

The influence of sea temperature on air-masses. The influence of the sea on an air-mass varies with the nature of the air-mass and its trajectory. Air-masses arriving from the southern semi-circle are

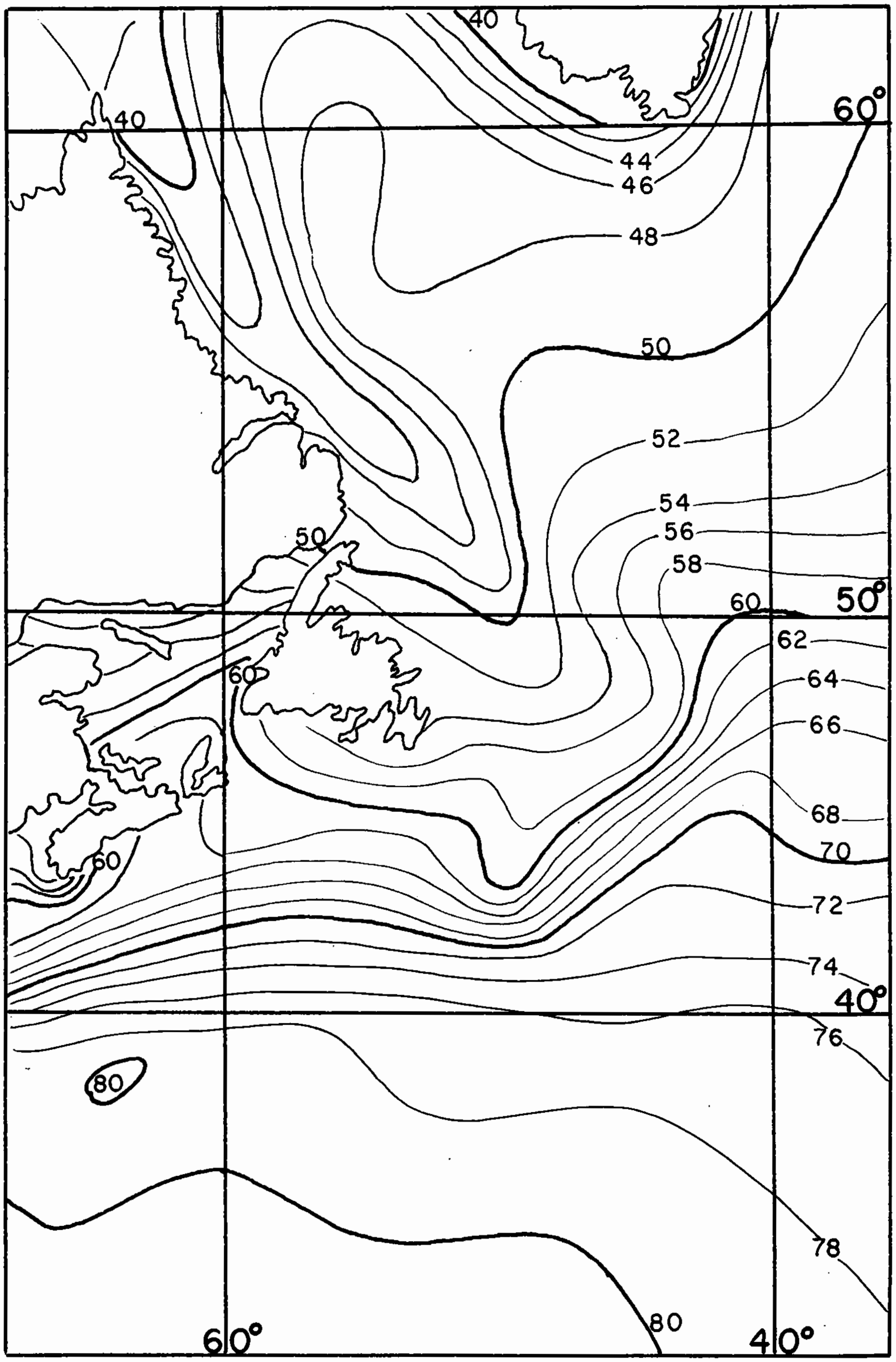


FIGURE I

MEAN SEA SURFACE ISOTHERMS (°F.) FOR AUGUST*

* After Monthly Sea Surface Temperatures of North Atlantic Ocean, p. 10.

normally very warm and passing over a colder water surface, while the opposite is true for air arriving from the northern semi-circle. Northward moving air is cooled and becomes increasingly stable, while southward moving air becomes warmer and increasingly unstable.

The distribution of mean sea temperature has been used in selecting the maritime air-masses. The air-mass PM1 is subjected to a heating of 10° F. at the surface level during the last three hundred and seventy-five miles of its trajectory; the air-mass PM is exposed to a sea surface which cools 17° to 24° F. within the last four hundred and fifty miles of its trajectory; the air-mass PM2 is subjected to a sea surface which experiences a drop in temperature of about 10° F. within the last four hundred and fifty miles. The difference in mean sea temperature distribution along the trajectories of these air-masses results in substantial differences in air modification.

The cooling of northward moving air is generally sufficient to produce saturation with subsequent formation of thick cloud or fog. Continental air reaching Torbay after a short marine trajectory from the north shows little tendency for cloud or fog formation. Air from Labrador is relatively dry and, although cooled by the sea, it is not cooled to its saturation point. The mean dew point for the month of August at Goose Bay, Labrador, is 48° F., or about five degrees lower than the mean sea surface temperature off the Avalon Peninsula.

The over-all effect of the sea on the air has been shown by Jacobs to be annually small but seasonally significant. Annually the sea off Newfoundland loses no sensible heat to the atmosphere. The heat lost to the atmosphere through winter convection is regained by the warming of the water by the air in summer.[30] In August, therefore, the net effect of the sea is to cool and stabilize the air.

Variations in the mean sea temperature. Mean sea surface temperatures are statistical averages, and there may be large deviations from the mean value daily or seasonally.[31] At present there appears to be no satisfactory method of taking into account the daily variations. The seasonal variation off Torbay is associated with the strength of the Labrador Current, whose strength shows a significant correlation to the north-south gradient of mean sea level pressure off the Labrador coast.

Newfoundland temperatures in the spring of the year reflect the extent of the ice fields about the island, and the ice fields give evidence of the strength of the Labrador Current.

Hachey describes the Labrador Current as a river in the sea. The river flows parallel to the Labrador coast and then fans out over the Grand Banks, undergoing little change enroute. In spring the river overflows its banks distributing large quantities of ice westward and southward, while in summer the river effectively goes

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[30] Jacobs, Woodrow C., "Large-Scale Aspects of Energy Transformation Over the Oceans," Compendium of Meteorology, p. 1063-64.

[31] Hawley, William P. and Soule, Floyd M., International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Bulletin No. 29, p. 4.

underground.[32]

Huntsman has shown that in the month of June the water temperatures at twenty-five to fifty fathoms off Newfoundland are sufficiently cold to freeze non-saline water.[33]

To investigate the possibility of a cold summer following a spring when the ice season was heavy, methods used by Schell[34] and Walker[35] have been employed. The number of icebergs observed in the major shipping lanes off Newfoundland was used as a measure of the spring ice fields. The correlation coefficient obtained for the number of icebergs and the mean annual temperature at St. John's, Newfoundland, for the period 1911-39, was -.41; the one per cent significance level is also -.41, indicating that a significant relation probably exists. On the average, a year with a heavy ice season has a lower than normal mean temperature. More complete data were available for the month of August, and for the period 1900-41 a correlation coefficient of -.08 and a one per cent significance level of -.40 were obtained; therefore, it may be stated that there does not appear to be a linear relationship between the mean August temperature and the extent of the spring ice fields.

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[32] Hachey, H.B., "Canadian Interests in Arctic Oceanography," Arctic, 2:28-35.

[33] Huntsman, A.G., Arctic Ice on Our Eastern Coast, 12 pp.

[34] Schell, I.I., "Foreshadowing the Severity of the Iceberg Season off Newfoundland," Quarterly Journal of the Royal Meteorological Society, 78:271-72.

[35] Walker, Sir Gilbert, "Arctic Conditions and World Weather," Quarterly Journal of the Royal Meteorological Society, 73:226-56.

The Labrador Current may alter appreciably during the late spring, and the ice fields appear to be mainly a function of the winds experienced off Labrador in February and March. The use of the iceberg frequency is, therefore, more valid as a measure of the effect of the ice on the summer water temperature than as a measure of the Labrador Current strength during August.

With a strong Labrador Current or with storms which advect warmer surface water or upwell colder water, the sea surface temperature may differ appreciably from the normal. The effects of individual storms may cancel out over a period of a month, and not influence the mean monthly temperature. The Labrador Current deviations are more lasting and produce below or above normal sea temperatures for long periods of time; therefore, it would tend to affect the mean monthly temperature. On the other hand a strong Labrador Current is the result of strong and persistent west winds, which also tend to increase the continentality of the Newfoundland climate. It is, therefore, apparent that although changes in mean sea temperature have an influence on the daily temperature, they do not necessarily have an appreciable effect on the mean monthly temperature for August.

## CHAPTER VI

## THE ANNUAL TEMPERATURE CYCLE

Although the annual temperature cycle of Newfoundland is not too dissimilar to that of most of eastern Canada, it differs in that it is a product of two distinct temperature cycles, one continental and one maritime. The influence of the sea becomes more pronounced from west to east across Newfoundland, and at Torbay the influence is so great that the temperature cycle is maritime, with August being the warmest month and February the coldest.

Comparison with continental temperatures. A comparison of the temperatures experienced at Torbay with those of eastern Canadian observation stations of similar latitude is given in Table 1. The winter temperatures at Torbay are substantially higher. In summer the mean and extremes of the maximum temperatures are significantly lower at Torbay, while there is no apparent difference in the minimum temperatures.

Chatham and Quebec have almost identical temperature cycles. They both have slight maritime influences in their climate due to their proximity to the Gulf of St. Lawrence, but have definitely a continental climate.[34]

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[34] Connor, A.J., "The Climate of Canada," reprint from The Canada Year Book 1948-49, p. 5-6.

TABLE I

MEAN TEMPERATURES AT TORBAY AND CONTINENTAL OBSERVATION STATIONS OF SIMILAR LATITUDE

| Place | Daily Mean | Mean Minimum | Mean Maximum | Mean Extreme Minimum | Mean Extreme Maximum | Length of Record in Years |
|---|---|---|---|---|---|---|
| February: | | | | | | |
| Torbay | 24 | 17 | 30 | 3 | 45 | 11 |
| Quebec | 12 | 4 | 20 | -20 | 38 | 72 |
| Chatham | 14 | 2 | 25 | -23 | 43 | 50 |
| August: | | | | | | |
| Torbay | 60 | 53 | 68 | 43 | 80 | 11 |
| Quebec | 64 | 54 | 73 | 44 | 84 | 69 |
| Chatham | 64 | 54 | 75 | 42 | 88 | 63 |

NOTE: Temperatures given in all Tables are in °F..

The temperature cycle at Quebec and Chatham is similar to that of the continental air which moves over Newfoundland. With the exception of the winter months when modification over the sea through convection is rapid and irreversible, this continental cycle is clearly evinced in the temperature distribution at Torbay.

It is impossible to obtain a similar comparison of the maritime temperature cycle, which closely resembles that of the mean sea surface temperature about the Avalon Peninsula. Since the maritime air is subjected to a small land trajectory prior to its arrival at Torbay, the daytime maximum temperature is slightly higher than that of the sea surface and the minimum temperature is slightly lower.

The degree of the maritime influence may be ascertained from Figure 2, in which graphs of the annual temperature cycle for the following are given: (a) the mean maximum temperature at Quebec and Torbay, and the mean sea temperature off Torbay; (b) the mean minimum temperature at Quebec and Torbay, and the mean sea temperature off Torbay; (c) the mean daily temperature at Quebec and Torbay, and the mean sea temperature off Torbay. During the late winter and early spring the temperature of the sea surface off Torbay is dependent on the extent of the ice fields and the general wind direction, and for this period of the year the mean sea surface temperature has been estimated.

It is evident from Figure 2 that the annual temperature cycle at Torbay follows the sea cycle slightly more closely than that of Quebec. The maximum temperature cycle closely resembles that of con-

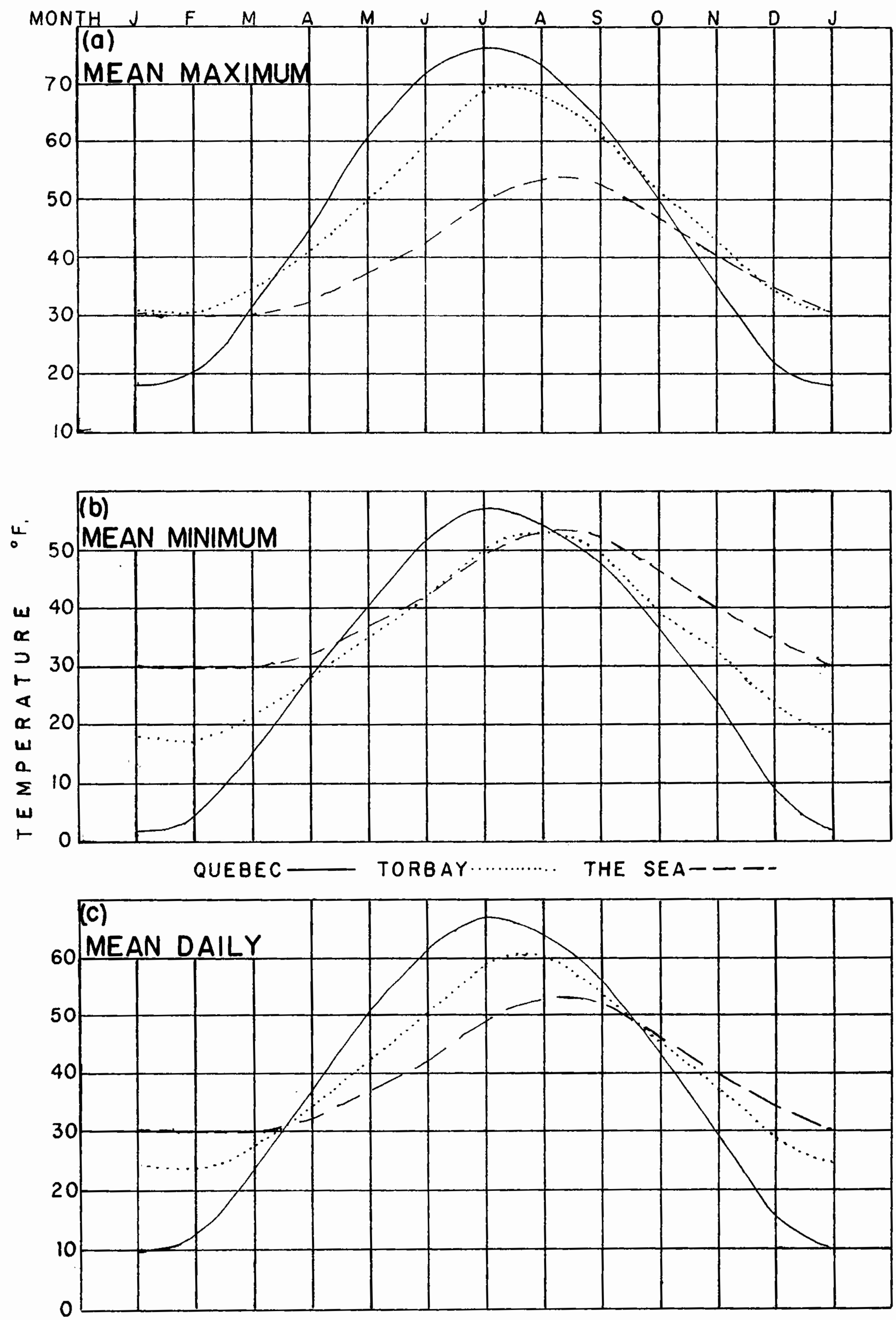


FIGURE 2

ANNUAL CYCLE OF TEMPERATURE AT TORBAY, QUEBEC, AND THE SEA OFF TORBAY tinental air in summer and the maritime air in winter, while the minimum temperature cycle resembles that of the sea in spring and the continent in autumn.

Throughout the year the distribution of wind direction is such that about 70 per cent of the air arriving at Torbay has an appreciable land trajectory. Summer maritime modification of the air arriving from the west produces a shallow stabilization which is destroyed in the overland trajectory; therefore, the summer maximum temperature cycle closely resembles the continental. Winter maritime modification warms the air; therefore, the daily maximum temperature at Torbay tends to approach the temperature of the sea surface. The land trajectory does not have the same effect on the minimum temperature, and it shows a tendency to continentality only in the autumn.

The annual temperature cycle at Torbay. A more complete picture of the annual temperature cycle of the mean daily maximum and minimum temperature at Torbay is given in Figure 3. Here, frequency polygons of the maximum and minimum temperature for each month are shown, with the frequency expressed in per cent of the whole. The polygons provide an excellent method of observing the combined effects of the maritime and continental temperature cycles.

Most striking in the polygons is the change from definite central tendency to marked dispersion from one season of the year to another. Reference to the temperature cycle curves in Figure 2, page 32, shows that the definite central tendency occurs when the means of the continental temperature and of the sea temperature are the same, while dispersion

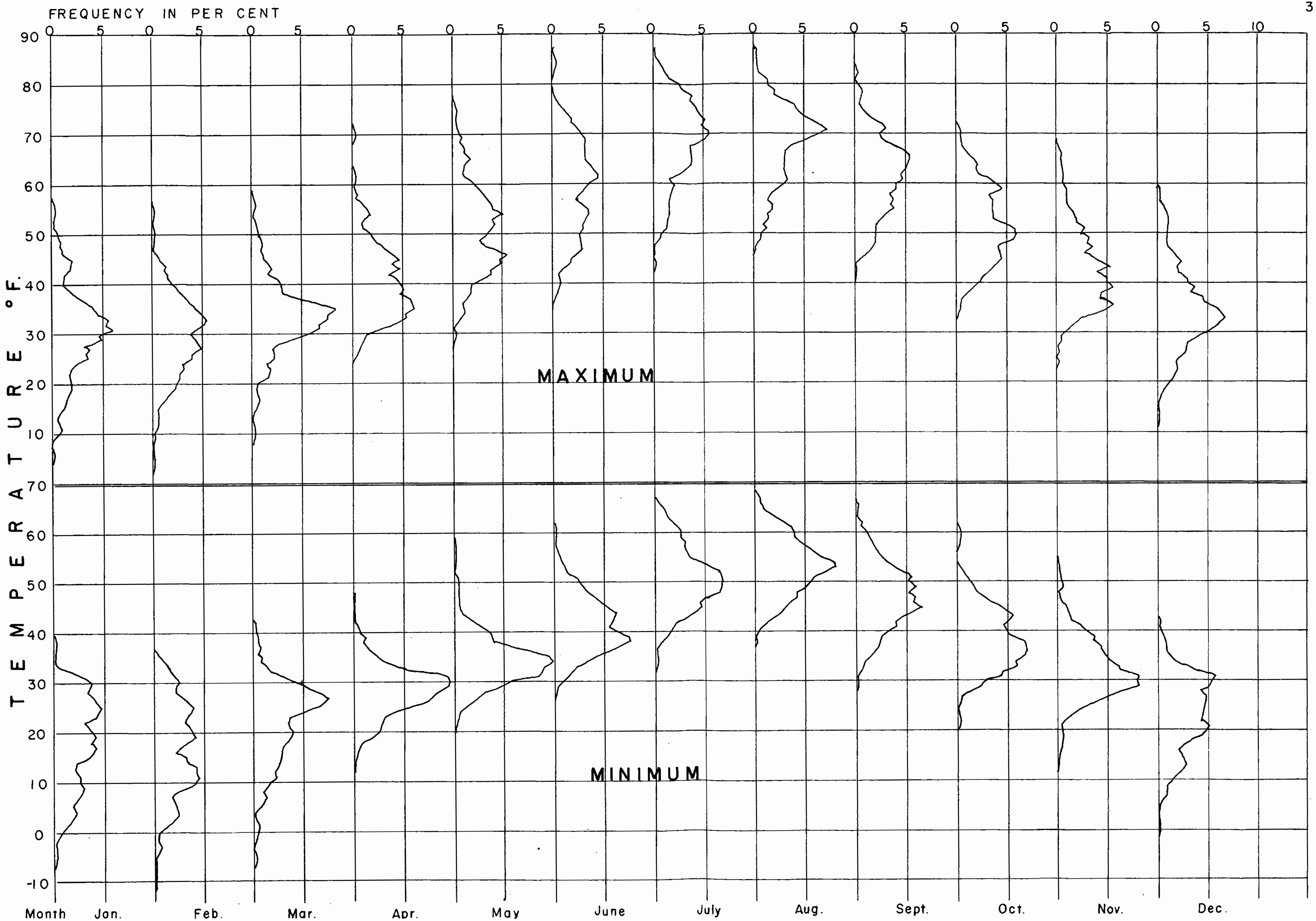


FIGURE 3

FREQUENCY POLYGONS OF THE DAILY MAXIMUM AND MINIMUM TEMPERATURE AT TORBAY occurs when these two values differ. Double maxima are in evidence in many instances; they disappear when the mean temperatures of the maritime cycle and the continental cycle are the same, or when the modification of the continental air through convection has been great. Throughout the temperature cycle the change in central tendency and the appearance of two maxima indicate the influence of the two separate temperature cycles, continental and maritime.

August temperature and the annual cycle. The distribution of August temperature is influenced by the similarity of the sea temperature and the continental minimum, and by the dominance of the continental character in the maximum temperature.

Because of the similarity between the mean sea temperature and the continental minimum, the Torbay minimum temperature is normally distributed. The mean minimum temperature for the eleven year period 1942-52 is 52.8°F.; the standard deviation is 5.5°F.; and the skew, using the third moment about the mean divided by the cube of the standard deviation as a measure,[35] is .08 or negligible.

A marked difference exists between the mean sea temperature and the mean maximum temperature of the continental air; therefore, the maximum temperature at Torbay is considerably more dispersed than the minimum temperature. The mean daily maximum temperature for the eleven year period 1942-52 is 67.7°F.; the standard deviation is 7.8°F.; and the skew of the maximum temperature distribution is -.28 or appreciable.

[35]Richardson, C.H., An Introduction to Statistical Analysis, p. 101.

Before smoothing the frequency polygon, there existed a pronounced maximum at 72°F.; the polygon is skewed towards this maximum such that the median value is 69.6°F.. This primary maximum is comparable to the mean maximum temperature of the continental air (73°F.). A poorly defined secondary maximum resulting from maritime circulations is located at 61°F..

The dominance of the continental temperature cycle in the maximum temperatures at Torbay is manifest through the pronounced dispersion and skew in the temperature distribution. The similarity in the continental and maritime minimum temperatures renders the two types indistinguishable during the month of August.

## CHAPTER VII

## THE DISTRIBUTION OF MAXIMUM AND MINIMUM TEMPERATURE

The complexity of the temperature distribution at Torbay is due to the combined effects of the continental and maritime air. A study of the temperatures associated with air-masses or wind direction indicates more distinctly the role played by the sea and the continent.

An analysis of the maximum and minimum temperature according to air-mass partially takes into account such air properties as stability and humidity. It does not, however, take into account the direction of the surface wind, which is very important. On the other hand, an analysis strictly on the basis of wind direction fails to take into account the important values accounted for in an air-mass analysis.

Neither air-mass nor circulation provide, in themselves, an entirely satisfactory method of temperature investigation; therefore, both have been used to study the distribution of the daily maximum and minimum temperature.

The variation of temperature with wind direction. The extent of the land area about Torbay and the difference between the continental and maritime air-masses result in a marked variation of the mean maximum or minimum temperature with wind direction.

The mean of the daily maximum and minimum temperature for each $10^{\circ}$ of the geostrophic wind direction have been determined for Torbay, and these are presented in Figure 4, page 39, and Figure 5, page 40. Both Figures 4 and 5 are presented in the form of polar diagrams which are superimposed on rough maps of the Torbay area; the centre of the polar diagram coincides with the position of the observation station. This method of presentation permits a comparison of the mean temperature with the extent of land about the observation station; in Figure 5 height contours are given that topographical features may be considered.

The polar diagram of the mean maximum temperature shows a pronounced difference between the land and sea circulations. Over the sector $200^{\circ}$ to $310^{\circ}$, measured clockwise, the mean temperature is virtually constant at $72^{\circ}$F., while for the sector $360^{\circ}$ to $070^{\circ}$ it lies between $57^{\circ}$F. and $58^{\circ}$F., and for the sector $080^{\circ}$ to $150^{\circ}$ it is about $60^{\circ}$F.. The remaining sectors display mean temperatures which are midway between those of adjacent sectors.

The variation in mean minimum temperature with geostrophic wind direction is shown in Figure 5, page 40. The distribution is quite different from that of the maximum temperature due to the similarity of the sea surface temperature to the continental minimum and to the variation of stability with wind direction. With winds arriving from the sector $120^{\circ}$ to $280^{\circ}$ the mean minimum temperature is about $55^{\circ}$F., while with winds arriving from the remaining sector the mean minimum temperature is about $49^{\circ}$F..

<u>Air-mass</u> <u>and</u> <u>circulation</u> <u>temperature</u> <u>distribution</u>. The distributions of the daily maximum and minimum temperature for the air-masses and circulations, for which the mean temperature is relatively constant, are given graphically in Figures 6 and 7, pages 42-43, and numerically

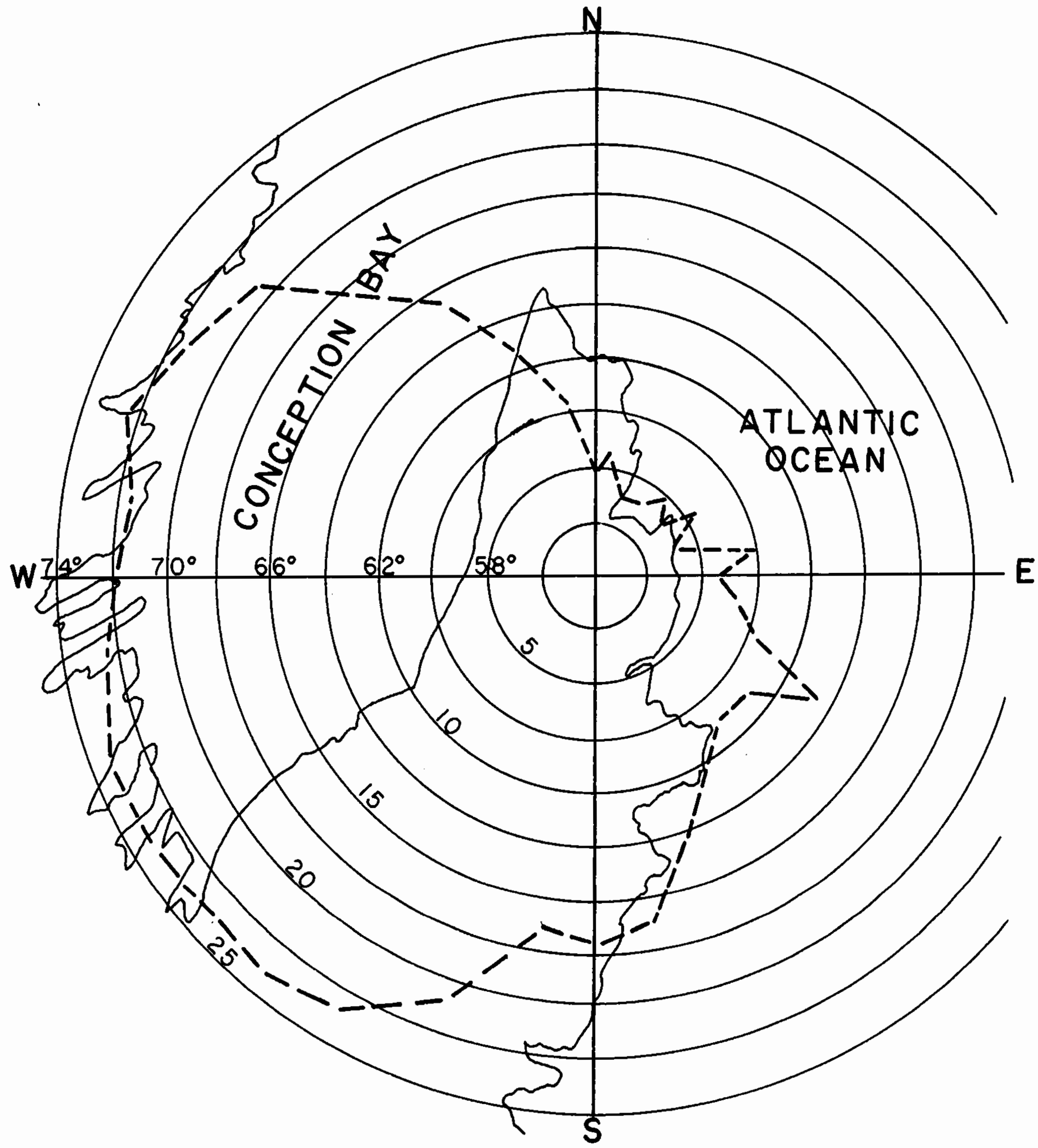


FIGURE 4

MEAN MAXIMUM TEMPERATURE ACCORDING TO WIND DIRECTION

Note: The dashed line describes the mean maximum temperature. Temperatures are measured in °F. along the 270° axis and distance in miles in the southwest quadrant.

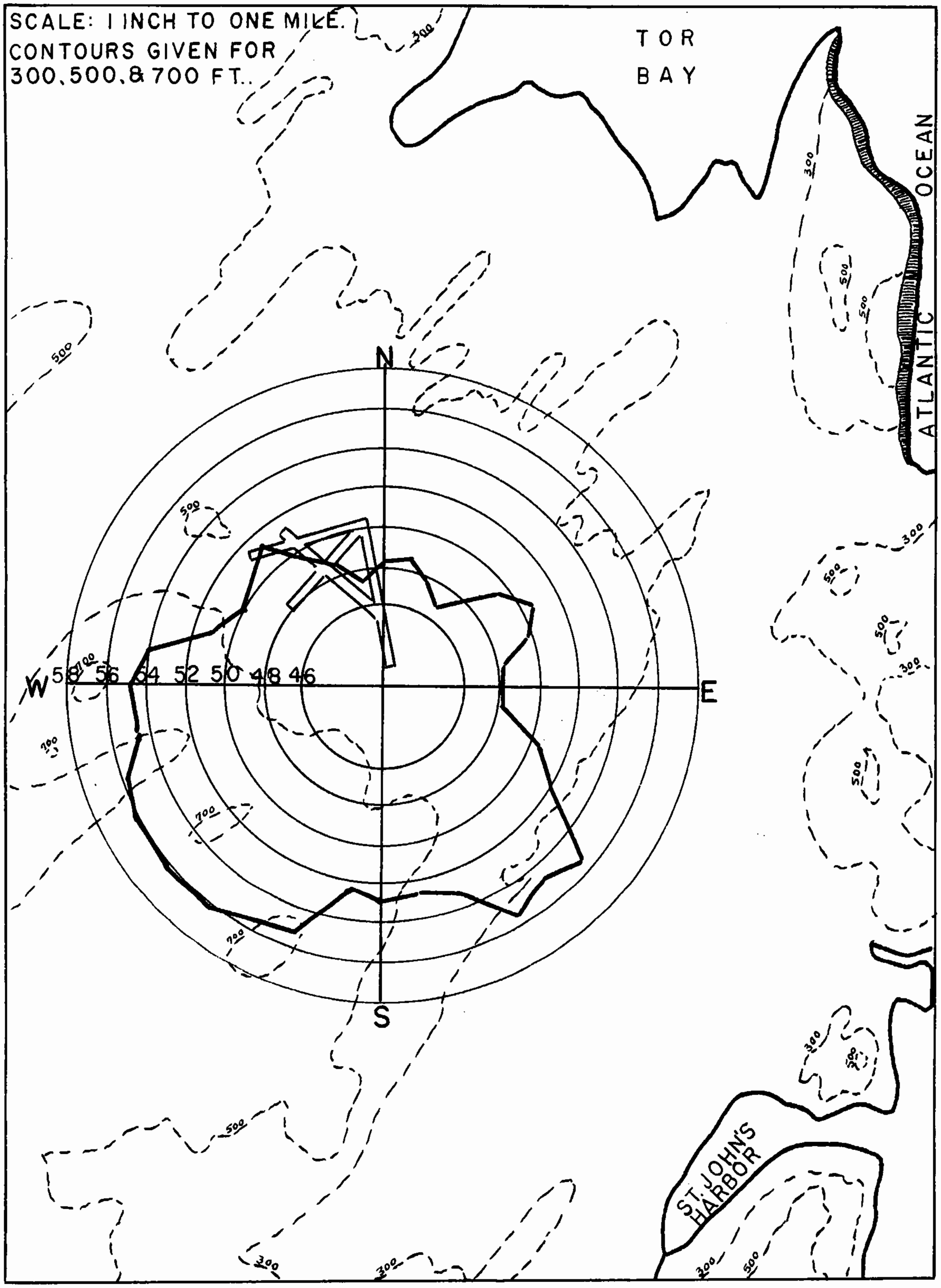


FIGURE 5

MEAN MINIMUM TEMPERATURE ACCORDING TO WIND DIRECTION in Table II, page 44. The paucity of data used in determining the distributions for some of the lesser air-masses makes these subject to question. A comparison of the air-mass frequencies from night to day also suggests that there may have been some bias in choosing between T and PM and between PC and PM1 at night. Despite these possibilities, the distributions do give a very lucid picture of the maximum and minimum temperatures.

In selecting data for these distributions it has been necessary to eliminate those cases where air-mass change has rendered unrepresentative the maximum or minimum temperature reported for the day. For this reason the number of cases used for each air-mass has been reduced to about 80 or 90 per cent of those possible, with the exception of the PM air-mass for which it has been possible to use only 46 per cent of the total number possible. A high percentage of the incursions of PM air over Newfoundland is associated with rapidly moving storms, and its presence is normally of relatively short duration.

Both circulation and air-mass temperature distributions bring the effects of the sea and continent into prominence. By day, westerly circulations are basically continental and the mean temperature experienced at Torbay approximates those of other eastern Canadian localities; by night, there appears to be little distinction between the minimum temperature in the major continental and maritime circulations, but the effect of the cold sea to the north of the Avalon Peninsula is appreciable.

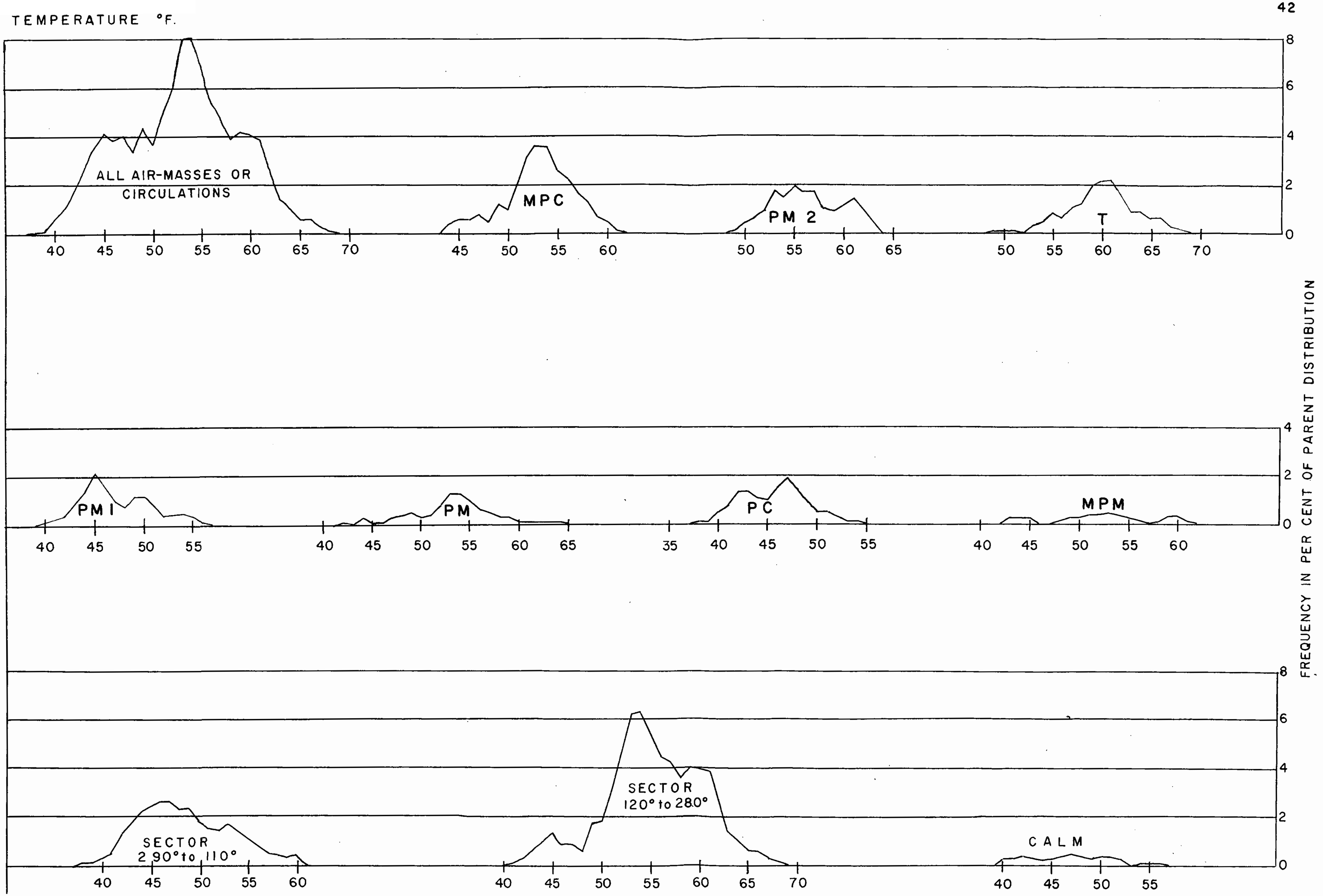


FIGURE 6

FREQUENCY POLYGONS OF THE TORBAY MINIMUM TEMPERATURE ACCORDING TO AIR-MASS AND CIRCULATION

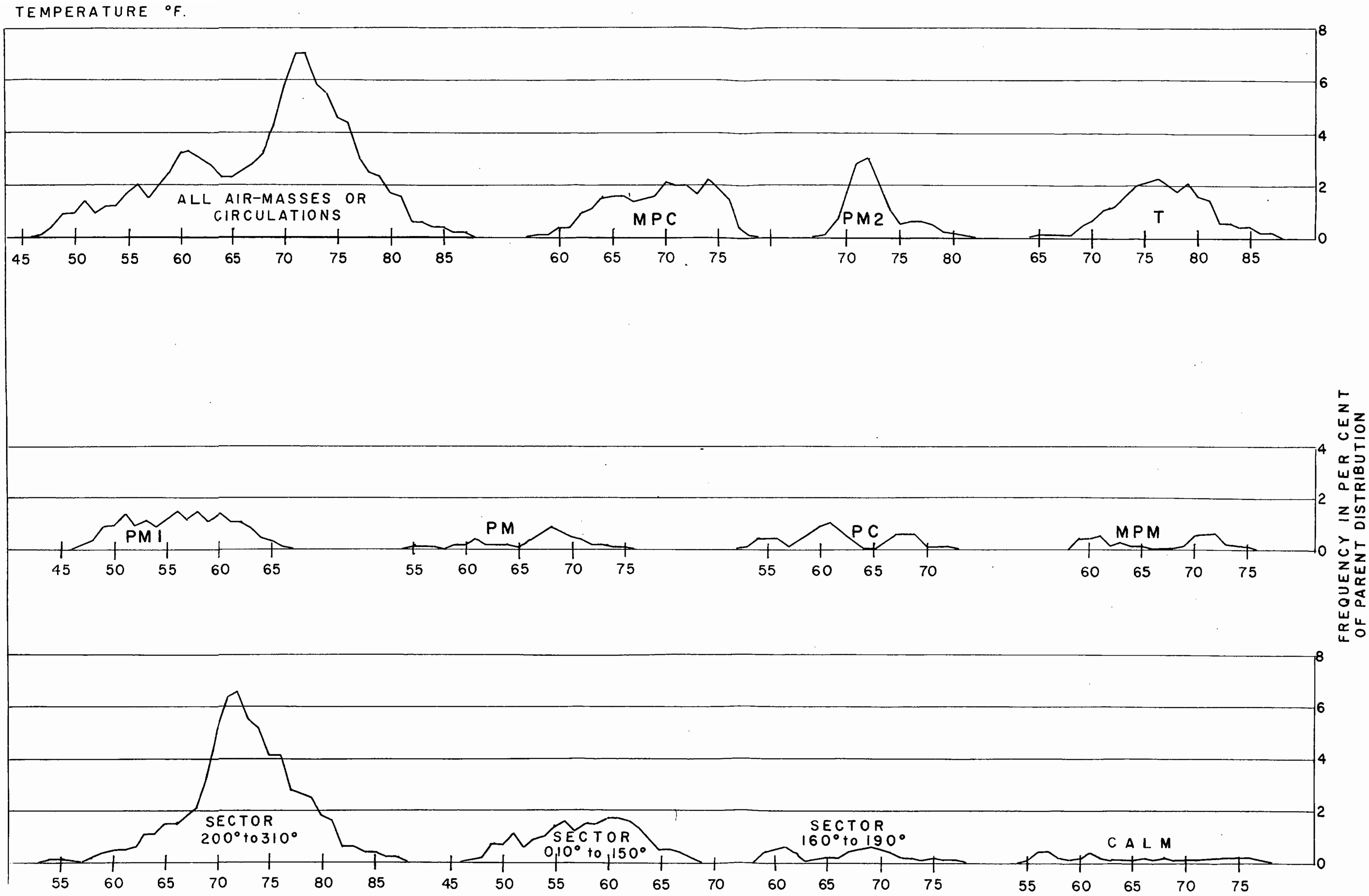


FIGURE 7

FREQUENCY POLYGONS OF THE TORBAY MAXIMUM TEMPERATURE
ACCORDING TO AIR-MASS AND CIRCULATION

TABLE II

THE MEAN, STANDARD DEVIATION, RANGE, AND FREQUENCY OF OCCURRENCE OF THE DAILY MAXIMUM AND MINIMUM TEMPERATURE ACCORDING TO AIR-MASS AND CIRCULATION

| Air-mass or Circulation | Maximum Temperatures | | | | Minimum Temperatures | | | |
|---|---|---|---|---|---|---|---|---|
| | No. Cases | Mean | Standard Deviation | Range | No. Cases | Mean | Standard Deviation | Range |
| MPC | 70 | 69.4° F. | 4.5° F. | 19° F. | 70 | 53.2° F. | 3.5° F. | 16° F. |
| PM | 17 | 66.4 | 5.1 | 19 | 24 | 53.1 | 4.5 | 21 |
| PM1 | 50 | 56.5 | 4.7 | 19 | 35 | 47.3 | 3.6 | 15 |
| PM2 | 39 | 72.6 | 2.5 | 12 | 42 | 56.4 | 3.4 | 13 |
| MPM | 11 | 66.7 | 5.5 | 14 | 11 | 52.0 | 5.2 | 17 |
| T | 64 | 76.5 | 4.1 | 21 | 41 | 60.1 | 3.6 | 18 |
| PC | 20 | 61.7 | 4.8 | 17 | 36 | 45.6 | 3.3 | 14 |
| 200° to 310° | 176 | 72.6 | 5.3 | 32 | | | | |
| 010° to 150° | 57 | 57.6 | 3.9 | 20 | | | | |
| 120° to 280° | - | - | - | - | 168 | 55.4 | 5.0 | 26 |
| 290° to 110° | - | - | - | - | 79 | 48.4 | 4.5 | 21 |
| All cases | 341 | 67.7 | 7.8 | 39 | 341 | 52.8 | 5.5 | 27 |

The complexity of the frequency polygons of the daily maximum and minimum temperatures[36] are readily explained in the light of these distributions.

The value of the refinement of the temperature data according to air-mass and circulation is evinced by the difference between the arithmetic mean, standard deviation, and range of these groupings and those of the parent temperature distribution. The reduction in the range and standard deviation and the distinct differences in means indicate that the refinement is a positive asset in temperature prediction.

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[36] _Cf_. p. 34.

CHAPTER VIII

MAXIMUM TEMPERATURE RELATIONS

The increase in temperature, by day, of the air near the ground is caused by the receipt of solar energy at the ground in excess of the energy lost at the ground through radiation and other processes. Weather conditions, which may limit the solar energy received or affect the distribution of the energy received by the air from the ground, also limit or affect the maximum temperature. The influence of the more significant weather conditions such as cloud, warmth of the air stratum near the ground, and wind speed is discussed and investigated in this chapter.

I. PROCESSES ASSOCIATED WITH DAYTIME HEATING

Daytime heating is directly ascribed to the energy gained at the ground through insolation, and weather conditions which limit the insolation received at the ground bear a relation to the daytime maximum temperature. Solar radiation may be reflected back to space by clouds, the earth, and the atmosphere. It is partially absorbed by the clouds and water vapor present in the atmosphere. While the bulk of all incoming solar radiation reaches the ground, it is estimated that annually 33 per cent is reflected back to space from clouds.[37] The pure atmosphere, atmospheric pollution, and water vapor reflect sunlight back to space; but the quantity reflected is small, and the

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[37] Geiger, Rudolph, Climate Near the Ground, p. 2.

variability of the reflectors is smaller still. Clouds are the major variable factor which limit the insolation incident upon the ground.

Energy received at the ground may be distributed both within the ground and the air. The energy distribution within the ground depends on its thermal conductivity and capacity. The rate of dissipation within the ground is relatively small, and the ground surface may become extremely hot as a result. Energy is received by the air near the ground through radiation from the earth's surface, eddy diffusion, and conduction. Convection and radiation play a dominant role in the interchange of energy between the ground and the air.

## II. INVESTIGATION OF THE RELATIONS

Since this study is of exclusive data, many factors associated with the daytime energy exchange need not be considered. Humidity, pollution, evaporation and stability are largely a function of air-mass or circulation; for this reason, they have been partially considered. Solar elevation, the time of heating, and nature of the ground need not be considered since the study is restricted to a single location and to a single month.

The significant factors to be considered are: (1) the reflection of insolation from clouds; (2) radiation from the ground to the air; (3) eddy diffusion. The investigation of maximum temperature relations takes into account directly or indirectly these factors and the influence of the sea. In it the following relations are considered: (1) the influence of cloud albedo; (2) the warmth of the near-ground air stratum; (3) the effect of wind speed; (4) the sea breeze. The albedo relation gives directly the effect of loss of insolation through cloud reflection and absorption; the effects of radiation and convection are manifest in the relationship between the warmth of the air near the ground and the maximum temperature; the increase in eddy diffusion through wind is considered in the investigation of temperature with wind speed.

Cloud albedo. Clouds are the major variable factor which prevents insolation from reaching the ground. On the average, clouds reflect 55 per cent of the solar radiation incident upon them; they may absorb 20 per cent of the incident radiation. Marked deviations from the average albedo do occur, and for overcast skies the albedo may range from 15 to 85 per cent depending on the cloud type.[38]

Assuming a linear relation between the cloud albedo and the maximum temperature, correlation coefficients were determined for the air-masses and circulations. These and related data are presented in Table III. The correlations are generally low and of small confidence. The best correlations are obtained for the maritime circulation and the PM air-mass.

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[38] Fritz, Sigmund, "Solar Radiant Energy," Compendium of Meteorology, p. 29.

TABLE III

RELATIONS BETWEEN CLOUD COVER, EXPRESSED AS ALBEDO, AND THE MAXIMUM TEMPERATURE

| Air-mass or Circulation | No. of Cases | Correlation Coefficient r | 95% Probability of true value of r being within: | .01 Significance Level | Mean Temperature | Mean Albedo % |
|---|---|---|---|---|---|---|
| MPC | 71 | -.36 | -.14 and -.55 | -.30 | 69 | 20 |
| PM | 17 | -.92 | -.78 and -.97 | -.61 | 67 | 44 |
| PM1 | 50 | -.28 | -.01 and -.53 | -.36 | 56 | 55 |
| PM2 | 38 | -.27 | .06 and -.55 | -.41 | 72 | 27 |
| T | 56 | -.39 | -.13 and -.59 | -.35 | 76 | 32 |
| PC | 21 | -.48 | -.05 and -.76 | -.55 | 62 | 18 |
| 200° to 310° | 156 | -.28 | -.14 and -.43 | -.20 | 73 | 27 |
| 010° to 150° | 57 | -.50 | -.27 and -.68 | -.33 | 58 | 51 |

The length of the land trajectory is probably responsible for the more pronounced effect of cloud cover on temperature with maritime circulations. As the period of heating increases, energy received from the ground is distributed through a deeper section of the troposphere, and the rate of temperature increase in the air near the ground becomes less rapid. Air arriving directly off the sea has experienced a very short period of heating, and the warming is confined to the lowest stratum. Variations in the amount of heating produce marked variations in the air temperature, and for this reason cloud cover may have a pronounced effect on the maximum temperature.

There is some doubt as to the validity of the assumption of a linear relation between cloud albedo and the maximum temperature. When the air is very unstable, the presence of cloud may appear to have very little effect on the maximum temperature. Robinson states that radiation may be equally important as convection in warming the lower troposphere,[39] and strong radiation accounts for the superadiabatic lapse rates which occur near the ground. These radiative effects make possible a fair correlation between albedo and the maximum temperature even when the air is unstable.

In order to observe the degree of interrelation between the weather variables used, the correlations for cloud albedo and the relations between albedo and wind speed were investigated.

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[39]Robinson, G.D., "Two Notes on Temperature Changes in the Troposphere Due to Radiation," <u>Centenary Proceedings</u>, pp. 26-29.

In thirty-five cases of maritime circulation a correlation coefficient of .01 was obtained for the association of cloud albedo and thickness, while for one hundred and one cases of offshore circulation a coefficient of .03 was obtained. It may be claimed, therefore, that there is little association of these values and that their effects on maximum temperature are relatively independent.

The variation of cloud albedo with wind speed is given in Table IV. With offshore winds there does not appear to be a significant association of cloud albedo with wind speed, the highest albedos occurring with very light and very strong winds. With omshore winds there is an increase in the average albedo with an increase in wind above twenty-five knots.

The average effects of cloud albedo on the maximum temperature are given in Table V, page 53. With offshore winds the maximum temperature averages about four degrees higher with sunny skies than with very dull skies. With onshore winds sunny days average six degrees warmer than days with a heavy overcast.

Thickness. The air near the ground is warmed during the day through the gain of heat from the ground by eddy diffusion and radiation. Within an air-mass class, barring the effects of cloud and wind, the methods by which the energy gained is dispersed do not vary appreciably; the maximum temperature, therefore, is a function of the general warmth of the air at a specific time of day.

The effects of insolation on each air-mass may be anticipated from the average aerological ascents presented in Appendix A. These

TABLE IV

THE RELATION BETWEEN ALBEDO AND GEOSTROPHIC WIND SPEED

| Geostrophic wind speed in kts. | 0 - 14 | 15 - 24 | 25 - 35 | 36 or more |
|---|---|---|---|---|
| Onshore Circulation: | | | | |
| Average Albedo in % | 45 | 44 | 52 | 66 |
| No. of cases | 17 | 18 | 12 | 9 |
| Offshore Circulation: | | | | |
| Average Albedo in % | 28 | 22 | 25 | 28 |
| No. of cases | 24 | 62 | 58 | 12 |

TABLE V

THE EFFECT OF CLOUD ALBEDO ON THE MEAN MAXIMUM TEMPERATURE

| Albedo in per cent | 0 - 10 | 11 - 30 | 31 - 50 | 51 - 70 | 71 - 85 |
|---|---|---|---|---|---|
| Circulation 010° to 150° | | | | | |
| Mean Maximum | 60.6 | 60.3 | 57.5 | 56.0 | 56.2 |
| No. of cases | 8 | 10 | 8 | 15 | 15 |
| Circulation 200° to 310° | | | | | |
| Mean Maximum | 73.4 | 73.1 | 71.4 | 71.3 | 69.5 |
| No. of cases | 63 | 43 | 29 | 13 | 8 |

averages are given according to air-mass, and have been prepared from four years of data. The means of the temperature for the indicated pressure levels and layers of stability or instability which were a dominant characteristic have been used in drawing the average ascents.

The preponderance of the heat transfer from the ground to the troposphere during the day is confined to the air layer below 850 millibars; therefore, the relation between the thickness of this layer and the maximum temperature has been used in this study.

The correlation coefficients and relevant data for the maximum temperature and thickness are given in Table VI. The correlations are generally significant, but are highly significant for the offshore circulation and for the MPC air-mass; the regression equations for this circulation and air-mass give a reasonably accurate prediction of the maximum temperature. Warm stable maritime air-masses give the poorest correlations.

When skies are sunny it is common practice to use the temperature of the air at 850 millibars in predicting the daytime maximum temperature. On a rough assumption that the offshore circulations are sunny (average albedo 27 per cent), the value of the correlation coefficient relating maximum temperature and the 850 millibar temperature was calculated. The value obtained was .68 which indicates that the 850 millibar temperature is not as useful as the thickness which, for the same set of data, had a correlation coefficient of .78.

Wind speed. Brunt has shown that the transfer of heat by mixing increases the entropy of the system, and results in the potential temp-

TABLE VI

THE RELATIONS BETWEEN THE MEAN MAXIMUM TEMPERATURE AND THE THICKNESS OF THE STRATUM BETWEEN 1,000 AND 850 MILLIBARS AT 15.00 G.M.T.

| Air-mass or Circulation | No. of Cases | Correlation Coefficient r | 95% Probability of true value of r being within: | .01 Significance Level | Regression Equations [x] | 2 x Standard Error |
|---|---|---|---|---|---|---|
| MPC | 46 | .74 | .57 and .85 | .37 | Y = .724X - 255 | 6.3 |
| PM | 12 | -.06 | -.61 and .54 | .71 | | |
| PM1 | 31 | .65 | .38 and .82 | .46 | Y = .517X - 172 | 7.2 |
| PM2 | 19 | .42 | -.05 and .74 | .57 | | |
| T | 39 | .49 | .18 and .70 | .41 | Y = .463X - 135 | 6.5 |
| PC | 13 | .67 | .18 and .89 | .69 | Y = .763X - 275 | 7.6 |
| 200° to 310° | 108 | .78 | .68 and .84 | .24 | Y = .687X - 237 | 6.5 |
| 010° to 150° | 35 | .57 | .29 and .76 | .42 | Y = .504X - 165 | 7.6 |

[x] The key to the letters used in the regression equations is as follows: Y is the predicted value of the maximum temperature in °F.; X is the thickness in tens of geopotential feet.

erature of the system becoming equal to the mean of the potential temperature of the constituents.[40] Turbulence due to wind tends to neutralize the gradient of potential temperature, resulting in an adiabatic lapse rate. With clear skies the daytime maximum temperature occurs at a time when the potential temperature near the ground decreases with height; therefore, the effect of increased wind would be to decrease the maximum temperature.

A complication to this generalization is introduced by the proximity of the ocean. The diurnal variation of temperature of the air over the sea is negligible.[41] The only warming received by day by the maritime air is that over the short land trajectory between the coast and the observation station. The length of the time of warming, therefore, is inversely proportional to the wind speed, and the mean maximum temperature decreases as the wind speed increases.

The effect of increasing wind on the mean temperature is shown by the data in Table VII. In this table the mean temperatures are presented for every five knot range of geostrophic wind speed for the two major circulations. The value of the table is hampered by the paucity of data for very light and very strong winds. With offshore winds there is an increase in the mean maximum temperature as the wind increases from very light to about twenty-five knots, while beyond this strength the temperature decreases steadily. With onshore

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[40] Brunt, David, Physical and Dynamical Meteorology, p. 74.

[41] Sverdrup, H.U., Oceanography for Meteorologists, p. 80.

TABLE VII

THE MEAN MAXIMUM TEMPERATURE FOR RANGES OF GEOSTROPHIC WIND SPEED

| Geostrophic Wind in knots | 5 or less | 6-10 | 11-15 | 16-20 | 21-25 | 26-30 | 31-35 | 36-40 | 41-45 | 46-50 | 51-55 | 56-60 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Circulation sector 010°-150° | | | | | | | | | | | | |
| Mean Maximum °F. | 59.4 | 62.6 | 60.4 | 56.0 | 58.2 | 53.0 | 54.2 | 54.7 | 50.0 | 58.3 | -- | 50.5 |
| No. of cases | 8 | 5 | 11 | 8 | 8 | 3 | 4 | 3 | 1 | 3 | 0 | 2 |
| Circulation sector 200°-310° | | | | | | | | | | | | |
| Mean Maximum °F. | 67.0 | 71.1 | 71.3 | 72.6 | 74.6 | 73.9 | 74.1 | 71.9 | 69.0 | -- | 71.5 | |
| No. of cases | 2 | 11 | 39 | 27 | 32 | 22 | 11 | 8 | 2 | 0 | 2 | |

winds there is a steady decrease of the mean maximum temperature with increasing speed until the wind reaches a velocity of thirty-five knots; beyond this value the results are not conclusive. The influence of wind speed appears to be sufficient to vary the mean maximum temperature through a temperature range of seven to nine degrees.

The abnormal effect of wind speed for the offshore circulation may be attributed to the sea breeze. The sea breeze is most probable with very light gradient winds and the cooling effect of the breeze would produce the observed result.

The influence of wind speed on temperature is dependent on the degree of stability of the air near the ground. The degree of stability is, on the average, indicated by the air-mass type; however, as a further check on the effects of stability, the variation of the mean maximum temperature with wind speed was determined according to the curvature of the mean sea level isobars.

For the offshore circulation the following distribution of curvature was obtained: (1) seventy-two anticyclonic cases with a mean albedo of 20 per cent and a mean temperature of 72°; (2) thirty-three instances of cyclonic curvature with an average albedo of 25 per cent and a mean temperature of 71°; (3) fifty-one cases with no apparent curvature, and with an average albedo of 31 per cent and a mean temperature of 73°. The warmth and cloudiness of the last mentioned case is due to the high incidence of humid tropical air in this particular group.

The mean maximum temperatures, for ranges of wind speed according to isobaric curvature, are given in Table VIII, and they are generally

## TABLE VIII

## THE EFFECT OF STABILITY ON TEMPERATURE-WIND RELATIONS

| Geostrophic wind in kts. | Anticyclonic Curvature | | | Cyclonic Curvature | | |
|---|---|---|---|---|---|---|
| | 0 - 15 | 16 - 25 | 26 or more | 0 - 15 | 16 - 25 | 26 or more |
| Sector 200° to 310°: | | | | | | |
| Mean Maximum °F. | 70.7 | 74.9 | 72.5 | 70.2 | 72.1 | 69.5 |
| No. of cases | 33 | 24 | 15 | 9 | 18 | 6 |
| Sector 010° to 150°: | | | | | | |
| Mean Maximum °F. | 61.1 | 56.9 | 59.0 | 60.0 | 57.8 | 52.8 |
| No. of cases | 15 | 9 | 3 | 5 | 5 | 10 |

higher with anticyclonic curvature. Although the data are too few to be conclusive, strong onshore winds with cyclonic curvature appear to produce much lower maximum temperatures than those with anticyclonic curvature. The significance of the data is partly hidden by the association of cloud amount with wind speed and curvature.

The sea breeze. The true sea breeze is an antitriptic wind, or a wind which blows in the direction of the pressure gradient at right angles to the isobars and isotherms. The action of the sea breeze may be obscured by the gradient wind.[42]

The sea breeze develops through unequal heating of the air over adjacent land and sea areas. It is most frequent over Newfoundland in the spring when the sea is quite cold and the heating of the ground by the sun is intense. The density gradient which develops along the coast results in a landward movement of the air from the sea. This movement is usually evinced as a landward deviation of the surface wind direction. Mid-afternoon winds tend to reach the gradient value through increased convection, and it is most difficult to observe a sea breeze effect with moderate offshore gradient winds. The effect is quite evident when the pressure gradient is light and when it acts at right angles to the gradient wind.

The sea breeze is of concern in temperature prediction when it results in a shift of the surface wind direction from offshore to onshore;

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[42] Defant, Friedrich, "Local Winds", Compendium of Meteorology, p. 655.

discussion of the sea breeze in the remainder of this study has been restricted to such instances.

Through reflection of insolation back to space, clouds may appreciably limit the warming of the air near the ground. Defant has determined the association between sea breeze and cloud for the Black Sea, and claims that the probability of occurrence increases from 27 per cent with virtually overcast skies to 90 per cent with sunny skies.[43]

Thirty-three pronounced sea breezes were observed in the period investigated. In each case the surface wind changed from offshore to onshore and back during the day while the geostrophic wind was of an offshore direction. The frequency with which these occurred in relation to the wind speed when the geostrophic wind was from the sector 200° to 310° is given in the following table.

TABLE IX

FREQUENCY OF OCCURRENCE OF A PRONOUNCED SEA BREEZE IN RELATION TO THE GEOSTROPHIC WIND SPEED

| Geostrophic wind in kts. | Less than 5 | 6-10 | 11-20 | 21-30 | Above 30 |
|---|---|---|---|---|---|
| No. of cases | 9 | 4 | 11 | 2 | 0 |
| Per cent of possible cases | 100 | 28 | 17 | 3 | 0 |

A sea breeze is caused by a density difference; therefore, the temperature at which it starts will be a function of the general warmth

[43] Ibid., p. 658.

of the air near the ground, or thickness of the near-ground air stratum. The maximum temperature is generally reached just before the surface wind shifts to onshore, and this temperature may be considered as that at which the sea breeze begins.

The correlation coefficient for thickness and maximum temperature for twenty-one instances of sea breeze occurrence was determined to be .92 with a one per cent significance level of .55, and a 95 per cent probability that the true value of the correlation coefficient lies within .81 and .97. The regression equation obtained for this highly significant relation is:

$$Y = 1.100X - 423$$

where Y is the predicted maximum temperature and X is the thickness of the air stratum between 850 and 1,000 millibars in tens of geopotential feet. There is a 95 per cent probability that the observed value of the maximum temperature will lie within one degree of the predicted value.

In summation it may be stated that: (1) a sea breeze is most probable when there are clear skies and the geostrophic wind is less than fifteen knots; (2) when there is a sea breeze, the maximum temperature is closely related to the thickness of the air stratum near the ground.

CHAPTER IX

# MINIMUM TEMPERATURE RELATIONS

In the absence of insolation the ground experiences a continual loss of heat through radiation. The rate of cooling depends on the radiating temperature, the rate at which radiant energy is returned to the earth from the atmosphere, and the liberation of heat through the deposition of dew. The minimum temperature, therefore, is related to: (1) the warmth of the air stratum near the ground; (2) the amount and type of cloud cover; (3) the dew point which indicates the temperature at which the rate of cooling changes. These three relationships and that of the minimum temperature to wind speed are considered in this chapter.

## I. PROCESSES AFFECTING MINIMUM TEMPERATURE

Radiation within the atmosphere warms the air below an inversion and cools the air above it. After the formation of a nocturnal ground inversion there is a strong flux of heat downward which tends to warm the air nearest to the ground. The fact that the inversion continues to develop indicates that the heat loss at the ground surface through radiation, and the distribution of this heat loss through conduction and diffusion, are the most decisive factors in the nocturnal cooling of the air near the ground.[44]

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[44] Möller, Fritz, "Long-Wave Radiation," Compendium of Meteorology, pp. 38-48.

The earth, clouds, and atmospheric water vapor and carbon dioxide participate in an energy exchange with the energy emitted from each being roughly proportional to the fourth power of its absolute temperature. With clear skies the amount of the downward radiation from the air stratum near the ground is relatively large. Möller states that 37 per cent of the radiation reaching the ground proceeds from the lowest ten metres, 71 per cent from the lowest one hundred metres, and 88 per cent from the lowest five hundred metres; he also claims that the effect of the ground inversion is such that it may reduce the effective ground radiation loss to four fifths or even as low as one half of its possible value[45]. The sky radiation reaching the ground is increased by the presence of clouds. Brunt states: "The net loss of heat by the ground is therefore considerably diminished, approximately by an amount equal to the radiation from the cloud in the wave-lengths of the transparent band."[46] The transparent band refers to those wave lengths in the infra-red spectrum in which water vapor does not absorb. The intensity of the cloud radiation depends on the temperature of the base of the cloud which, in turn, is dependent on the height of the base.

Large amounts of energy may be released through the deposition of dew, a process which seriously affects the rate of cooling of the ground. As the air near the ground cools it may reach a saturation point with respect to water vapor content. Further cooling

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[45] Ibid., p. 39.

[46] Brunt, David, Physical and Dynamical Meteorology, p. 143.

results in the deposition of dew and the release of the heat of condensation, which alters the rate of cooling appreciably.

The cooling of the air near the ground results in the formation of a positive gradient of potential temperature in the vertical direction. Since the effect of turbulence within the air is to destroy the vertical gradient of potential temperature, an increase in wind destroys the nocturnal inversion and causes a temperature increase near the ground.

Cooling of the thin air layer near the ground results in a horizontal gradient of air density wherever the ground is not level. This causes drainage of the thin cold skin of air into valleys and its replacement by warmer air from higher levels. In this way local topography may play a significant role in the minimum temperature regime.

The warming of the ground surface from the subsoil depends on the thermal conductivity and specific heat of the soil. These factors and the length of the cooling period need not be considered by virtue of the exclusive nature of the data used.

## II. INVESTIGATION OF THE RELATIONS

The variables which appear to have a significant effect on the minimum temperature are cloud cover, water vapor content of the air, warmth of the air stratum near the ground, and wind speed and direction.

Thickness. When clouds are absent, most of the radiation reaching the ground at night is derived from the air stratum near the ground. The average temperature of this stratum is a fair measure of the radiation it emits, as well as a measure of the initial radiating temperature of the ground. The vertical thickness of the stratum is an excellent measure of the mean temperature of the stratum.

The coefficients of correlation and other pertinent data showing the relationship between thickness and minimum temperature are given in Table X. Although none of the coefficients are very large, they are significant for the circulations and for the air-masses which are associated mainly with southwest winds.

The individual air-masses have characteristic vertical temperature gradients. The averages of aerological ascents for the air-masses may be seen in Appendix A. The nocturnal inversion is visible in the T air-mass by 03.00 G.M.T., while at this time both the PC and the PM1 air-masses show very little or no indication of an inversion. These air-mass peculiarities are partly taken into account in the circulations since the air-masses PM1 and PC arrive mainly from the north, and the more stable air-masses arrive from the south.

The thickness of the air stratum between 850 and 1,000 millibars exhibits a significant relationship with minimum temperature. This relationship is best expressed in an analysis according to circulation which appears to incorporate the effect of the vertical temperature structure of the air.

Cloud albedo. The reduction of the net radiation loss at the ground through the presence of cloud is inversely proportional to the

TABLE X

RELATIONS BETWEEN THICKNESS OF THE AIR STRATUM BETWEEN 850 AND 1,000 MILLIBARS AT 03.00 G.M.T. AND THE MINIMUM TEMPERATURE

| Air-mass or Circulation | No. of Cases | Correlation Coefficient r | 95% Probability of true value of r being within: | .01 Significance Level | Regression Equations* | 2 x Standard Error |
|---|---|---|---|---|---|---|
| MPC | 56 | .56 | .35 and .72 | .35 | Y = .450X - 150 | 6.0 |
| PM | 14 | .31 | -.27 and .73 | .66 | | |
| PM1 | 23 | .39 | -.04 and .70 | .53 | | |
| PM2 | 24 | .53 | .15 and .77 | .52 | Y = .341X - 97 | 5.8 |
| MPM | 9 | .19 | -.55 and .77 | .80 | | |
| T | 28 | .06 | -.34 and .42 | .48 | | |
| PC | 18 | .13 | -.37 and .57 | .59 | | |
| 120° to 280° | 108 | .58 | .46 and .68 | .24 | Y = .606X - 219 | 8.4 |
| 290° to 110° | 53 | .59 | .37 and .74 | .35 | Y = .471X - 161 | 7.7 |

* In the regression equations Y is the predicted value of the minimum temperature, X is the thickness in tens of geopotential feet.

cloud height. The cloud albedo is roughly inversely proportional to the cloud height; therefore, albedo has been employed as a measure of the radiative power of the cloud. On this very coarse assumption correlation coefficients were determined as a measure of the relationship between cloud cover and minimum temperature.

The problem is much more delicate than the treatment awarded it. Möller suggests that the departure from expected radiative losses may be due to the presence of thin invisible cloud veils.[47] Such fine details in cloud structure are beyond the scope of present day forecasting; therefore, the coarse methods used in the investigation are probably justified.

The average effects of cloud cover on the minimum temperature are presented in Table XI. The correlation coefficients for the airmasses and circulations are small and of low significance. The table indicates that the distribution of cloud is much the same for both high and low minimum temperatures. The conclusion that the net effect of cloud on minimum temperature is small must not be construed as meaning that the effect of cloud in an individual instance is small. The results obtained are representative of strictly average conditions.

The dew point. The release of heat through the formation of dew retards the rate of cooling of the ground at night. The rate of cooling changes when the dew point is reached; therefore, the minimum

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[47] Möller, loc. cit.

TABLE XI

RELATIONS BETWEEN THE CLOUD ALBEDO AND THE MINIMUM TEMPERATURE

| Air-mass or Circulation | No. of Cases | Correlation Coefficient r | 95% Probability of true value of r being within: | .01 Significance Level | Mean Albedo % |
|---|---|---|---|---|---|
| MPC | 71 | .03 | -.21 and .26 | .30 | 24 |
| PM | 23 | .17 | -.27 and .55 | .53 | 66 |
| PM1 | 34 | .22 | -.14 and .53 | .44 | 61 |
| PM2 | 39 | .18 | -.15 and .48 | .41 | 33 |
| MPM | 13 | .24 | -.43 and .74 | .69 | 46 |
| T | 39 | .01 | -.31 and .33 | .41 | 50 |
| PC | 31 | .16 | -.21 and .49 | .46 | 28 |
| $120^\circ$ to $280^\circ$ | 164 | .17 | .01 and .32 | .20 | 38 |
| $290^\circ$ to $110^\circ$ | 77 | .07 | -.22 and .29 | .29 | 45 |

temperature is related to the dew point.

The association of the dew point with the minimum temperature may also be linked with cloud cover and radiation. In determining the relationship the dew point of the air at 18.30 G.M.T. has been used. At this time convection is most active and the dew point is representative of the moisture content of the air stratum near the ground. The dew point is also an excellent indicator of the night-time formation of very low cloud in the warm air-mass circulations. These added associations enhance the close relationship between the dew point and minimum temperature.

The correlations determined for the dew point and minimum temperature are quite significant in most instances; these and other pertinent data are presented in Table XII. The relationships for circulation are more significant and useful than those for air-mass. The values obtained are exceptionally good when it is considered that advective change in the dew point has not been considered.

The regression equations were determined for those relationships which were significant. The usefulness of these equations in temperature prediction is indicated by the value of twice the standard error of estimate; in 95 per cent of the cases the actual values lie within four to seven degrees of the predicted value.[48]

Wind speed. Aside from the land and sea trajectory differences, wind has a pronounced effect on the nocturnal minimum temperature

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[48]Moroney, M.J., Facts From Figures, p. 296.

TABLE XII

RELATIONS BETWEEN THE DEW POINT AT 18.30 G.M.T. AND THE SUBSEQUENT MINIMUM TEMPERATURE WITHIN THE SAME AIR-MASS

| Air-mass or Circulation | No. of Cases | Correlation Coefficient r | 95% Probability of true value of r being within: | .01 Significance Level | Regression Equations* | 2 x Standard Error °F. |
|---|---|---|---|---|---|---|
| MPC | 48 | .42 | .15 and .63 | .37 | Y = .33X + 35 | 6.5 |
| PM | 17 | .55 | .09 and .82 | .61 | | |
| PM1 | 24 | .74 | .47 and .88 | .52 | Y = .55X + 20 | 3.9 |
| PM2 | 30 | .57 | .26 and .78 | .46 | Y = .45X + 31 | 5.5 |
| MPM | 9 | .28 | -.49 and .80 | .80 | | |
| T | 32 | .58 | .28 and .78 | .45 | Y = .40X + 35 | 5.6 |
| PC | 15 | .57 | .07 and .84 | .64 | | |
| 120° to 280° | 125 | .71 | .61 and .79 | .23 | Y = .59X + 22 | 7.2 |
| 290° to 110° | 44 | .64 | .42 and .79 | .39 | Y = .51X + 22 | 5.9 |

* The key to the regression equations is as follows: Y is the predicted value of the minimum temperature; X is the dew point in °F..

through speed. Radiative processes tend to produce an inversion near the ground. The effect of turbulence is to neutralize the vertical potential temperature gradient; therefore, wind tends to destroy the ground inversion and to increase the air temperature near the ground. Since turbulence increases with wind speed, the minimum temperatures tend to be higher on nights when the wind is strong.

Turbulence is due to friction between the air and the ground, and between air strata. The amount of turbulence depends on the nature of the ground and is proportional to the wind speed.

The amount of warming through turbulence depends, not only on the amount of turbulence, but also on the stability of the air. In general, air arriving from the sector 120° to 280° displays a marked increase in potential temperature with height in the near-ground stratum and the effect of increased wind on this air is to produce a marked warming near the ground. By comparison, the air-masses arriving from the north are considerably less stable, and northerly winds do not produce appreciable warming near the ground. Averages of the aerological ascents for the different air-masses are presented in Appendix A, and both PM1 and PC, which dominate the northerly circulation, display relatively unstable lapse rates in the lower levels.

The relation between wind speed and the minimum temperature is not linear. Once sufficient turbulence exists to destroy the ground inversion further turbulence may result in either warming or cooling, depending on the temperature distribution of the air at higher levels.

The effect of wind speed on minimum temperature is shown in Table XIII, and it is quite different for each circulation. With southerly winds there is an increase in average minimum temperature with speed until a geostrophic wind of twenty-five knots is reached; with very light winds the mean minimum temperature is about five degrees colder than with moderate winds. A continuous decrease in the mean minimum temperature, over a range of eight degrees, occurs as the northerly winds increase from very light to very strong.

The apparent anomaly in the temperature-wind relationship for northerly winds is due to the shortness of the land trajectory and to the inherent instability of the air. The very short land trajectory does not permit a ground inversion of any size to develop. Air arriving from this sector is cold and unstable, and with very strong winds the modification caused by the sea is incomplete.

The coldness of the air and the instability present in the northerly circulation are proportional to the wind speed. Although from classical considerations it might be expected that the coldest temperatures will occur when there are light winds and clear skies, the absolute minimum temperatures at Torbay for the year and for most of the winter months have occurred simultaneously with gales, precipitation, and overcast skies. The absolute minimum temperature for the month of January occurred when the surface winds were recorded as forty miles per hour. With extremely strong northerly winds the rate of advection of air is so rapid that it does not receive the normal modification from the sea; superadiabatic lapse rates are observed near the ground

TABLE XIII

MEAN MINIMUM TEMPERATURES FOR RANGES OF GEOSTROPHIC WIND SPEED

| Wind speed in kts. | 1-5 | 6-10 | 11-15 | 16-20 | 21-25 | 26-30 | 31-35 | 36-40 | 41-45 | 46-50 | 51-55 | 56-60 | 65-70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Circulation 120° to 280° | | | | | | | | | | | | | |
| No. of cases | 7 | 14 | 41 | 39 | 36 | 17 | 6 | 3 | 3 | 1 | | | |
| Mean minimum | 51.6 | 53.8 | 54.4 | 55.9 | 57.1 | 56.5 | 55.5 | 56.0 | 54.0 | 56.0 | | | |
| Mean albedo (%) | 63 | 32 | 32 | 34 | 37 | 35 | 44 | 22 | 37 | | | | |
| Circulation 290° to 110° | | | | | | | | | | | | | |
| No. of cases | 6 | 13 | 22 | 7 | 17 | 5 | 3 | 2 | | | | 3 | 1 |
| Mean minimum | 51.2 | 47.2 | 50.4 | 48.4 | 47.2 | 49.4 | 47.0 | 45.0 | | | | 44.0 | 43.0 |
| Mean albedo (%) | 43 | 31 | 44 | 55 | 29 | 42 | 68 | 55 | | | | 70 | 75 |

level in air associated with these winds. This relation between wind speed and air temperature is largely responsible for the apparent anomaly in the wind-temperature relationship.

Terrain and the land breeze. Topography and the land-sea distribution have a pronounced influence on the minimum temperature regime. A polar diagram of the mean minimum temperature, according to geostrophic wind direction and superimposed on a large-scale map with contour heights, has been shown in Figure 4, page 39. The influence of hills and valleys may be conjectured from this illustration. The distribution of land and sea has been partly introduced into the study through the use of circulation, but for minimum temperature the circulation is based more on stability, since there is little to distinguish between the average continental and the average maritime minimum temperature.

Drainage of the cold air at night from Torbay toward the sea results from the sloping terrain and the land breeze effect. From the hills two miles southwest of the observation station, the ground slopes steadily downward toward the sea, a drop of seven hundred feet occurring within the five miles. Air, which cools by contact with the ground at night, slides down this slope toward the sea and is replaced by warmer air from higher levels.

The combined effects of this drainage and the land breeze may cause an appreciable increase in the offshore wind. The increased turbulence due to this increment and the increased advective warming result in higher minimum temperatures.

The nocturnal increases in offshore winds occur under conditions which are similar to those noted for the sea breeze. In a seven year period there were twenty-seven instances when this drainage and land breeze effect were noticeable. The following are generalized conditions associated with these occurrences:

(1) On the average, the surface wind increased eight miles per hour from the southwest; the extreme increase was eleven.

(2) The peak of the breeze is reached at about 02.30 N.S.T.; deviations of two to three hours from this time are common.

(3) The breeze maintained at least 50 per cent of its strength over an average period of five hours.

(4) Skies were virtually clear in 75 per cent of the cases.

(5) The breeze acts independently of the gradient wind, its effect being to add a southwesterly component to the surface wind.

# CHAPTER X

## TEMPERATURE PREDICTION

The distributions of temperature according to air-mass and circulation, and the relations between temperature and other more readily predictable weather conditions, make possible a reasonably accurate temperature prediction. Use of the many individual relationships is awkward and made difficult through interrelation. Partial regression equations, which introduce all the major variables affecting temperature, provide a simple, yet thorough, method of temperature prediction.

Significant temperature relations. The most significant variable that influences both maximum and minimum temperature is wind direction. The variability of temperature with wind direction is taken into account in the use of circulation, and correlation coefficients of temperature relationships for the circulations have been far more significant than those for the air-masses. An invaluable insight into the temperature regime is provided by the temperature distributions and relations according to air-mass, but circulations provide the most useful relations for prediction and have the added advantage of simplicity.

Three significant relations were obtained for the maximum temperature. The best relation was with thickness, correlation coefficients of .78 and .57 being obtained. The other significant relations were with wind speed and cloud albedo. While thickness is of less significance with an onshore wind than with an offshore wind, the opposite is true for albedo. The regression equation relating thickness and maximum temperature for offshore winds provides a reasonably accurate temperature forecast, but it is evident that the use of thickness alone is not sufficient in all instances.

Three significant relations were noted for the minimum temperature. The best is that with the dew point for which correlation coefficients of .71 and .64 were obtained. The other significant relations were those with thickness and wind speed; the correlation coefficients obtained for the thickness relations were almost as high as those for the dew point. Because of the small standard deviation of minimum temperature the regression equations for temperature and dew point are useful in predicting the minimum temperature.

A highly significant correlation was noted for the maximum temperature and thickness on days when a sea breeze occurs. When a sea breeze is certain, the regression equation for this relation provides a highly satisfactory prediction of the maximum temperature.

Multiple relations. Although simple relations give adequate temperature predictions in some instances, generally many variables must be considered. Three significant relations have been observed for both the maximum and minimum temperature; two of these relations are linear, the third non-linear. The combined effect of these variables on the temperature have been taken into account through the use of adjusted partial regression equations.

The maximum temperature is mainly a function of thickness and wind speed for offshore winds. The offshore circulation embraces most of the cases of maximum temperature; therefore, the maximum temperature relations for ranges of wind speed and albedo have been determined, and these are presented in Table XIV. Except for instances of very strong winds, these relations are quite significant; the regression equations are most useful in temperature prediction. These relations are for a very select group of data and similar refinements of the data for the other sectors are neither possible nor desirable since a very large number of equations would be required.

Using the weather variables which show a significant linear relation with maximum or minimum temperature, partial regression equations were determined for each of the major circulations. Graphs were made of the average bias for wind speed of the predictions made from these regression equations. A correction of the prediction for this bias allows all the significant variables to be taken into account.

In some instances wind is related to thickness,[49] and the partial regression equation, therefore, partly takes wind speed into account. A simple correction to the regression prediction for wind speed is not possible, and the bias of the prediction was used as a device to introduce the full effect of the wind speed. The bias was determined for each five knot range of geostrophic wind speed, and smoothed graphs were drawn from the values obtained. The graphs of the bias for the four partial regression equations are given in Figure 8, page 81.

The multiple correlation coefficients[50] were determined for the partial regression equations with the wind correction modification.

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[49] Cf., p. 70.

[50] Moroney, M.J., Facts From Figures, p. 309.

TABLE XIV

MAXIMUM TEMPERATURE AND THICKNESS RELATIONS FOR RANGES OF OFFSHORE GEOSTROPHIC WIND SPEED AND ALBEDO

| Conditions | No. of Cases | Correlation Coefficient r | 95% Probability true value of r lies between: | .01 Significance Level | Regression Equations* | 2 x Standard Error °F. |
|---|---|---|---|---|---|---|
| Wind 15 knots or less<br>Albedo 15% or less | 23 | .73 | .45 and .88 | .53 | Y = .732X - 257 | 5.8 |
| Wind over 15 knots<br>Albedo 15% or less | 34 | .85 | .72 and .92 | .44 | Y = .654X - 221 | 5.2 |
| Any wind<br>Albedo 20 to 40% | 29 | .84 | .68 and .92 | .47 | Y = .844X - 309 | 6.5 |
| Any wind<br>Albedo over 40% | 22 | .67 | .33 and .85 | .54 | Y = .517X - 162 | 7.4 |

* The key to the regression equations is as follows: Y is the predicted value of the maximum temperature; X is the thickness of the stratum 850 to 1,000 millibars at 15.00 G.M.T. in tens of geopotential feet.

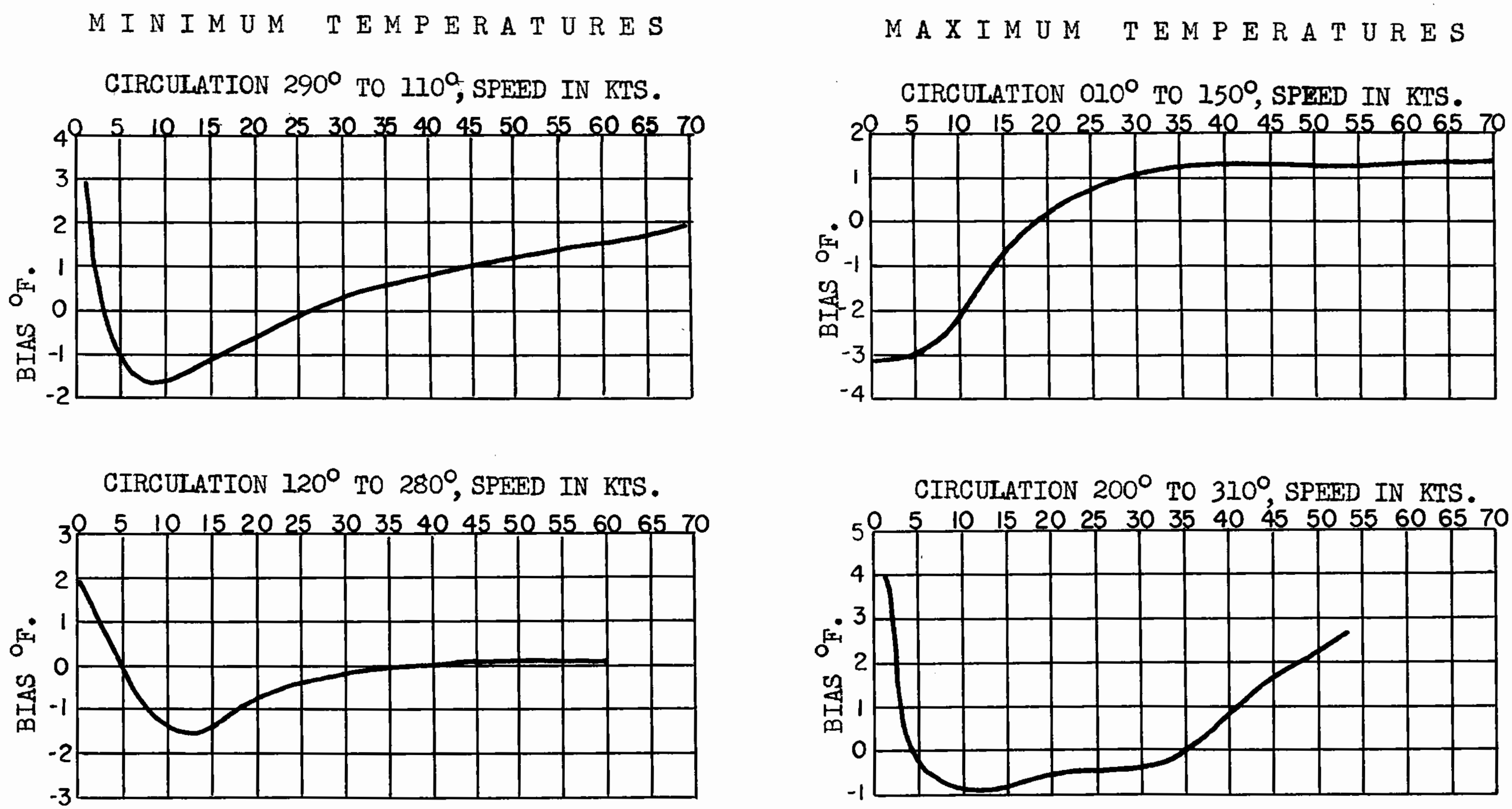


FIGURE 8

BIAS OF THE PREDICTED MAXIMUM AND MINIMUM TEMPERATURES ACCORDING TO WIND SPEED

These and the equations are given in Table XV, page 83. Values of twice the standard error of estimate for the equations indicate that, using the regression equations, there is a 95 per cent probability that the observed value of temperature will lie within five to six degrees of the predicted value.

The four adjusted partial regression equations incorporate the significant factors of wind direction, wind speed, thickness of the air stratum near the ground, and dew point or cloud albedo into the temperature prediction. They provide an accurate forecast of maximum or minimum temperature for the great majority of cases. Interpolation would be appropriate for the small sectors not covered by the equations; where the use of the equations is impossible, the distributions of temperature according to air-mass and circulation are useful. The sea breeze is partly accounted for in the wind bias correction, but when a sea breeze is certain the regression equation for thickness and maximum temperature for instances of sea breeze may be employed. In most instances, however, the adjusted regression equations are applicable, and they provide a quite accurate forecast of temperature.

TABLE XV

MULTIPLE CORRELATION COEFFICIENTS AND ADJUSTED PARTIAL REGRESSION EQUATIONS RELATING MINIMUM TEMPERATURE TO WIND SPEED, DEW POINT, AND THICKNESS; AND MAXIMUM TEMPERATURE TO WIND SPEED, CLOUD ALBEDO, AND THICKNESS

| Circulation | No. of Cases | Multiple Correlation Coefficient | Adjusted Partial Regression Equations * | 2 times the standard error of estimate $^\circ$F. |
|---|---|---|---|---|
| Maximum temperature | | | | |
| $200^\circ$ to $310^\circ$ | 108 | .81 | Y = .67X - .06Z - 228 + C | 6.0 |
| $010^\circ$ to $150^\circ$ | 35 | .80 | Y = .46X - .06Z - 143 + C | 5.6 |
| Minimum temperature | | | | |
| $290^\circ$ to $110^\circ$ | 27 | .82 | Y = .19X + .54U - 64 + C | 4.5 |
| $120^\circ$ to $280^\circ$ | 81 | .77 | Y = .26X + .49U - 91 + C | 6.5 |

* The key to the letters used in the partial regression equations is as follows:
Y is the predicted value of the maximum or minimum temperature, in whole degrees F..
X is the thickness of the stratum 850 to 1,000 millibars in tens of geopotential feet.
Z is the cloud albedo expressed in per cent.
U is the dew point at 18.30 G.M.T., in degrees F.,
C is the correction in degrees F. to be applied for wind, as determined from the graphs in Figure 8, page 81.

## CHAPTER XI

## SUMMARY AND CONCLUSIONS

<u>Summary</u>. Current maximum and minimum temperature prediction methods are not adequate for the Canadian Atlantic coast. The high frequency of air-mass change, coastal temperature phenomena, and the adjacent expanse of sea prevent the use of these methods which usually require clear skies, absence of air-mass change, and the use of auxiliary observation stations. A thorough knowledge of the coastal temperature regime and related weather conditions compensates for these deficiencies.

The annual cycle of temperature along the coast is complex, being composed of two distinct cycles which are associated with the continental and maritime types of air. While air over the continent experiences large diurnal variations in temperature and is warmest in the month of July, air over the sea undergoes a negligible diurnal variation and, like the sea, it is warmest in the month of August. At Torbay the annual temperature cycle is maritime; in summer the sea modification of the dominant westerly circulation is shallow and destroyed over the land by day; therefore, the maximum temperature cycle is continental although the daily mean temperature and the minimum temperature cycles are maritime.

Whenever there is a marked difference in the mean temperature of the continental and maritime air, there is a wide dispersion of the daily values of temperature; when the average temperatures of the continental and maritime air are the same, there exists a marked grouping of temperature near the mean. During the month of August the mean sea temperature and the mean maximum temperature of the continental air are similar, and the distribution of the minimum temperature at Torbay is normal and concentrated about the mean. The maximum temperature distribution, on the other hand, shows a wide dispersion and a pronounced skew since the mean maximum temperature of the continental air is about twenty degrees higher than the mean sea temperature.

Variations in the mean sea temperature off Torbay may be reflected in the daily values of the maximum and minimum temperature when the winds are onshore, but they do not appreciably affect the monthly average of the daily mean temperature.

The temperature distributions of the air-masses and circulations were determined. These provide a more lucid picture of the temperature regime, showing distinctly the effects of the continental and maritime air. The value of these distributions in temperature prediction is indicated by the difference between the mean temperature of each and that of the entire group, and by the smaller range and standard deviation of temperature that need to be considered. The mean temperature of a circulation may depart as much as ten degrees from that of the entire group; the ranges and standard deviations of most distributions are significantly smaller than that of the parent distribution.

The relationships were determined between temperature and weather conditions which reflect the activity of the main processes affecting the maximum and minimum temperature. Many of these relationships were approximately linear and could be expressed as regression equations; the effect of wind speed on temperature was non-linear and generally anamalous.

The maximum temperature is a function of the amount of insolation reaching the ground, but it is also dependent on the ways in which this energy is distributed. Clouds are the major factor which limit the incoming solar radiation. The processes, by which the energy is distributed, are many, but they produce a maximum temperature which is a function of the warmth of the air stratum near the ground. Wind speed has a pronounced effect on the maximum temperature through its relation with eddy diffusion.

The relations between the maximum temperature and the wind speed, cloud albedo, and thickness were found to be significant. Those factors having a linear relation to temperature were used in the development of partial regression equations, which, used with a graphically obtained wind speed correction, give a quite accurate prediction of the maximum temperature.

The wind speed correction applied to these equations takes into account the effect of the sea breeze. However, if a sea breeze occurs when the gradient wind is offshore, the maximum temperature may be accurately predicted by means of a regression equation relating the temperature to thickness.

Downward radiation from the atmosphere and clouds and the release of heat through the formation of dew influence the net loss of energy experienced at the ground at night. The cooling of the ground surface results in the cooling of the air immediately above it; the degree of cooling at the ground, therefore, determines the nocturnal minimum temperature.

The energy received at the ground during the night varies with the water vapor content of the air, the warmth of the air immediately above the ground, and the height of any cloud which may be present. Turbulence tends to destroy the nocturnal ground inversions; as the wind speed increases, turbulence increases, and the air near the ground is effectively warmed.

The relations between the nocturnal minimum temperature and the dew point, the thickness of the air stratum near the ground, and the wind speed were found to be significant. The association of cloudiness with very cold air in a maritime locality makes it impossible to determine the effect of cloud on minimum temperature on an average basis. The relation between wind speed and temperature for the northerly circulation is anomalous due to the association of strong winds with the advection of very cold, unstable air.

Partial regression equations were developed which relate minimum temperature to thickness and dew point. A quite accurate forecast of the minimum temperature is made possible by applying a graphically obtained wind speed correction to the regression equations.

The use of the temperature distributions for the air-masses and circulations permits a reasonable prediction of the maximum or minimum temperature under any circumstances; the use of the adjusted regression equations permits an accurate forecast of these temperatures when more data are available.

Conclusions. Temperature prediction in coastal localities may be improved by (1) a thorough knowledge of the air-mass and circulation temperature distributions and (2) a knowledge of the degree of dependence of the maximum and minimum temperature on other basic weather data. The distributions give a lucid picture of the temperature regime along the Atlantic coast. The relations between the maximum or minimum temperature and other weather conditions may be used in making quite accurate temperature predictions with coastal phenomena taken into account.

The coastal temperature cycle is part continental and part maritime; the temperature regime may be separated into these components through the use of air-mass or circulation.

The arithmetic mean, standard deviation, and range of the temperature distributions for air-mass and circulation differ appreciably from those of the parent distribution; this indicates their usefulness in temperature prediction.

Thickness of the air stratum near the ground, cloud albedo, and wind speed bear a significant relation to the maximum temperature. With offshore winds the maximum temperature may be predicted successfully by the use of thickness alone.

The mid-afternoon dew point of the air, the thickness of the air stratum near the ground, and wind speed have a pronounced influence on the nocturnal minimum temperature; the relation between dew point and the minimum temperature is especially good.

The relationships determined were found to be more significant for circulation than for air-mass. This and the comparative simplicity of using circulation recommend its use in temperature prediction.

While most coastal phenomena are taken into account in the various relationships through the use of circulation, sea and land breeze effects must be considered independently. A sea breeze is of consequence when it causes the surface wind to shift from offshore to onshore; it is most likely to occur when skies are clear and when the geostrophic winds are light. When a sea breeze is certain, the maximum temperature may be accurately predicted through the use of a regression equation relating maximum temperature and thickness of the air stratum between 850 and 1,000 millibars. The land breeze is most likely to be pronounced when skies are clear and the geostrophic wind light. Under these circumstances the offshore winds increase by about eight miles per hour, and higher than expected minimum temperatures may result.

Adjusted partial regression equations relating the maximum temperature to the wind speed, cloud albedo, and thickness, and the minimum temperature to wind speed, dew point, and thickness, provide a method of accurate temperature prediction on the basis of circulation. Four such equations were determined which permit a quite accurate prediction of temperature under most circumstances. When these equations are inapplicable, a reasonably accurate prediction may be made through the use of the air-mass and circulation temperature distributions.

These conclusions apply to summer months; further investigation is necessary to determine the distributions and relations for the other seasons. The effect of the sea on continental air in winter is opposite to that in summer, and the temperature relations in winter will be quite different.

Many factors influence temperature and this study has attempted to introduce only the most important. The influence of cloud on minimum temperature is very significant and warrants further investigation; its use in this study has not been possible since much more data would be required to determine its full effect. The indicated usefulness of the developed equations convincingly establishes that the major processes have been taken into consideration.

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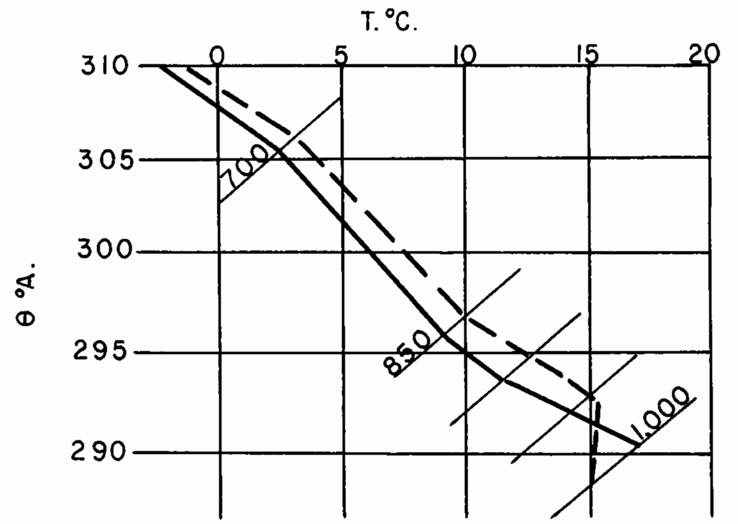
# APPENDICES

APPENDIX A

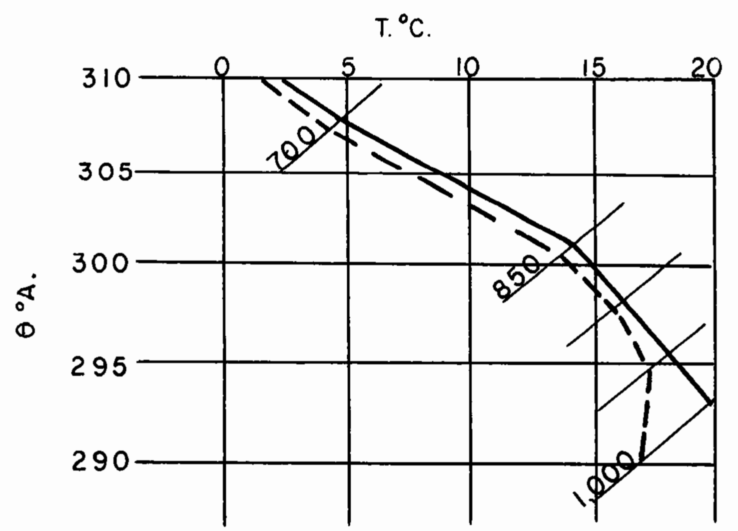
AVERAGE TEPHIGRAMS OF THE MAJOR AIR-MASSES FOUND AT TORBAY




AIR-MASS MPC

Average of twenty-six 03.00 G.M.T. ascents -----.

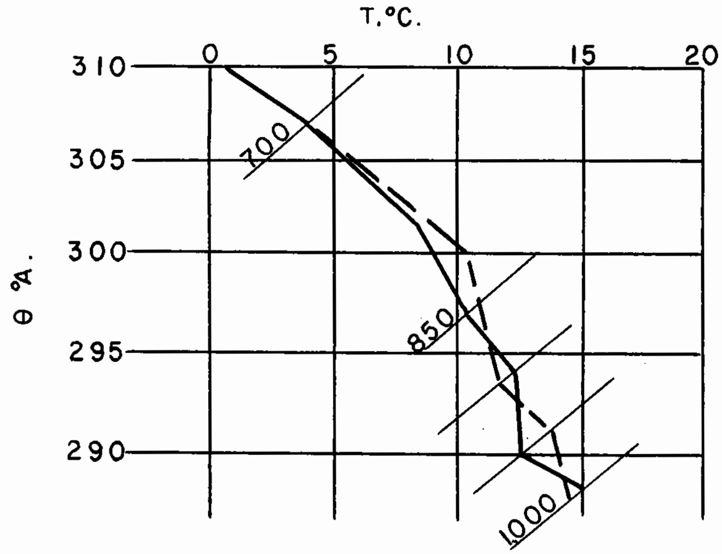
Average of twenty-six 15.00 G.M.T. ascents _____.




AIR-MASS T

Average of eighteen 03.00 G.M.T. ascents -------.

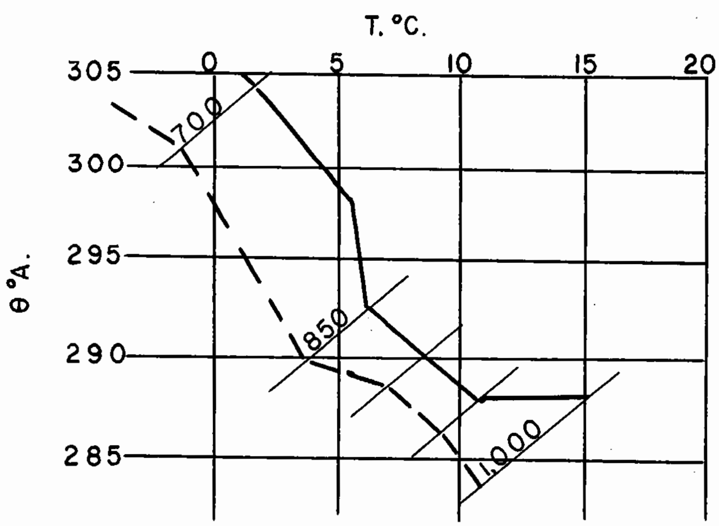
Average of nineteen 15.00 G.M.T. ascents _______.




AIRMASS PM

Average of eight 03.00 G.M.T. ascents -------.

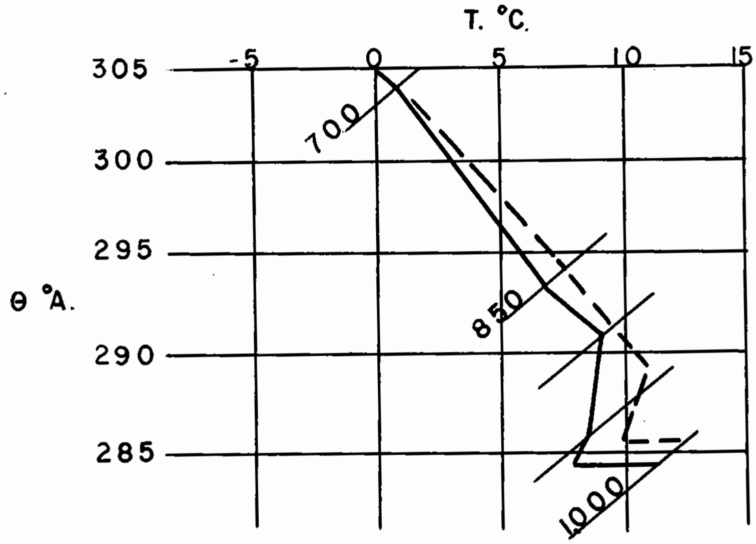
Average of five 15.00 G.M.T. ascents _______.




AIRMASS PC

Average of six 03.00 G.M.T. ascents -------.

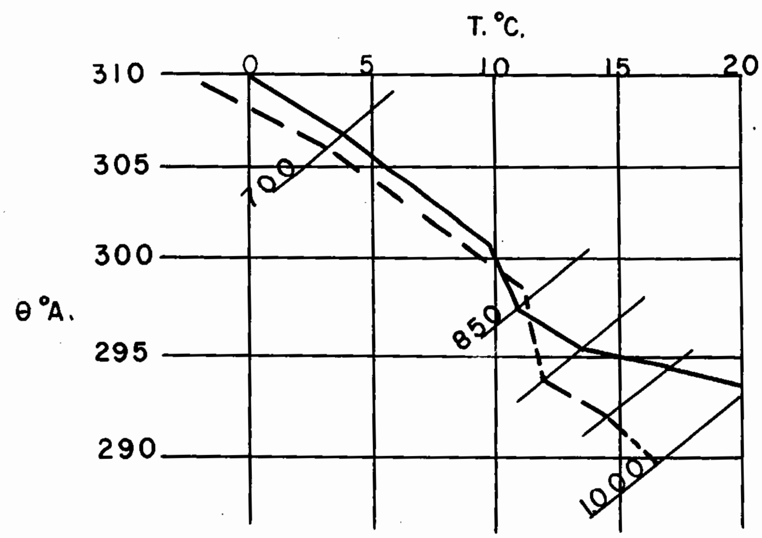
Average of five 15.00 G.M.T. ascents ______.




AIR-MASS PM1

Average of fifteen 03.00 G.M.T. ascents ------.

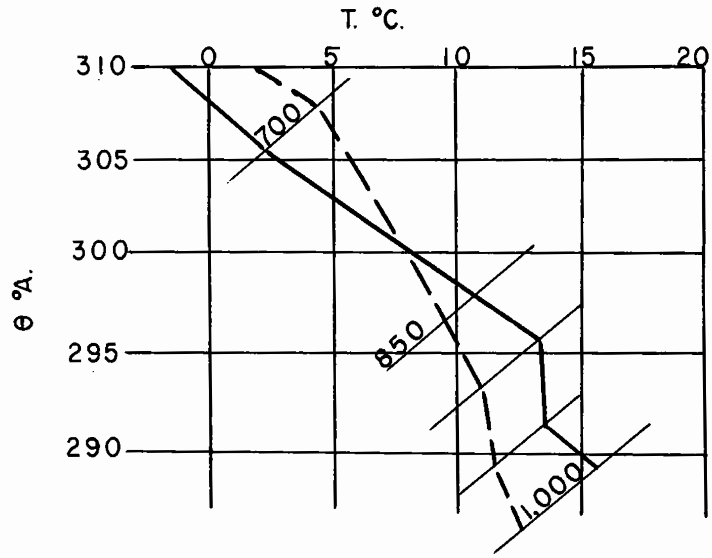
Average of fifteen 15.00 G.M.T. ascents ______.




AIR-MASS PM2

Average of ten 03.00 G.M.T.ascents -------.

Average of eleven 15.00 G.M.T. ascents _____.




AIR-MASS MPM

Average of four 03.00 G.M.T. ascents - - - - - .

Average of four 15.00 G.M.T. ascents ________..

In the above diagrams the pressure levels for 1,000, 950, 900, 850, 700 millibars have been indicated.

APPENDIX B

NON-TRANSMITTED PORTION OF INSOLATION INCIDENT ON CLOUDS AT NOON DURING THE MONTH OF AUGUST, FOR OVERCAST SKIES

(after Haurwitz *)

| Cloud type | Non- transmitted portion in per cent |
|---|---|
| Cirrus | 15 |
| Cirrostratus | 16 |
| Altocumulus | 48 |
| Altostratus | 59 |
| Stratocumulus | 65 |
| Stratus | 75 |
| Nimbostratus | 85 |
| Fog | 83 |

* Haurwitz, B., "Insolation in Relation to Cloud Type," Journal of Meteorology, 5:111.