PAPERS IN PHYSICAL OCEANOGRAPHY AND METEOROLOGY

PUBLISHED BY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

AND

WOODS HOLE OCEANOGRAPHIC INSTITUTION

VOL. X, NO. 1

MEASUREMENTS OF TEMPERATURE AND HUMIDITY IN THE LOWEST 1000 FEET OF THE ATMOSPHERE OVER MASSACHUSETTS BAY

BY

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Contribution No. 362 from the Woods Hole Oceanographic Institution

CAMBRIDGE AND WOODS HOLE, MASSACHUSETTS

NOVEMBER, 1946

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PREFACE

The measurements presented in this paper and much of the work in interpreting them were accomplished for the Office of Scientific Research and Development under contract OEMsr-262 with the Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts. All the members of Group 42, led by Mr. Donald E. Kerr, contributed in one way or another to the success of the observational program. Dr. R. B. Montgomery and Mr. Isadore Katz planned and supervised the meteorological measurements and, together with Mr. Patrick J. Harney and the author, conducted a meteorological analysis of the observations. Those directly responsible for obtaining the airplane soundings were Mr. Robert H. Burgoyne and Mr. Earl Boardman, who flew in the Curtiss monoplane, and Mr. Arthur E. Bent and Mr. D. G. Wilson, who flew in the AT-11. Mr. Harney was primarily responsible for the soundings obtained from the blimp. Measurements from the boat, particularly those of surface water temperature, were extremely valuable in interpreting the airplane soundings and were obtained mainly through the efforts of Mr. F. D. Parker.

The armed services of the United States contributed much in the way of equipment and personnel to the observational program. The Army Air Forces made available an airplane (AT-11) and pilots, and assigned trained personnel to aid in the gathering and interpretation of the data. The Coast Guard supplied a boat and a crew to man it. The Navy furnished an airship for sounding purposes during part of the program.

The U. S. Weather Bureau furnished special forecasts each day during the measuring program, supplied meteorological data, and made weather maps available for use in the analysis.

Near the beginning of 1946, the material was transferred to the Woods Hole Oceanographic Institution, where further analysis and preparation for publication have been carried out as part of a contract (NObs-2083) with the Bureau of Ships, Navy Department. Acknowledgment is especially due to Dr. Montgomery, who, in addition to his contributions at the Radiation Laboratory, has furnished the author with much valuable advice during the preparation of this paper at Woods Hole.

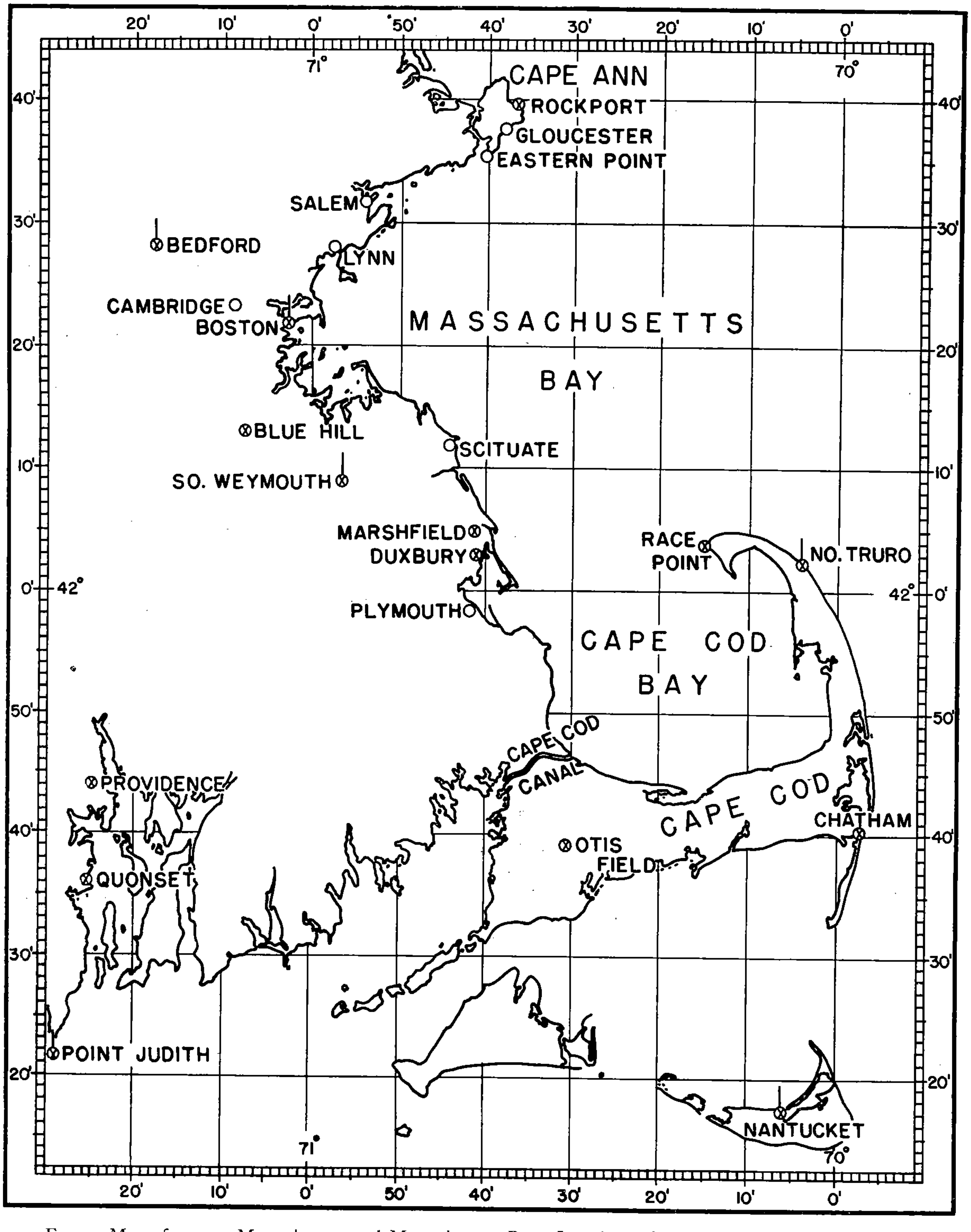

FIG. 1. Map of eastern Massachusetts and Massachusetts Bay. Locations of places mentioned in the text are shown by circles. A cross within a circle indicates a station from which surface weather reports are available, a vertical line above a circle indicates a station where pilot-balloon observations are made.

PART I. GENERAL CONSIDERATIONS

1. Introduction

In the summer and fall of 1944, psychrometric measurements were made in the lowest 1000 ft of the atmosphere over Massachusetts Bay. They were designed to show vertical distributions of temperature and humidity in more detail than had any previous observations over a comparable height range. The measuring program was carried out under the general direction of Mr. Donald E. Kerr by members of the Radiation Laboratory, Massachusetts Institute of Technology, in connection with studies concerning the propagation near the sea surface of radio waves of the order of centimeters or a few meters in length. The meteorological measurements were desired because they yielded information about vertical distributions of refractive index of air for radio frequencies. The vertical distribution of refractive index is of great importance in the propagation problem (Sheppard, 1946), that in the lowest 1000 ft being of primary significance for the study at the Radiation Laboratory.

Previous to the Radiation Laboratory measurements, vertical distributions of temperature and humidity over the ocean had been obtained from two types of observations. First, some investigators had made measurements from several fixed levels on moving ships; observations made in this manner are discussed by Sverdrup (1946). Vertical distributions determined by this method are sufficiently detailed for application to the propagation problem, but are necessarily confined to a layer which is too shallow. Secondly, a few kite soundings made over the ocean have been published. In 1913 Taylor (1914; 1915; 1917) made 14 such soundings from the whaling ship "Scotia" over the Grand Banks of Newfoundland. They reached heights of about 3000 ft. In 1915, 27 kite soundings were made aboard the U. S. Coast Guard Cutter "Seneca," including some over the Labrador current, some over the Grand Banks, and some over the Gulf Stream (Wood, 1915). These reached an average height of about 3000 ft. Observations of the type made by the "Scotia" and "Seneca," while covering a sufficient height range, do not show vertical distributions of temperature and humidity in enough detail to be of material assistance in the propagation problem.

For the Massachusetts Bay program a psychrograph was developed which could be carried aloft by aircraft or a balloon, or pulled up a pole or the mast of a ship. Only by use of aircraft could the desired height of 1000 ft be reached, but soundings obtained by the other methods furnished supplementary information. Nearly 500 airplane soundings were made, most of them in air which had traveled less than 50 miles over water since leaving land. They were used in a comparison of vertical distributions of refractive index with observed characteristics of radio transmission, as described elsewhere (Kerr, 1947). Furthermore, all the soundings were studied individually in relation to weather data from near-by land stations in order to determine what meteorological processes had led to the observed vertical distributions.

The main purpose of this paper is to present some of the meteorological information which the airplane soundings and their analyses have made available. To this end, 51 selected soundings are included, showing observations made under a variety of meteorological conditions. Each sounding is accompanied by a short discussion, which contains the results of the meteorological analysis and which attempts to point out the significant features of the sounding. Secondarily, the paper is designed to illustrate the type of measurements that can be made by use of the new techniques, to bring to general attention the application to meteorology of some of the work done in connection with the propagation problem, and to publish the vertical distributions of refractive index for the chosen soundings as examples of the observed distributions.

Before the individual soundings and analyses are presented in Part II, it is desirable to discuss certain matters which form a background to their consideration. A discussion of the propagation problem and related meteorological problems which is much more exhaustive than the one given here is being published elsewhere (Kerr, 1947).

As for application of the Massachusetts Bay observations to specific meteorological problems, two papers have already been completed concerning observed temperature and humidity distributions in sea breezes (Craig et al, 1945) and in the convective layer above the sea (Craig, 1946). It is hoped that other applications will follow.

2. Meteorological Observations

The plan for the observations over Massachusetts Bay was to gather all possible information concerning the weather and resulting vertical distributions of refractive index near the surface for comparison with observed characteristics of radio transmission. Figure 1 is a map of the Massachusetts Bay region and shows the location of places which are mentioned in this paper. Continuous point-to-point radio transmission was maintained between Race Point and Eastern Point, and, during part of the experiment, radar ranges were observed at Race Point.

The available meteorological information included (a) surface reports from all standard weather stations in the region, as well as from two special stations set up at Marshfield (later moved to Duxbury) and Race Point; (b) pilot-balloon observations where regularly available in the region; (c) radiosonde observations at the Army Air Forces weather station in Cambridge, supplemented where necessary by others made at Portland, Maine, and Lakehurst, New Jersey, and by airplane observations up to about 10,000 ft made at Quonset, Rhode Island; (d) over-land soundings in the lowest few hundred feet obtained by use of psychrographs at Marshfield (or Duxbury) and Race Point; (e) reports from a boat in the Massachusetts Bay region, including measurements of surface water temperature usually obtained by use of a mercurial sea-surface thermometer towed beside the boat, observations of atmospheric conditions at deck level, and soundings made with a psychrograph carried aloft on either the mast or a balloon; (f) airplane soundings made over Massachusetts Bay.

The airplane soundings proved to be the most important single source of meteorological information. The *M. I. T. psychrograph* (Kerr, 1947), used in obtaining these, measures temperature and wet-bulb temperature by means of electrical resistors. When mounted on an airplane, it has been called an *aeropsychrograph*. For the observations presented here, it was mounted on either a four-place Curtiss monoplane, cruising at about 90 miles per hour, or a twin-engined Beechcraft (Army AT-11), cruising at about 170 miles per hour (an air speed near 135 miles per hour was used while obtaining the soundings). The planes ascended or descended at the rate of about 100 ft per minute in a tight spiral, about 1 mile in diameter. Temperature and wet-bulb temperature were automatically recorded inside the plane, where an observer marked the record at the heights where readings were desired. These heights were generally chosen as 20 ft, 50 ft, 100 ft, 150 ft, 200 ft, and multiples of 100 ft up to 1000 ft. The lowest measurement was obtained during level flight, the height being controlled by visual estimate; the other heights were determined by pressure altimeter. On the AT-11 these methods were sometimes supplemented by use of a radio altimeter. Immediately following one set of measurements, the procedure was repeated between the surface and 500 ft in order that check measurements might be available. Corrections for heating due to the motion of the air past the thermometer were applied (Kerr, 1947). A few soundings were made from a Navy airship (blimp), by suspending a psychrograph below the slowly ascending airship.

3. Meteorological Background

Atmospheric conditions observed in the airplane soundings may be classified according to whether the air near the surface is warmer or cooler than the water. In the case of air warmer than water, characterized by stable hydrostatic equilibrium and alternately referred to as a case of cooling from below or of positive temperature excess, vertical transfer of momentum, heat, or water vapor may be accomplished by mechanical turbulence due to the wind. In the case of air cooler than water, characterized by unstable hydrostatic equilibrium and alternately referred to as a case of heating from below or negative temperature excess, vertical transport may be effected by convection due to the density distribution as well as by mechanical stirring.

A column of air which has been completely mixed or stirred by either or both of these processes may be called *homogeneous*. Homogeneity is characterized by a dry-adiabatic lapse rate of temperature (temperature decreases with height at a rate close to 5.4 F per 1000 ft) and by zero vertical gradient of specific humidity. The lapse rate of dew point is very close to 0.95 F per 100 ft, while the vapor pressure decreases by nearly 4 per cent in 1000 ft. In such a column the potential temperature, potential dewpoint, and potential vapor pressure are all independent of height.[1]

Vertical distributions for the case of air colder than water have been discussed and illustrated elsewhere (Montgomery, 1946; Craig, 1946). Further examples are included among the soundings to follow, and the discussions which accompany them need no explanation here.

In the case of soundings representing cooling from below, which constitute a large majority of the total number made over Massachusetts Bay, the primary meteorological problem has been to gain some information about the manner and rate at which air is modified as it leaves land and passes progressively longer distances over cooler water. In many cases the modification is caused chiefly by mixing, or eddy diffusion.

A valuable tool in the study of the airplane soundings, particularly those representing cooling from below, is a *characteristic diagram* having temperature and vapor pressure as basic coordinates. As illustrated in Figure 2, the ordinate is temperature and the abscissa is vapor pressure, and the diagram may bear *saturation curves*, representing the equilibrium vapor pressure over ice, water, or salt water.[2] Its value in the study of mixing lies in the following proposition, a proof of which has been presented by Taylor

[1] The potential temperature, potential dew point, and potential vapor pressure are defined as the temperature, dew point, and vapor pressure the air would have if it were changed adiabatically from its actual pressure to some standard pressure. In the discussion which follows, potential values will always be referred to sea-level pressure, to afford direct comparison with values of temperature and humidity at the sea surface.

[2] The saturation vapor pressure over salt water with salinity 35 per mille is approximately 98 per cent of the value over fresh water of the same temperature.

(1917): If two masses of air, each characterized by given temperature and vapor pressure and represented on the characteristic diagram by a point, are mixed in any proportion, then the resulting mixture is represented on the characteristic diagram by a third point which lies on a straight line joining the original two points. In the study of low-level soundings, where mixing may take place over an appreciable height range, it is necessary to take potential temperature and potential vapor pressure as coordinates in order that the principle may hold. In this case, of course, the saturation curves hold only for air at sea level. For each sounding presented, the measurements are shown plotted on a characteristic diagram with these coordinates and with the *characteristic curve* drawn through them.

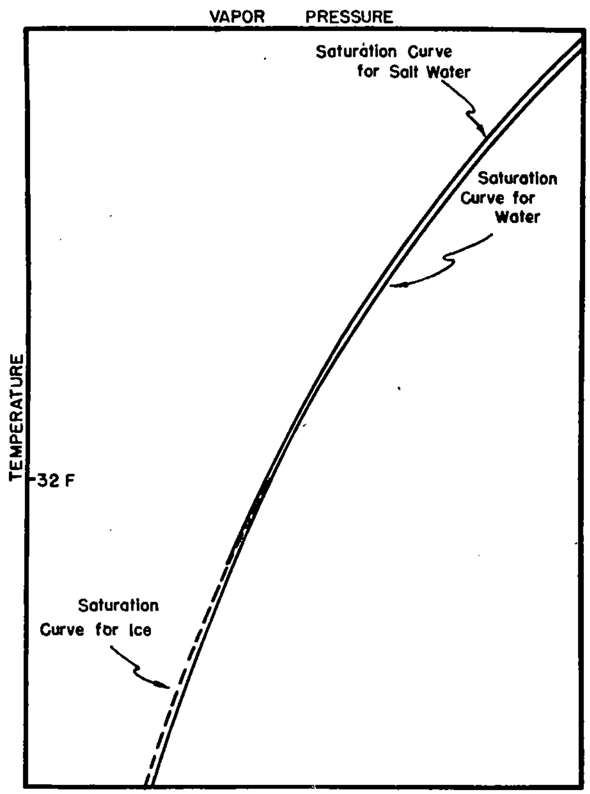

FIG. 2. Schematic representation of a characteristic diagram which has temperature as ordinate and vapor pressure as abscissa, and which shows equilibrium vapor pressure over water, salt water, and ice by means of saturation curves.

When air leaves land and passes over cooler water, the modification which it undergoes is influenced by a number of factors, especially wind speed and temperature contrast with the water. Other factors which are often of importance are the vertical distribution of temperature in the air before leaving land, the vertical wind shear, radiation from the air, and the variability of the temperature of the water over which it passes. It is convenient to consider the simplest case where the air is initially homogeneous, passes over water of uniform temperature, and where, further, the effects of shear and radiation may be neglected. This will be referred to as the *ideal case* for the study of eddy diffusion, and will be discussed first. Later, the effects of departures from the conditions outlined will be mentioned.

Consider the ideal case with reference to the characteristic diagram in Figure 3, where the coordinates are potential temperature and potential vapor pressure. The unmodified air is homogeneous, and hence may be represented by a point A. The air in contact with the water surface assumes the temperature and vapor pressure determined by the water temperature, and hence may be represented by a point B, which lies on the saturation curve for salt water. Mixing then takes place between these air masses, and measurements in the mixed air are represented by points which lie on the straight line joining A and B, as, for example, do points C and D in Figure 3. It follows that under ideal conditions the vertical distributions of temperature and humidity are not independent of one another, and may be called *similar*. It also follows that the temperature of the sea surface may be obtained by extrapolating the straight line through observed points in the modified layer until it intersects the saturation curve. Some soundings illustrating similarity are shown, including some where extrapolated water temperatures agree well with measured water temperatures.

In studying the ideal case it has been desirable to select certain independent variables to describe meteorological conditions affecting the modification which results from mechanical mixing. Those chosen are temperature excess (potential temperature of the unmodified air less water temperature), wind speed at 1000 ft, distance the air at 1000 ft has traveled since leaving land (called, for brevity, "1000-ft trajectory"), and either index deficit (refractive index at the water surface less potential refractive index in the unmodified air) or humidity deficit, defined analogously.[3] These parameters are indicated for each sounding.

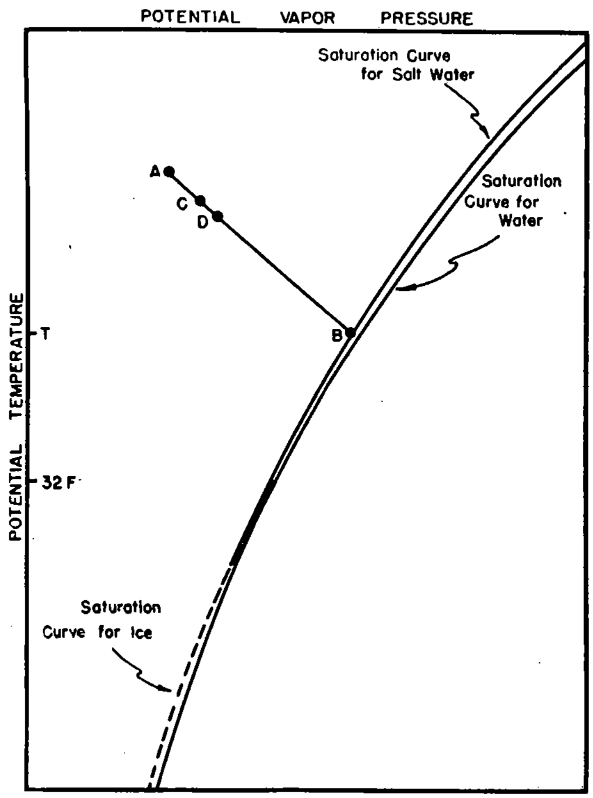

FIG. 3. Characteristic curve produced by mixing when initially homogeneous air A passes over salt water of temperature T. The air in contact with the water is represented by the point B, while points C and D, lying on the characteristic curve, represent air which might result from the mixing. The coordinates here are potential temperature and potential vapor pressure, so that the saturation curves hold only for air at sea level.

There are, of course, many significant departures from ideal conditions, and some of the soundings illustrate them. In cases where any of these are important, the vertical temperature and humidity distributions are not similar. In all cases, however, the characteristic curve terminates at the point on the saturation curve determined by the water temperature. Brief discussions of departures from ideal conditions follow.

Initial stratification. This term is used to indicate that the air leaving land is not homogeneous but is stable. The unmodified air is represented on the characteristic diagram by a curve rather than by a point; after the air passes over water, this curve extends to the point designating the water temperature. Mixing then tends to shorten the characteristic curve. The initial stability decreases the mixing which occurs when the air passes over water, and makes an estimate of the effects of over-water modification difficult for the particular measured sounding, since initial conditions are not clear.

Shearing stratification. This refers to the fact that, because of variation in wind speed and direction between the surface and 1000 ft, air strata at different levels have different over-water trajectories. Its most frequent effect on the soundings occurs during the morning when the air over land is being heated by convection and the potential temper-

[3] The temperature excess, humidity deficit, and index deficit are related so that any two define the third. Temperature excess is conveniently chosen as one variable because it indicates directly the stability of the air.

ature in the convectively stirred layer increases as the day advances. Then at some distance offshore the air aloft, having moved faster and left land later, is potentially warmer than the air near the surface. This leads to stability, even though the air at any level may have been part of a homogeneous column when it left land. The change in wind direction with height must also be considered; because of it, the air at different levels may have left land at different places as well as different times.

Radiation. Radiation from the air usually acts to decrease the temperature of the air column. It may be particularly important when the air has passed several hours over water, or when the mechanical mixing is small so that radiative cooling is comparatively more important, or when liquid water is present in fog or clouds. However, it appears from a study of the soundings over Massachusetts Bay that the effect of radiation may often be neglected when the time over water is small and the wind sufficiently strong.

Changing water temperature. Changes in the temperature of the water over which air moves may be such that the temperature excess is increased or decreased, even to the extent of changing its sign. The principle of similarity does not ordinarily hold and the characteristic curve may show a bend because of the change. Examples of this are shown.

It is apparent from the foregoing discussion that knowledge of the distribution of surface water temperature in Massachusetts Bay is necessary for a careful study of the airplane soundings. Observations with bearing on this subject have been summarized and discussed by Bigelow (1924), and measurements made from the boat used in the Massachusetts Bay program furnish additional information. Regarding the important question of horizontal variations, temperatures measured from the boat in the summer during any single traverse between Eastern Point and Race Point varied by as much as 3 C to 4 C, the coldest water being located near the former. Between Duxbury and Race Point the variation is usually somewhat less. On the other hand, in October, when autumnal cooling has set in, the water temperature in Massachusetts Bay has been found to be considerably more uniform; some traverses between Eastern Point and Race Point, for example, showed variations of the order of 1 C. Since the boat did not approach closer than 2–5 miles to shore when water temperatures were being measured, the figures quoted above do not include horizontal variation in inshore waters. At a given location, the measurements show that the water temperature may increase during the morning and early afternoon by as much as 2 C, while sometimes the increase is negligible. As might be expected, clear skies and light winds are favorable for a relatively large rise in surface temperature. Under these conditions, furthermore, there may be a large vertical thermal gradient near the surface; since all techniques for measuring "surface" temperature actually involve the sampling of water a short distance below the surface, the measured temperature may be significantly lower than the actual surface temperature.

4. Refractive Index

The refractive index of air at radio frequencies is determined by the pressure, temperature, and vapor pressure. Anomalies in the propagation of very short radio waves are caused by anomalies in the vertical gradient of refractive index. The vertical distribution of pressure in the lowest 1000 to 2000 ft of the atmosphere is so uniform that the effect of this variable is shown with sufficient accuracy by assuming that the sea-level pressure is 1000 mb and that the mean temperature of the air column is given by the surface temperature. With this approximation, the refractive index is given directly if the temperature and vapor pressure are known.

A parameter representing refractive index and convenient for meteorologists is the *potential refractive index*, or simply *potential index*, defined by

$$\Phi = (n_p - 1)10^6,$$

where n_p is the refractive index the air would have if it were changed adiabatically from its actual pressure to some standard pressure. In this paper, the standard pressure is sea-level pressure, which, for the purpose of computing Φ, is assumed to be 1000 mb. The approximate relation used to compute Φ in this paper is

$$\Phi = \frac{c}{\theta}\left(p_0 + \frac{be_p}{\theta}\right),$$

where θ is the potential temperature, e_p is the potential vapor pressure, p_0 is the sea-level pressure assumed to be 1000 mb, and c and b are constants having the values $c = 79$ K mb^{-1}, $b = 4800$ K. The relation between potential index and potential temperature and potential vapor pressure is nearly linear over the range of the variables encountered in any one sounding. Hence, in the ideal case, the vertical distribution of the potential index is similar to that of temperature or humidity. Furthermore, the temperature and vapor pressure of air in contact with salt water are known. Therefore, potential index at the water surface is uniquely determined by the water temperature; it increases with increasing water temperature.

The potential index is independent of height in homogeneous air. This distribution is very nearly the same as that accepted as *standard* in terms of the resulting radio propagation; the potential index in a standard layer decreases with height at the rate of only about 0.4 per 100 ft, whereas the vertical gradient of potential index in the lowest 1000 ft of the atmosphere is often found to have an absolute value of at least 10 per 100 ft. If the potential index decreases more rapidly with height than it would in a standard layer, propagation conditions are called *superstandard;* if it decreases less rapidly or increases with height, they are called *substandard*. In terms of radio performance, it is often found that superstandard conditions indicate radio ranges which are greater than normal, substandard conditions indicate radio ranges which are less than normal.

Another parameter used to represent refractive index is designated by M. The value of M is greater than that of Φ by an amount approximately equal to $z/(25$ ft$)$, where z is the height above sea level. M increases with height at the rate of 3.6 per 100 ft in a standard layer. When M does not change with height, the vertical distribution of refractive index is such that an electromagnetic wave propagated in a direction tangential to the earth's surface is refracted with the same curvature as the surface of the spherical earth. When M decreases with height (Φ decreases with height at a rate greater than 4.0 per 100 ft), the wave is bent downward relative to the earth. This distribution of refractive index is referred to as an *M-inversion*.

The foregoing discussion is intended only to introduce the problem to those unfamiliar with it; a much more complete treatment may be found elsewhere (Kerr, 1947).

5. Method of Presenting Observations

For each sounding the measured values of temperature and dew point and the computed value of potential index are plotted against height. The height scale is in feet, with a supplementary scale showing meters, and the temperatures are given in Fahrenheit, with a supplementary centigrade scale. The open circles represent the measurements made during the first ascent or descent, while the smaller, solid circles are the check measurements. In all cases broken lines show the distributions the parameters would have in homogeneous air, for comparison with the observed distributions. Arrows show values at the sea surface, one arrow being sufficient to indicate both the temperature and the dew point[4] at the surface, the other showing potential index.

In each case a map and a section of the characteristic diagram are included, usually as insets on the soundings. The map, having north towards the top and having a scale of $1:4\times10^6$, shows a part of the Massachusetts Bay region appropriate to the sounding location, which is indicated by a solid circle. An arrow, usually beginning at some part of the coastline and terminating at the sounding point, indicates the trajectory of the air at 1000 ft over Massachusetts Bay, as estimated from the pilot-balloon reports in the region. On the characteristic diagram, the coordinates are not indicated but may always be understood as potential temperature (F) and potential vapor pressure (mb). The saturation curves are for salt water (left curve) and fresh water (right curve). All points, including those in the check sounding, are plotted, and all are indicated by small, solid circles. The characteristic curve is drawn for each sounding and terminates in all cases at that point on the saturation curve for salt water corresponding to the best estimate of water temperature.

The legend for each figure includes the following:

(a) The sounding indicator, which consists of a letter and a number. The former indicates the type of aircraft used to make the measurements, A standing for AT-11 (Beechcraft), B for blimp, and C for Curtiss. The soundings made by each type of aircraft have been numbered consecutively, including all the soundings made, not only those presented here.

(b) The latitude and longitude of the sounding position.

(c) Date on which the sounding was made.

(d) Time of the beginning and ending of both the first and second ascent or descent.

(e) Surface wind as estimated from the state of the sea by an observer on the plane. This consists of wind direction and wind force on the Beaufort scale. If either is lacking, the reported surface wind from the nearest land station is given in parentheses.

(f) 1000-ft trajectory, including the distance and time the air at 1000 ft has been over water, as well as the point where it was last over land. This is estimated from the 1000-ft winds reported at the pilot-balloon stations.

(g) 1000-ft wind as estimated from pilot-balloon observations at near-by land stations.

The discussion accompanying each sounding begins with a brief description of the weather conditions, as generalized from surface reports, in the entire Massachusetts

[4] Strictly speaking, the arrow shows a dew point which corresponds to saturation vapor pressure over salt water. This dew point is slightly higher than that referred to fresh water.

Bay region (unless specific stations are mentioned). This includes cloud conditions, fronts, and precipitation or fog. The main part of the discussion varies in content, depending on the aspects of the sounding which appear most interesting, but usually touches upon the conditions in the air when it left land and the effects the water has had upon it. In each case, information concerning the water temperature is given, including pertinent measurements and an appraisal of the estimate which can be made by extrapolation of the characteristic curve.

All times are stated in Eastern War Time (local mean time at longitude 60°W). Horizontal distances are in statute miles.

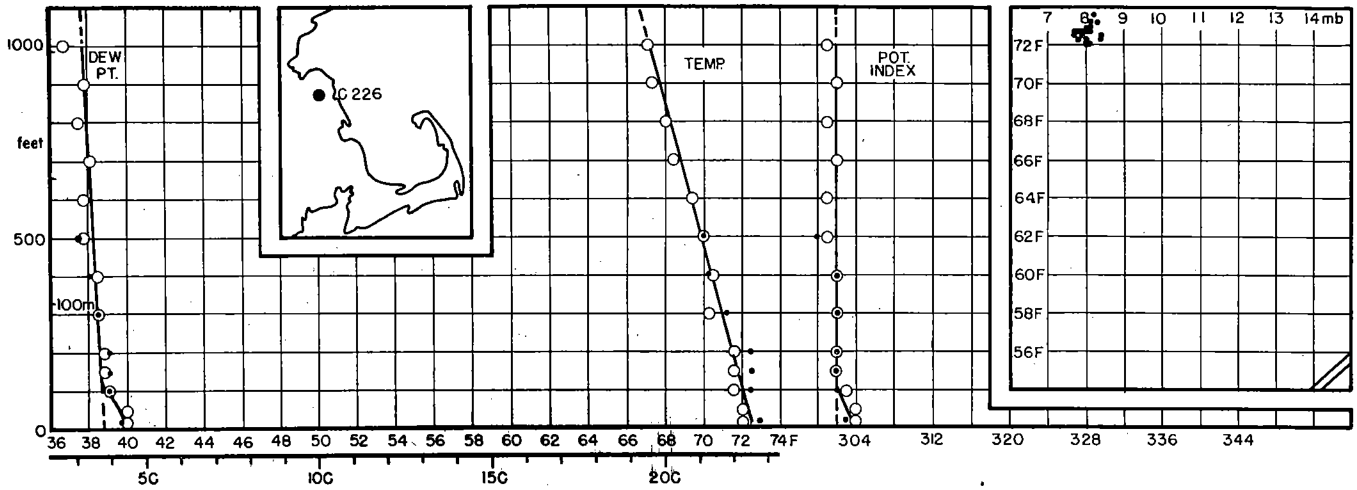

FIG. 4. C226; 70°50′W, 42°10′N (over land); 18 October 1944; o ascent 14^h35^m–14^h47^m, • ascent 14^h49^m–14^h54^m; wind 230° 18 mph at 1000 ft, SW 10 mph at surface.

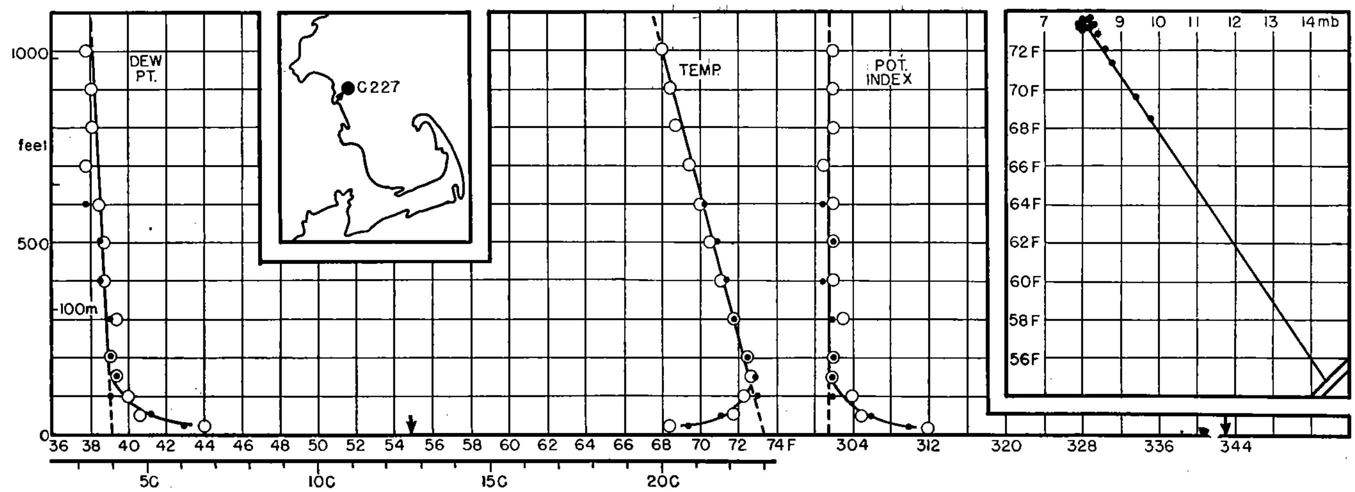

FIG. 5. C227; 70°40′W, 42°13′N; 18 October 1944; o ascent 15^h05^m–15^h15^m, • ascent 15^h20^m–15^h26^m; wind 230° 18 mph at 1000 ft, 2B (direction not observed) at surface (WSW 10 mph at South Weymouth); 1000-ft trajectory 4 mi, ¼ hr, from Scituate.

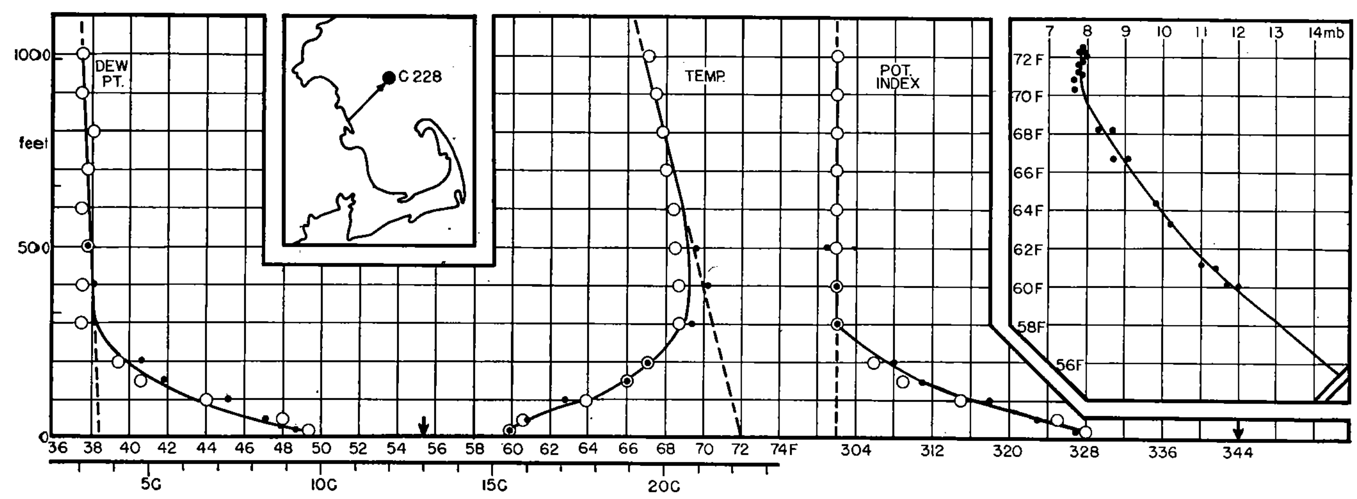

FIG. 6. C228; 70°25′W, 42°17′N; 18 October 1944; o ascent 15^h53^m–16^h03^m, • ascent 16^h05^m–16^h10^m; wind 230° 20 mph at 1000 ft, S 3B at surface; 1000-ft trajectory 19 mi, 1 hr, from Marshfield.

PART II. SOUNDINGS AND ANALYSES

There follow the 51 soundings and accompanying meteorological analyses which have been described and discussed in previous pages. Their selection from among the nearly 500 available soundings has been governed by the three considerations (a) that they should illustrate all the meteorological phenomena studied in connection with the sounding program; (b) that they should not, except in a few special cases,[5] duplicate soundings published elsewhere; and (c) that they should not include any of the relatively few soundings in which the reliability of the measurements was in question. The first 6 soundings (Figs. 4–9) are intended to illustrate certain basic concepts and are therefore not in the chronological order in which the remainder of the soundings are presented.

Figures 4, 5, 6, C226, C227, C228. Clear skies. The first of these three soundings was made over land, near the coast, and the others were made over water at different distances from shore.

The sounding over land shows approximately homogeneous air in the lowest 1000 ft. This homogeneity is believed to be typical of air over land in the vicinity of Massachusetts Bay during the afternoon. A balloon sounding to 250 ft at Duxbury at 14^h04^m (not presented here) also showed homogeneous air with potential temperature and dew point of 73 F and 39 F, which agree well with the corresponding values from C226. Furthermore, the prevailing surface temperature over land at 14^h30^m was about 72 F, sufficiently high, according to the 11^h00^m radiosonde observation at Cambridge, to indicate convective stirring of the air in the lowest 4000 ft.

C227 is a sounding made in air which, before leaving land, had properties very similar to those shown in C226. The air below 150 ft has been cooled and moistened during its 4-mile over-water trajectory, but the largest gradients of temperature, humidity, and refractive index are confined to the lowest 20 ft. The vertical distributions of temperature and humidity are similar, as may be seen from the characteristic diagram. The characteristic curve starts from a cluster of points, representing the unmodified, homogeneous air, continues as a straight line through measurements in the modified air, and intersects the saturation curve for salt water at a point corresponding to a water temperature of 55 F. This extrapolated water temperature compares very well with the value of 55.4 F measured by the boat 2 miles north of the sounding point at 18^h00^m.

While C227 appears to illustrate the effects of eddy diffusion only, there are strong indications that the vertical distributions in the air farther from shore, as shown in C228, have been influenced by shearing stratification. The characteristic curve through the modified air is not a straight line; its intersection with the saturation curve has been determined by a measurement of water temperature. Morever, the surface wind direction was observed from the plane to be south, and from the boat, situated 5 miles northwest at the same time, to be south-southeast. These observations show that the air near the surface must have an altogether different land origin and over-water trajectory than the air aloft. The latter appears, from the winds and its values of temperature and

[5] The soundings in Figures 5, 8, and 9 have been published elsewhere (Kerr, 1947) in slightly different form, but are included here so that they may be seen together with other soundings made on the same days. The data for the soundings shown in Figures 11 and 12 also have been published elsewhere, as is discussed in the analysis which accompanies the figures.

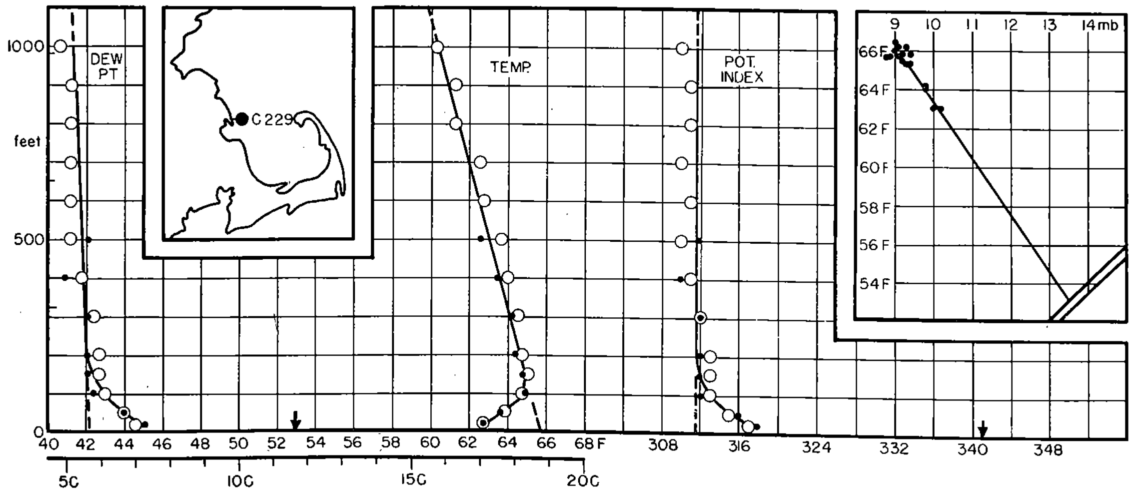

FIG. 7. C229; 70°36′W, 42°06′N; 19 October 1944; o ascent $10^{h}47^{m}$–$10^{h}57^{m}$, • ascent $11^{h}01^{m}$–$11^{h}06^{m}$; wind 270° 30 mph at 1000 ft, W 4B at surface; 1000-ft trajectory 2 mi, 1/15 hr, from Duxbury.

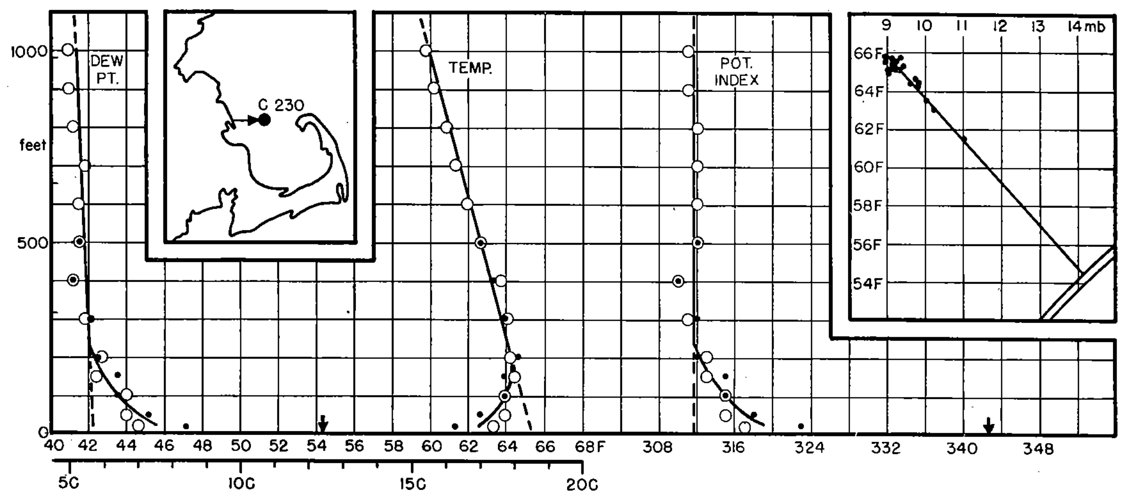

FIG. 8. C230; 70°28′W, 42°05′N; 19 October 1944; o ascent $11^{h}14^{m}$–$11^{h}24^{m}$, • ascent $11^{h}27^{m}$–$11^{h}32^{m}$; wind 270° 35 mph at 1000 ft, W 4B at surface; 1000-ft trajectory 9 mi, ¼ hr, from Duxbury.

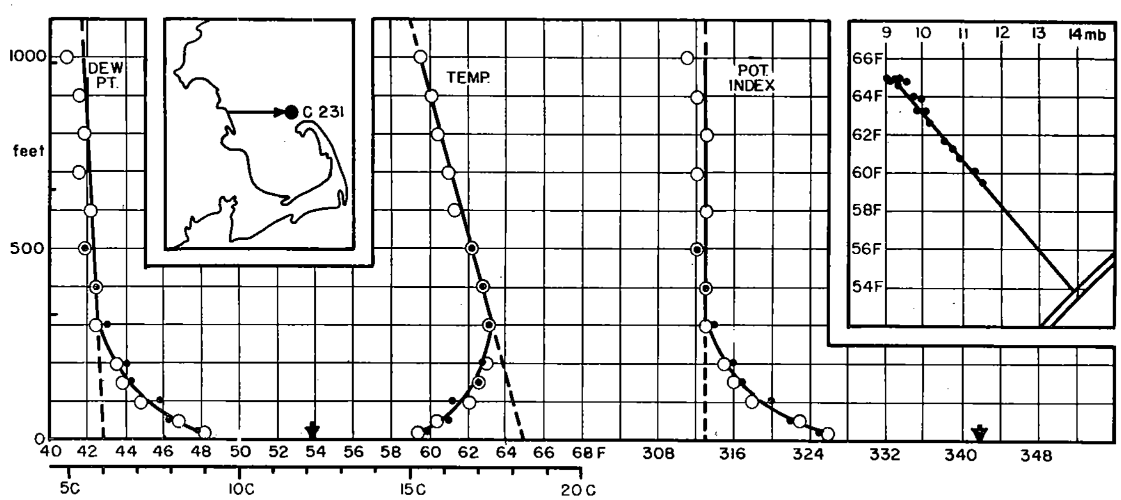

FIG. 9. C231; 70°16′W, 42°08′N; 19 October 1944; o ascent $11^{h}41^{m}$–$11^{h}51^{m}$, • ascent $11^{h}58^{m}$–$12^{h}03^{m}$; wind 270° 35 mph at 1000 ft, W 4B at surface; 1000-ft trajectory 23 mi, ⅔ hr, from Marshfield.

dew point, to have nearly the same history as the air in C227, but the lower air probably left land from some point on Cape Cod in the late morning.

These soundings illustrate three basic concepts which have proved to be of prime importance in the study of the soundings made in Massachusetts Bay. The concepts are those of homogeneity due to convective mixing, of similarity due to mechanical mixing in initially homogeneous air passing over cooler water, and of shearing stratification due to vertical shear of the horizontal wind.

Figures 7, 8, 9, C229, C230, C231. High scattered clouds. A cold front approaching from the northwest passed Boston at about 10^h30^m and South Weymouth at about 11^h30^m. No precipitation accompanied the front, but broken clouds at about 4000 ft appeared at each station in the area for an hour or two near the time of the frontal passage.

The air in all three soundings left land at about the same time and place, was initially homogeneous, and had nearly identical values of potential temperature and dew point in the mixed layer. Furthermore, in all three soundings essentially the same wind conditions and water temperature prevailed. The differences which appear in the soundings must then be due principally to the differences in length of over-water trajectory of the air column. It is of interest to examine the observations in the light of this consideration.

C229, C230, and C231 have over-water trajectories of about 2, 9, and 23 miles respectively. The heights to which the effect of the cooling has extended are progressively greater as the trajectory increases, being about 150, 250, and 350 ft. The temperature inversions extend nearly to these same heights. It is interesting to note that these heights increased from 0 to 150 ft during the first 2 miles over the water, and increased only an additional 200 ft during the next 21 miles.

All three soundings are fine examples of similarity, as can be seen from the characteristic diagrams. The derived water temperatures may be compared with measurements made during the following day: C229, about 53 F extrapolated, 53–54 F measured; C230, 54.5 F extrapolated, 55 F measured; C231, 54 F extrapolated, 54 F measured. Although the significance of this comparison is lessened by the time difference, the good agreement is in accord with extensive experience that the method of estimating water temperatures by use of the characteristic diagram yields reliable results.

Figure 10, C38. High thin scattered clouds. The air in this sounding left land in the early morning and was not initially homogeneous. The air in the lowest 500 ft has been cooled and moistened due to contact with the water. The water temperature is fixed within narrow limits since it must be lower than the temperature at 20 ft but higher than the dew point at the same level; a value of 61 F is indicated by the characteristic diagram. However, the air must have passed over colder water (perhaps 50 F) near the Maine coast at the beginning of its trajectory.

Figures 11, 12, C44, C45. High scattered clouds. A well-developed sea breeze was occurring at coastal stations during the time when these soundings were made, and the sea-breeze circulation is believed to have been important in producing the observed vertical distributions. These soundings, along with others made in the region during the morning, have been published in the form of vertical cross sections of potential temperature and humidity (Craig et al, 1945). They are presented again here so that they may be directly compared with many other soundings not connected with sea breezes. The usual

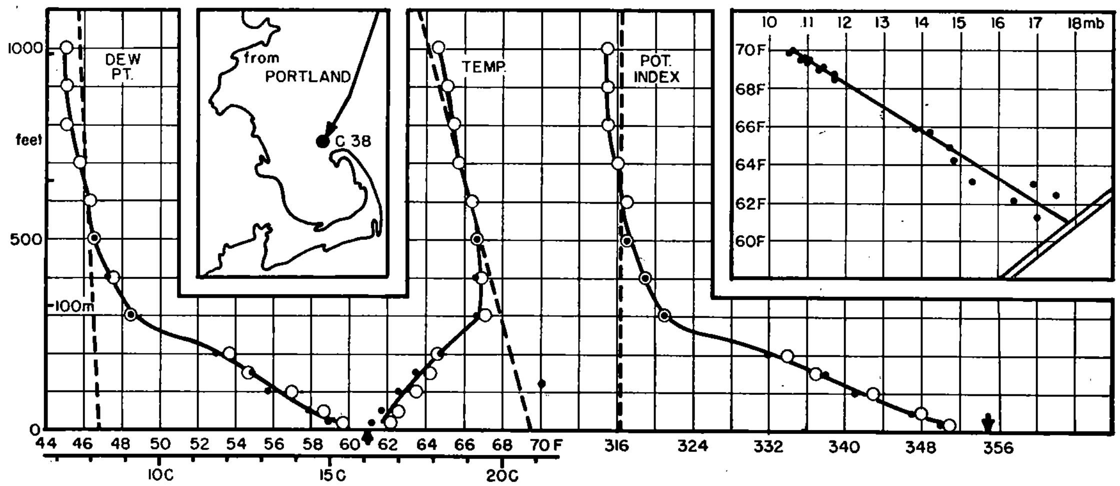

FIG. 10. C38; 70°16′W, 42°08′N; 1 July 1944; o ascent 10^h45^m–10^h55^m, • ascent 10^h59^m–11^h04^m; wind 30° 19 mph at 1000 ft, N 2B at surface; 1000-ft trajectory about 120 mi, 6 hr, from Portland, Maine.

treatment and analysis of low-level soundings, involving a consideration of over-water trajectory and the effects of eddy diffusion, fails here. The trajectory of the air near the surface is entirely questionable, and vertical motions associated with the sea-breeze circulation must be of considerable importance. In particular, the substandard layer between 400 and 600 ft and the superstandard layer from 700 ft to the upper limit of the measurements in C44 (and the corresponding layers in C45) cannot be the result of modification by the water or of initial stratification. The indicated water temperatures are only approximate and are derived from measurements made at the same time about 2 miles offshore near Marshfield. For details of the weather situation accompanying these soundings, the paper previously referred to should be seen.

Figure 13, C55. Southwest flow of tropical maritime air with haze and high thin overcast. Over-water modification extends to about 200 ft. Because of the negative humidity deficit, water vapor from the air in the modified layer has condensed on the sea surface. The resulting increase of humidity with height has led to a substandard distribution of potential index in this layer. At South Weymouth the temperature and dew point at 08^h30^m were 78 F and 72 F, and at 09^h30^m they were 80 F and 73 F. A comparison of these values with those in the sounding indicates that the air leaving land must have been convectively mixed up to about 800 ft. The stable distribution of temperature between 200 and 500 ft must then result from shearing stratification. The lighthouse in Boston Harbor, near the midpoint of the air's over-water trajectory, measured a water temperature of 67 F three hours later, so that the value of slightly under 66 F found by extrapolation on the characteristic diagram appears reasonable.

Figure 14, C71. Clear skies. The air in this sounding was initially homogeneous up to 700 ft and possibly higher. The observed stratification above that level is due to shearing stratification or initial stratification, probably the latter. The air passed first over cool inshore waters of temperature 60–62 F and was cooled and moistened in the lowest 300 ft. It then passed over warmer water of temperature somewhat above 64 F. The air in the lowest 50 ft, having been cooled below 64 F during the early part of its

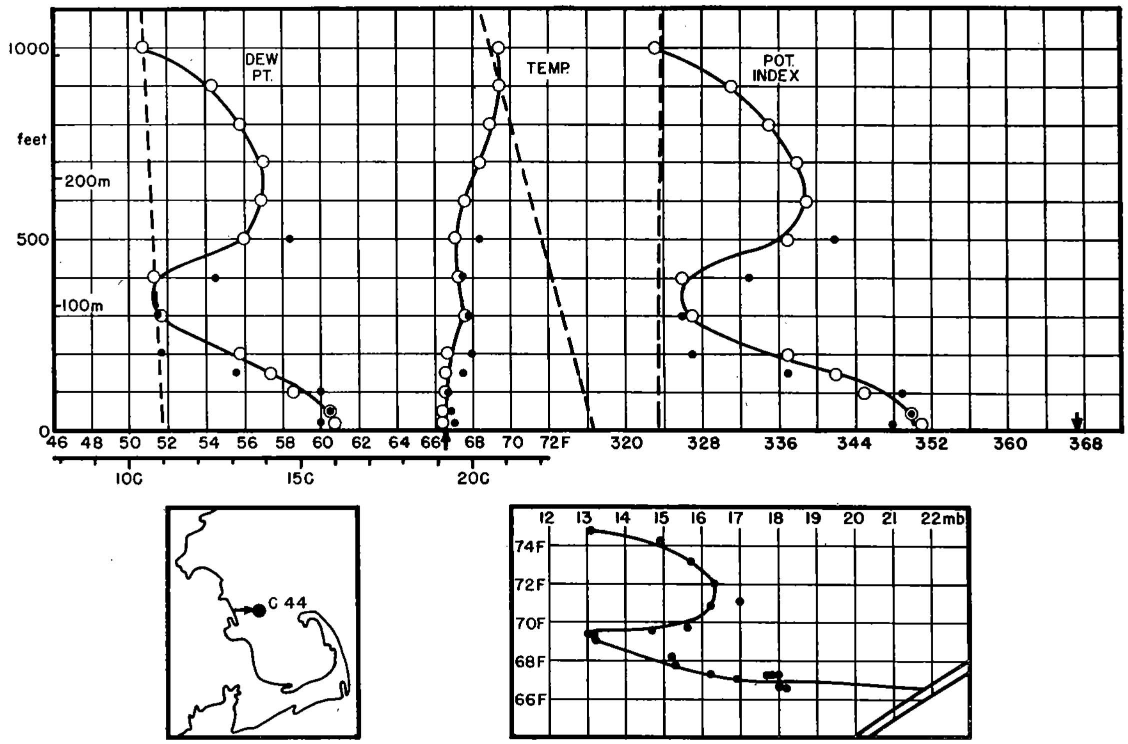

FIG. 11. C44; 70°32′W, 42°06′N; 5 July 1944; o ascent 11^h37^m–11^h47^m, • ascent 11^h49^m–11^h54^m; wind 270° 6 mph at 1000 ft, 1B (direction not observed) at surface (E at Marshfield); 1000-ft trajectory 7 mi, 1 hr, from Marshfield.

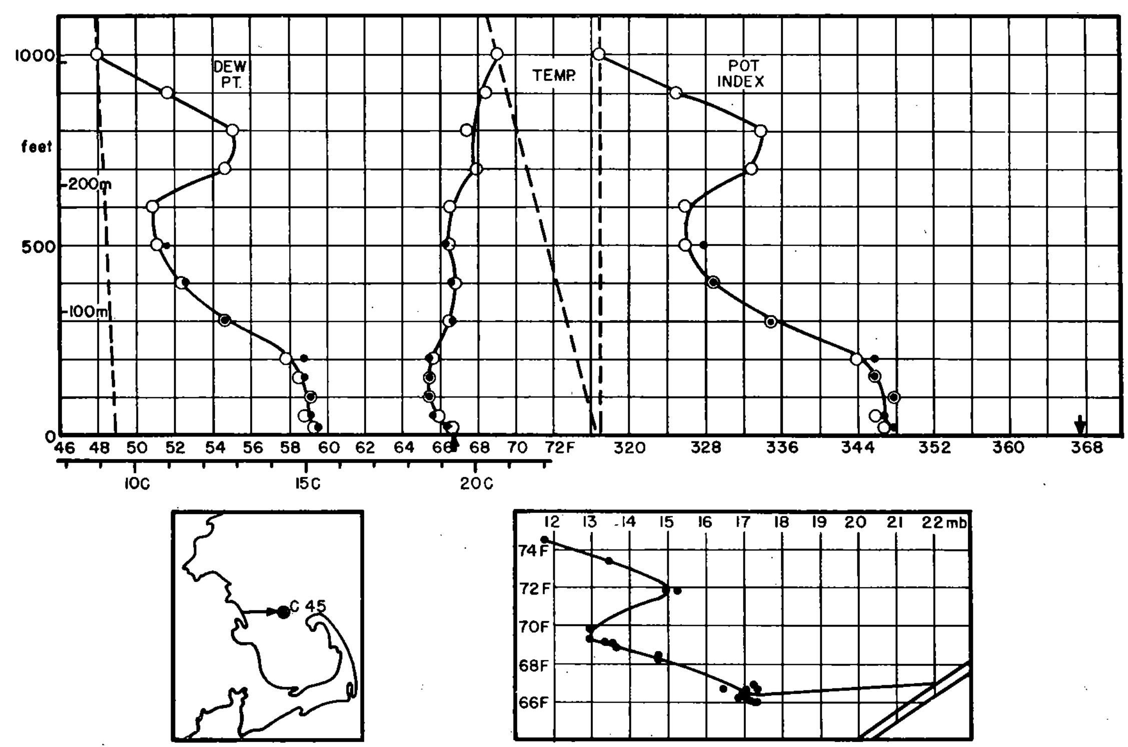

FIG. 12. C45; 70°25′W, 42°06′N; 5 July 1944; o ascent 12^h07^m–12^h17^m, • ascent 12^h19^m–12^h24^m; wind 270° 6 mph at 1000 ft, 1B (direction not observed) at surface (E to SE at Marshfield); 1000-ft trajectory 12 mi, 2 hr, from Marshfield.

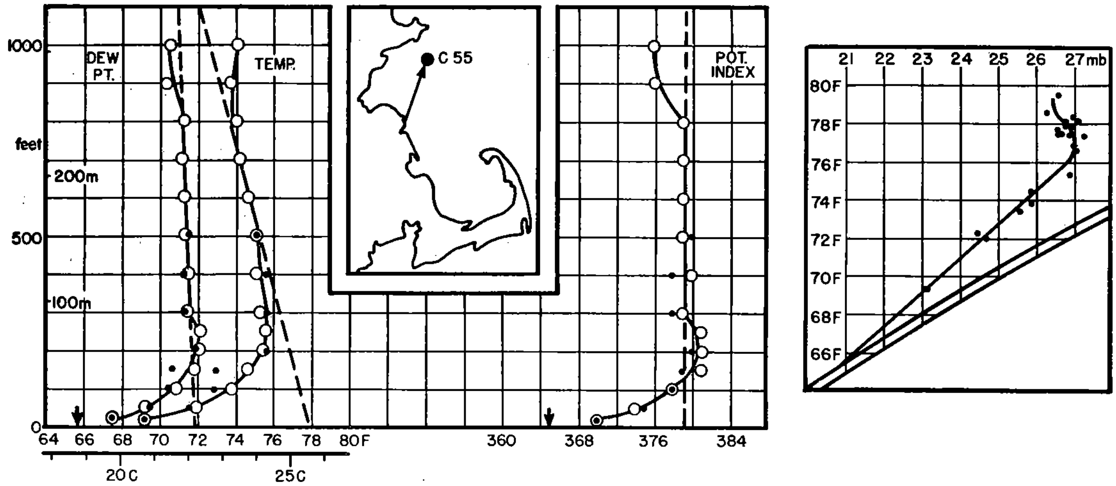

FIG. 13. C55; 70°36′W, 42°31′N; 12 July 1944; o ascent 10^h11^m–10^h21^m, • ascent 10^h23^m–10^h28^m; wind 200° 25 mph at 1000 ft, SW 3B at surface; 1000-ft trajectory 22 mi, 1 hr, from Scituate.

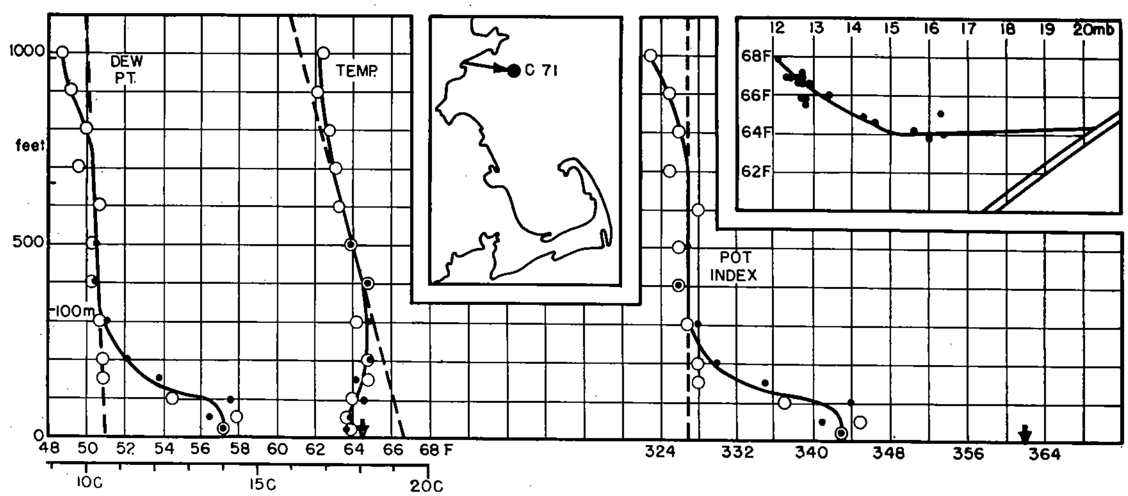

FIG. 14. C71; 70°36′W, 42°31′N; 22 July 1944; o ascent 10^h01^m–10^h11^m, • ascent 10^h14^m–10^h19^m; wind 280° 16 mph at 1000 ft, W 3B at surface; 1000-ft trajectory 15 mi, 1 hr, from Salem.

trajectory, has been heated and convectively mixed by this warmer water. Because of the variation of water temperature, the measured distributions do not show similarity; this is best illustrated by the bend in the characteristic curve. The portion of the curve below the bend points to the new water temperature; the portion above the bend probably points to the water temperature which was first effective in cooling the air.

Figure 15, C74. Clear skies. The dew point of the air near the surface is nearly the same as the water temperature, so that the over-water modification, which extends to about 200 ft, is important mainly in its effect on the temperature. The interesting part of this sounding is the slight temperature inversion and large change in humidity between 700 and 900 ft. This is definitely not the result of modification over the waters of Massachusetts Bay. The air in this sounding was apparently originally part of a dry polar continental air mass which moved over southern waters and was considerably moistened in the surface layer. The 10^h31^m radiosonde ascent at Cambridge and the 08^h00^m airplane observation at Quonset showed a large humidity lapse between the surface and 2000 ft. This has been intensified in the case of C74 by shearing stratification. The air near the surface has come quite directly from the waters south of Cape Cod, crossing the Cape during the morning, while the air at 1000 ft had a considerable trajectory over land before departing from Plymouth. It is especially interesting that the degree of stability existing between 700 and 900 ft is capable of preventing more mixing between the dry air above and the moist air below these levels.

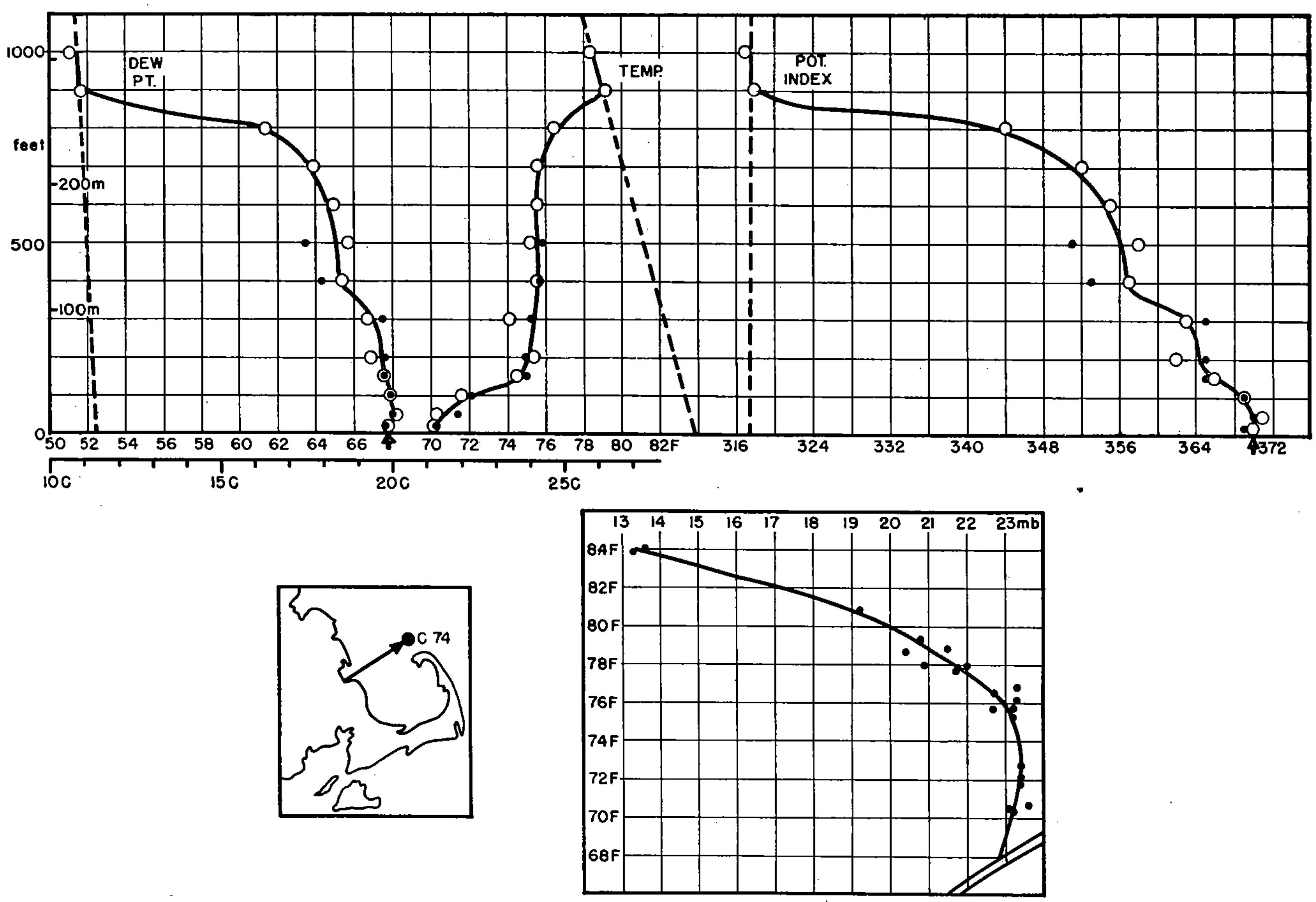

FIG. 15. C74; 70°16′W, 42°08′N; 24 July 1944; o ascent 10^h45^m–10^h55^m, • ascent 10^h57^m–11^h02^m; wind 240° 16 mph at 1000 ft, 2B (direction not observed) at surface (SSW at North Truro and South Weymouth); 1000-ft trajectory 24 mi, 1½ hr, from Plymouth.

Figure 16, C78. High scattered clouds. The two homogeneous layers in the sounding result from shearing stratification, since the air was homogeneous in the lowest 1000 ft before leaving land. That the air left land from the Scituate region and not from Boston is definitely shown by the surface temperatures of 76 F at 08^h30^m and 80 F at 09^h30^m at

South Weymouth, consistent with the potential temperatures in the homogeneous layers in the sounding. The surface temperature at Boston at 07^h30^m was only 72 F. The air has been cooled and moistened in the lowest 300 ft during the over-water trajectory. A water temperature of about 66 F follows from the characteristic curve.

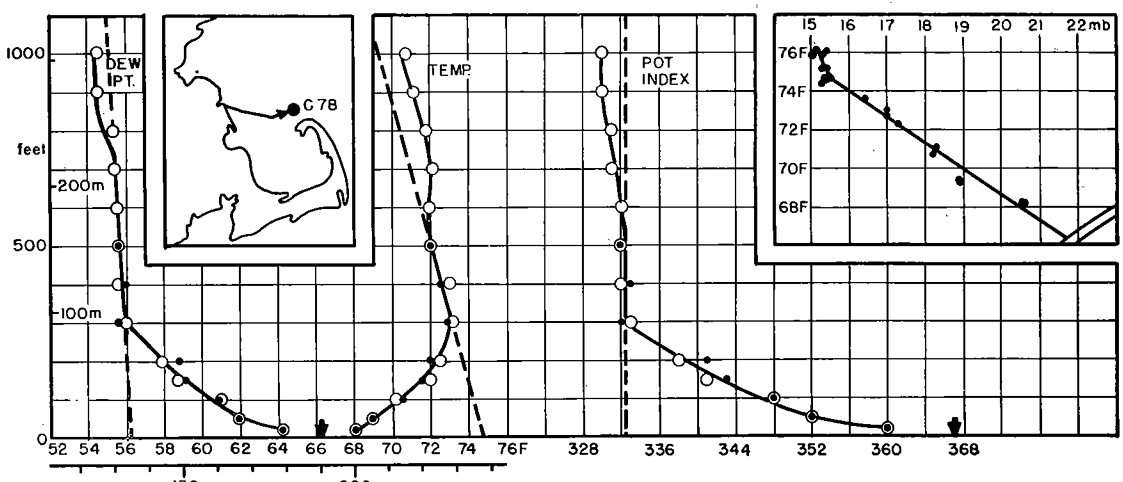

FIG. 16. C78; 70°16′W, 42°08′N; 26 July 1944; o ascent 10^h49^m–10^h59^m, • ascent 11^h02^m–11^h07^m; wind 260° 10 mph at 1000 ft, 1B (direction not observed) at surface (WSW at North Truro and South Weymouth); 1000-ft trajectory 25 mi, $2\frac{1}{4}$ hr, from Scituate.

Figure 17, C79. Generally overcast at about 4000 ft, some low clouds 500–1000 ft reported in the region, some light rain and fog. A warm front extends across Massachusetts Bay, lying at 14^h30^m near South Weymouth and somewhat south of North Truro.

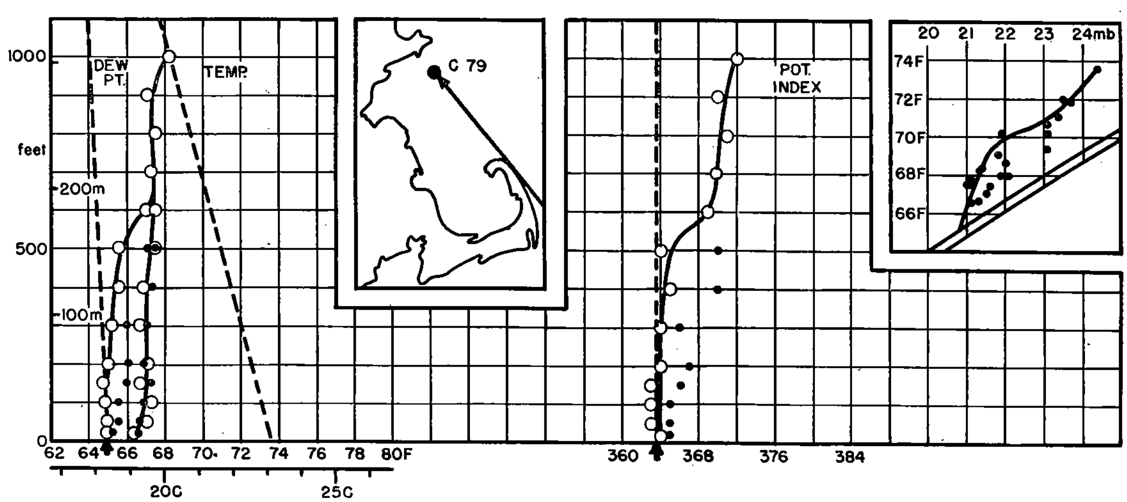

FIG. 17. C79; 70°36′W, 42°31′N; 27 July 1944; o ascent 14^h43^m–14^h53^m, • ascent 14^h56^m–15^h01^m; wind 140° 20 mph at 1000 ft, SE 4B at surface; 1000-ft trajectory > 100 mi, > 5 hr, source unknown (may have crossed Cape Cod).

The following surface reports, showing temperature, dew point, and wind, both before and after the frontal passage, indicate the characteristics of the front:

South Weymouth:	13^h30^m	72/68	ESE	9
	15^h30^m	74/72	S	10
North Truro:	15^h30^m	69/65	SSE	12
	17^h30^m	74/73	SSW	14

It is believed that the frontal surface is observed in C79 between 500 and 600 ft. This height corresponds to a slope of the frontal surface of about 1/250, a reasonable figure. Moreover, clouds were observed between 700 and 1000 ft and the measurements indicate saturation,[6] so that, at each height in this interval, one point represents both temperature and dew point. The measurement at 400 ft in the check sounding also indicates saturation. The water temperature is somewhat uncertain, as is the height of modification.

Figure 18, C82. High broken clouds; weak cold front passed North Truro at about 09^h. The surface temperature and dew point at 08^h30^m were 75 F and 61 F at South Weymouth, 71 F and 62 F at Blue Hill, and 73 F and 61 F at Boston. These tempera-

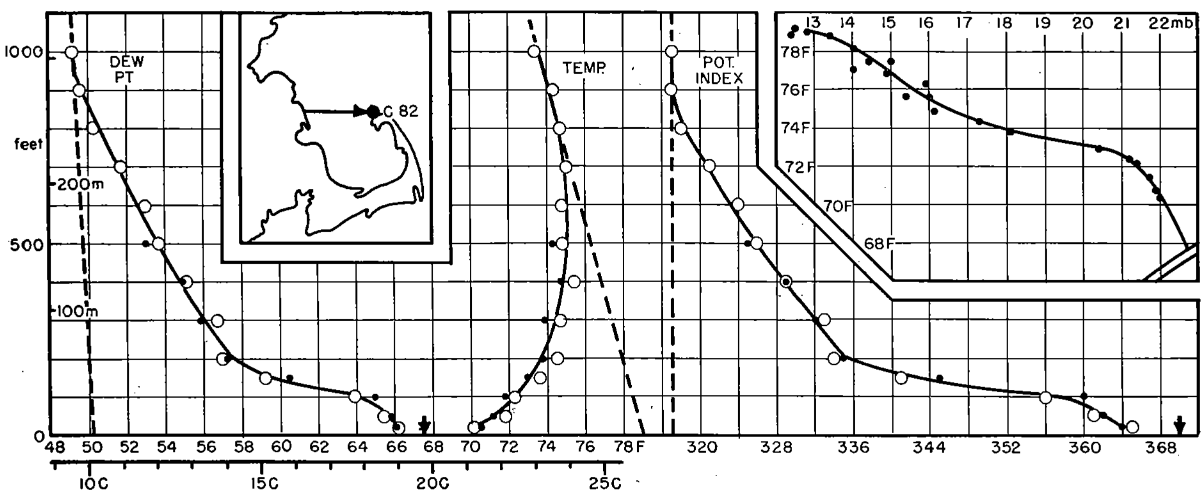

FIG. 18. C82; 70°16′W, 42°08′N; 31 July 1944; o ascent 10^h49^m–10^h59^m, • ascent 11^h03^m–11^h08^m; wind 270° 6 mph at 1000 ft, SW 1B at surface; 1000-ft trajectory 22 mi, 2½ hr, from Marshfield.

tures are lower than the potential temperatures above 200 ft in the sounding, and show that the air above that level was not convectively mixed before leaving land. Moreover, a large humidity decrease between the surface and 1000 ft was observed at Quonset at 08^h00^m and at Cambridge at 10^h30^m. Therefore, although some shearing stratification is indicated by the winds, the vertical distributions above 200 ft probably reflect mainly the conditions existing over land after nocturnal cooling. Because of the initial stability, the probability of significant shear, and the light winds, it is not clear to what height the

[6] The presence of water droplets in the air makes it necessary to modify somewhat the speed correction applied to the observed dry-bulb temperature. When application of the usual correction would give supersaturation, the vapor is assumed to be exactly saturated at the corrected wet-bulb temperature.

air has been affected during its over-water travel. However, it appears from the characteristic diagram and the surface dew points over land that this height lies between 100 and 200 ft. A water temperature of about 68 F is indicated by the characteristic curve; no measured value is available for comparison.

Figure 19, C100. Clear skies, southwest flow of very warm and moist air. The air in this sounding was not initially homogeneous above 300 ft, since surface temperatures

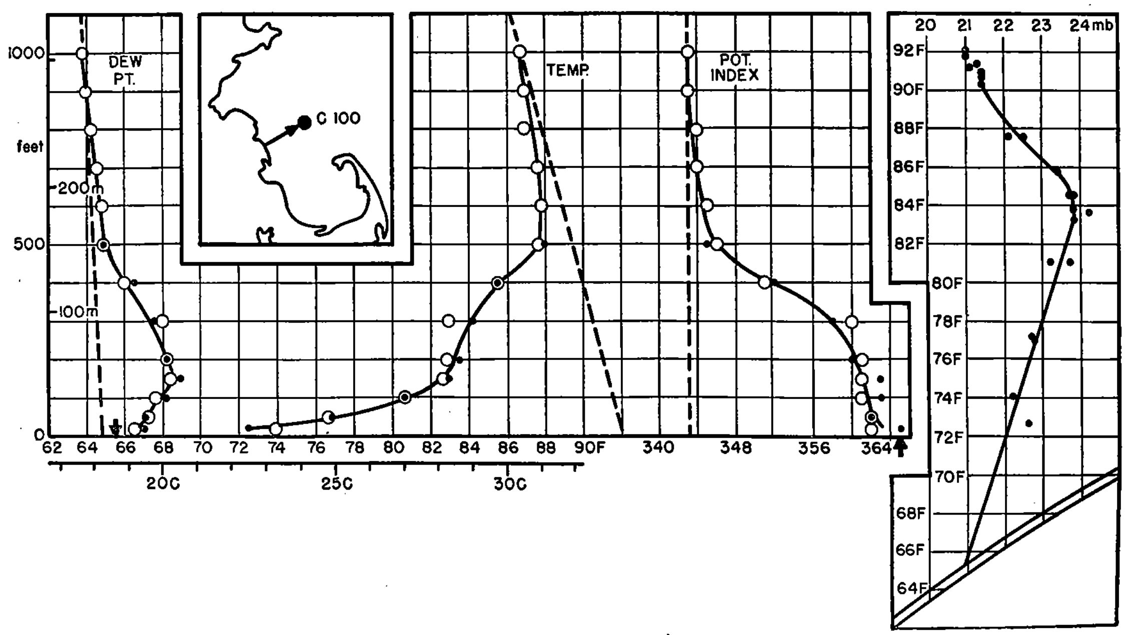

FIG. 19. C100; 70°28′W, 42°05′N; 12 August 1944; o ascent 10^h27^m–10^h37^m, • ascent 10^h40^m–10^h45^m; wind 240° 16 mph at 1000 ft, SSW 2B at surface; 1000-ft trajectory 13 mi, 1 hr, from Plymouth.

over land at 09^h30^m, about the time at which the air crossed the coastline, were only about 86 F. The surface dew point at South Weymouth was 69 F. The cooling and drying effect of the water extends to about 150 ft, the stratification above that level reflecting conditions over land or, to some extent, resulting from shear. Although the humidity deficit is negative, the temperature inversion is sufficiently strong to produce a superstandard gradient of refractive index in the modified layer. The water temperature is quite certainly less than the dew point of the air at 20 ft, 67 F, and appears from the characteristic diagram to lie between 65 F and 66 F.

Figures 20, 21, C104, C105. High scattered clouds and high humidity with southwesterly winds. The air measured in both of these soundings left land at about the same time and place and was initially homogeneous up to about 600 ft; above 600 ft the air was stable after nocturnal cooling. The air in C104, during the 2 miles over water, has been modified up to a height of about 50 ft. Since the temperature of the water is less than the dew point of the air, the air is losing water vapor as well as heat by contact with the cooler water surface. These two processes combine to produce a nearly standard distribution of refractive index down to the water surface. The water temperature is

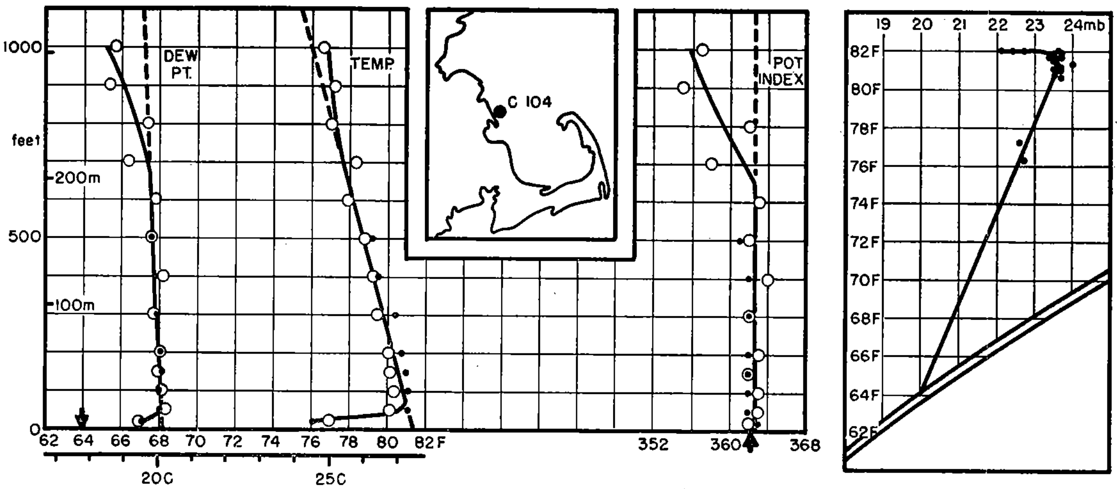

FIG. 20. C104; 70°36′W, 42°06′N; 15 August 1944; o ascent 09^h58^m–10^h08^m, • ascent 10^h13^m–10^h18^m; wind 250° 18 mph at 1000 ft, WSW 2B at surface; 1000-ft trajectory 2 mi, 1/10 hr, from Duxbury.

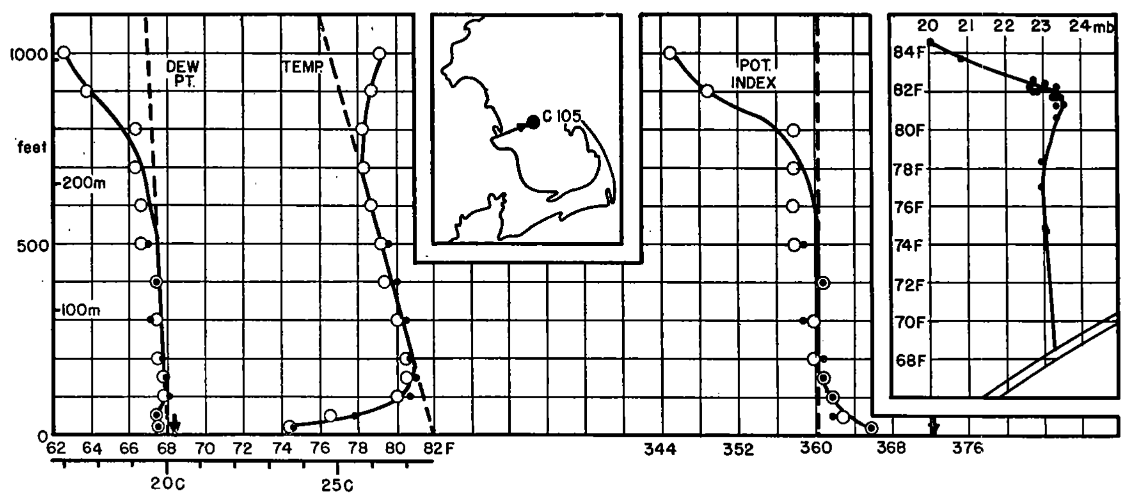

FIG. 21. C105; 70°28′W, 42°05′N; 15 August 1944; o ascent 10^h33^m–10^h43^m, • ascent 10^h46^m–10^h51^m; wind 250° 18 mph at 1000 ft, WSW 2B at surface; 1000-ft trajectory 11 mi, ⅔ hr, from Duxbury.

somewhat uncertain, but it is near 64 F, which is the value indicated by the characteristic curve. In the case of C105, the air passed first over coastal waters of about the same temperature as that indicated by C104 until it was cooled and dried in the lowest 150 ft. It is now being modified by warmer water of temperature 68–69 F. This water is warm enough to have reversed the humidity gradient near the surface, and the air in the lowest 50 ft is now gaining water vapor evaporated from the sea surface; the new water temperature, however, is still considerably less than the temperature of the air above 20 ft, so that marked stability persists above that level. The directly apparent result of this complex modification is a bend in the dew-point curve at 50 ft and a corresponding bend in the characteristic curve. The latter is very similar to that of C104 above the bend, but the bottom part points to the new water temperature.

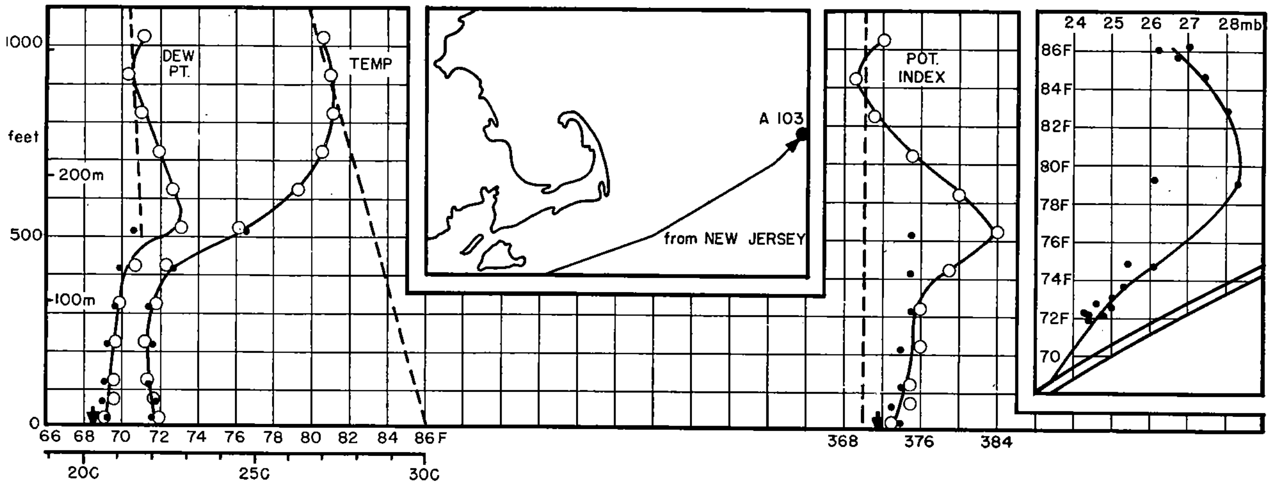

FIG. 22. A103; 68°38′W, 42°00′N; 15 August 1944; o ascent 15^h23^m–15^h30^m, • descent 15^h31^m–15^h36^m; wind 230° 40 mph at 1000 ft, SW 4B at surface; 1000-ft trajectory about 350 mi, 13 hr, from New Jersey.

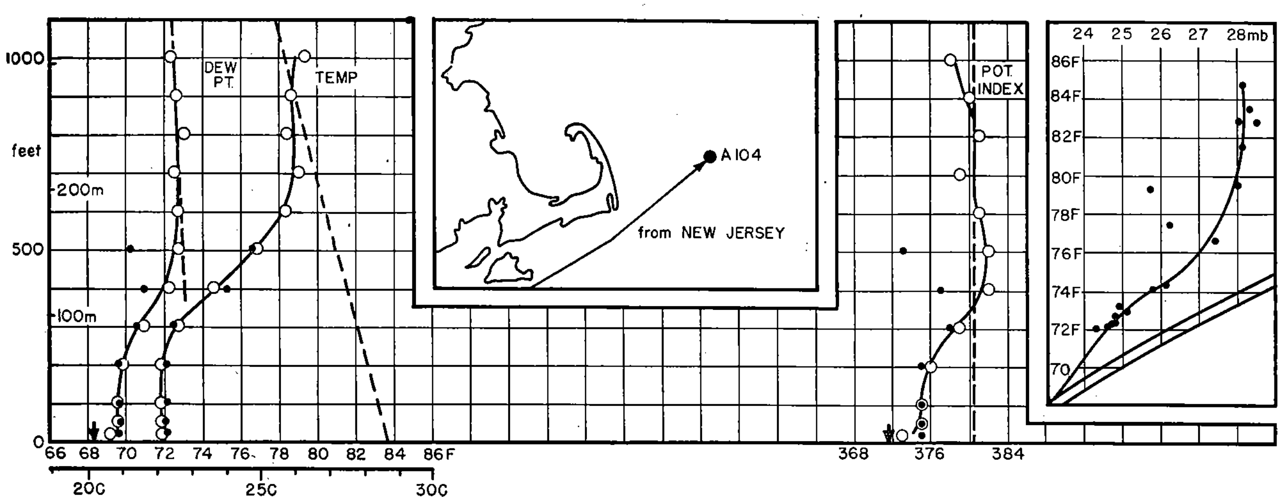

FIG. 23. A104; 69°24′W, 41°56′N; 15 August 1944; o descent 15^h56^m–16^h05^m, • descent 16^h07^m–16^h13^m; wind 230° 40 mph at 1000 ft, SW 3B at surface; 1000-ft trajectory about 310 mi, 12 hr, from New Jersey.

Figures 22, 23, A103, A104. Clear skies, hazy. These soundings measure air which has traveled considerably farther over water than the air in any other cases of stable equilibrium shown in this paper. Because of the much longer trajectories, the analysis of these soundings is much less definite than in other cases. As near as can be estimated from pilot-balloon observations, the air measured here left the New Jersey coast shortly after midnight and was not initially homogeneous. The soundings are chiefly interesting because the greatest stability is found above 300–400 ft, while the air below that level and above 20 ft has been made partially homogeneous by some process. Because of the length of time the cooling process has been operating and because the wind is appreciable, it appears reasonable that this mixing has been accomplished by mechanical turbulence;

the upper inversion in this case is a turbulence inversion, such as is often observed over land and is similar to effects noted for over-water soundings with shorter trajectories and smaller temperature excesses (see Figs. 24, 38, 39). On the other hand, the possibility cannot be ruled out that the air in the lowest 300–400 ft has at some time during its over-water travel been convectively mixed by warmer water. Furthermore, some shearing effects must be present, and radiation cannot be considered negligible. The water temperatures seem to be less than the air temperatures at 20 ft, since the lapse rates of temperature are not adiabatic; those indicated appear reasonable but must be considered questionable by ± 3 F.

Figure 24, B14. A cold front passed Boston at about 09^h30^m and North Truro at about 11^h30^m. Rain and fog before the frontal passage gave way to overcast clouds at about 7000 ft and scattered clouds at about 2500 ft after the frontal passage. The homo-

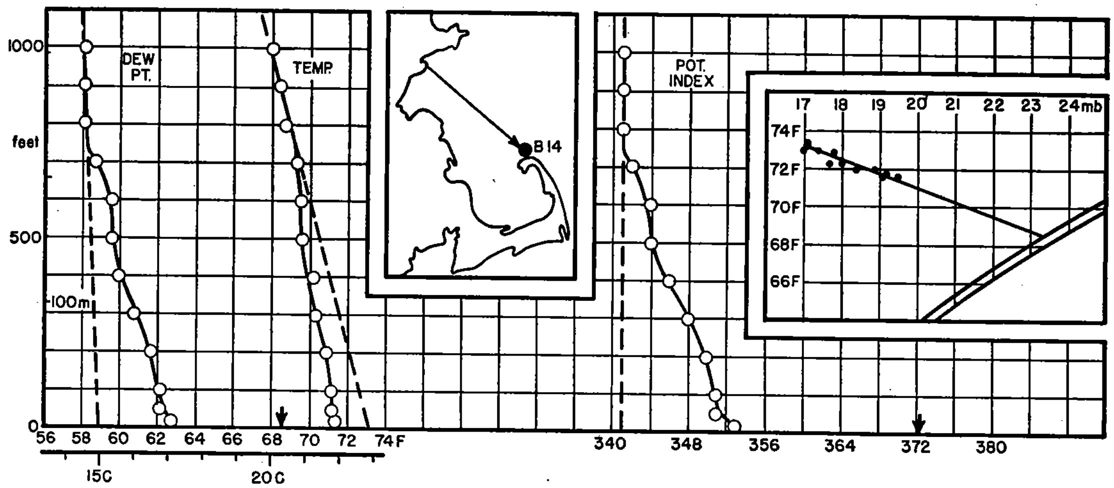

FIG. 24. B14; 70°13′W, 42°06′N; 18 August 1944; o ascent 14^h45^m–14^h54^m; wind 310° 30 mph at 1000 ft, NW 5B at surface; 1000-ft trajectory 45 mi, $1\frac{3}{4}$ hr, from Salem.

geneous layer above 700 ft in the sounding has potential temperature and dew point of 73 F and 59 F; the surface values over land at 13^h30^m were 76 F and 60 F at Bedford and 74 F and 61 F at Boston. Because of the small temperature excess and relatively strong wind, considerable mechanical mixing is taking place in the thermally stable air. This accounts for the rather high modification, about 700 ft. The temperature distribution in the modified air is of interest. The greatest stability is found below 50 ft where the mixing is necessarily small close to the surface; the lapse rate is then nearly dry-adiabatic up to 500 ft; above this is a stable layer, not quite an inversion, but of the same nature as a turbulence inversion. The boat measured a water temperature of 68 F at 10^h30^m near the sounding point and from 08^h30^m to 10^h30^m found temperatures of 68–70 F over the last 20 miles of the trajectory. These measurements agree well with the temperature of 68–69 F which follows from extrapolation of the characteristic curve.

Figure 25, C119. High broken clouds. This air was homogeneous over land and is now being cooled and moistened from below as it passes over the water. The modifica-

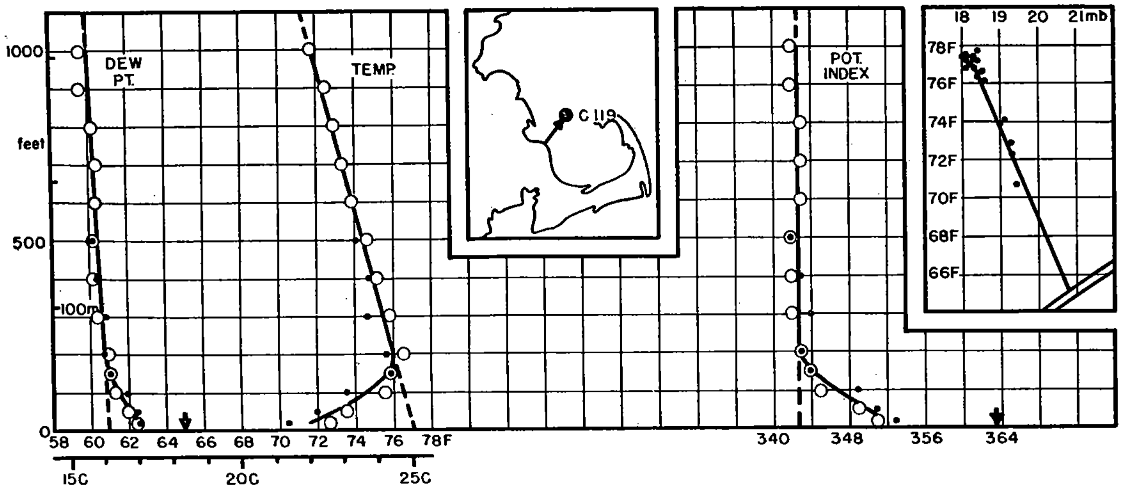

FIG. 25. C119; 70°28′W, 42°05′N; 21 August 1944; ○ ascent 14^h50^m–15^h00^m, • ascent 15^h03^m–15^h08^m; wind 220° about 35 mph at 1000 ft, SSW 4B at surface; 1000-ft trajectory 12 mi, $\frac{1}{3}$ hr, from Plymouth.

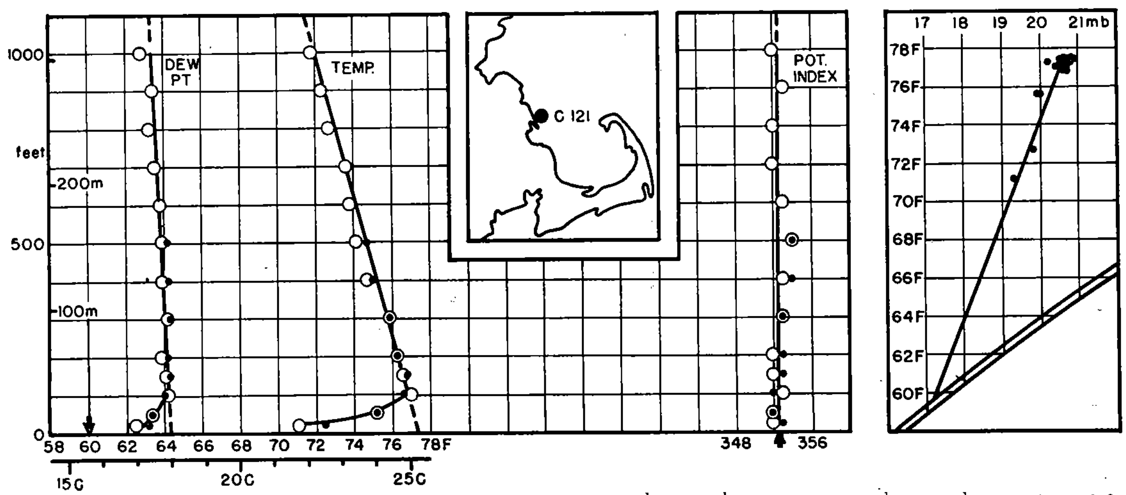

FIG. 26. C121; 70°36′W, 42°06′N; 22 August 1944; ○ ascent 14^h20^m–14^h30^m, • ascent 14^h33^m–14^h38^m; wind 260° 20 mph at 1000 ft, WSW 2B at surface; 1000-ft trajectory 3 mi, $\frac{1}{6}$ hr, from Duxbury.

tion extends to about 200 ft; above this level the air has essentially the same temperature and humidity as it had before leaving land. The water temperature, extrapolated from the characteristic diagram, is about 65 F.

Figure 26, C121. Broken clouds at 8000 ft, haze. The air measured by this sounding was homogeneous before leaving land. At South Weymouth the surface temperature was 77 F at 13^h30^m and 78 F at 14^h30^m; the corresponding surface dew points were 65 F and 66 F. These agree well with potential values in the observed homogeneous layer, which has persisted since the air left land. The effect of the water is confined to the lowest 100 ft, with the air in this layer losing both heat and water vapor by contact with the cooler water. The potential index of refraction in the air is the same as the value which

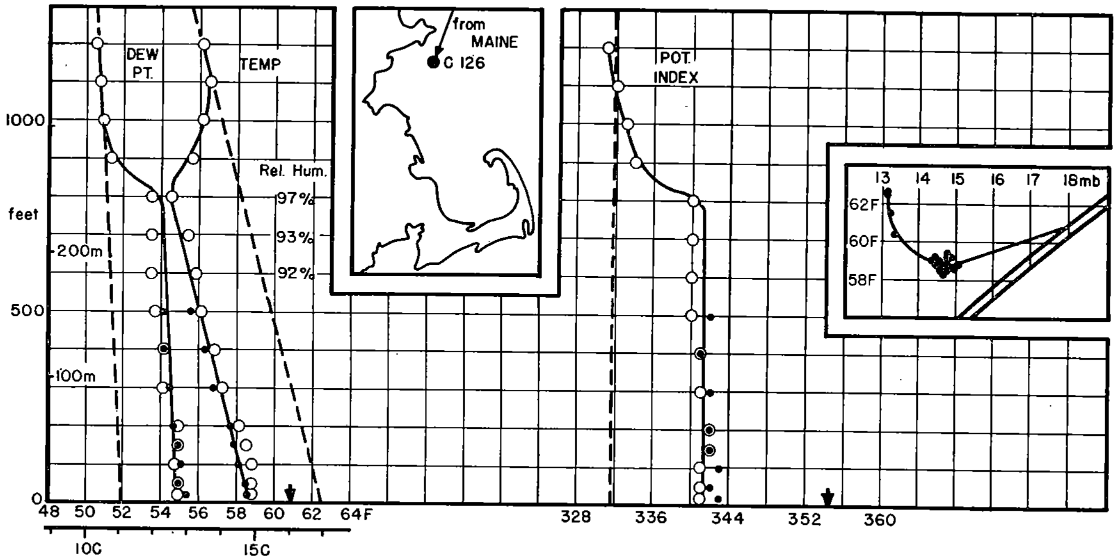

FIG. 27. C126; 70°36′W, 42°31′N; 24 August 1944; o ascent 10^h08^m–10^h20^m, • ascent 10^h31^m–10^h36^m; wind 20° 20 mph at 1000 ft, NNE 4B at surface; 1000-ft trajectory about 60 mi, 3 hr, from near Kennebunk, Maine.

corresponds to the water temperature, so that the index distribution near the surface has not been changed since leaving land. No measurements of water temperature are available and the extrapolated value of 60 F must be considered doubtful by ± 2 F.

Figure 27, C126. Broken clouds at about 3500 ft, overcast at about 7000 ft; cold front passed Rockport at about 04^h, now located between Cape Cod and Nantucket. This air left land early in the morning and was not initially homogeneous. It is being heated from below, and the vertical distributions of temperature, humidity, and refractive index are characteristic for the case where convective mixing is the predominant factor in the air's modification. Between 20 and 800 ft a homogeneous layer is observed. Near the surface is a shallow layer in which appreciable vertical gradients occur; this is not measured here, but is known to exist since between the surface and 20 ft the parameters must change from their values at the sea surface to their measured values in the homogeneous layer. Above the homogeneous layer is a stable layer marking the top of the convection. At 700 and 800 ft the plane was in a cloud, although the measurements at these levels do not indicate saturation. It is probable that radiation from the top of this cloud has contributed to the convection by cooling the layer from above. The indicated water temperature of 61 F was measured the next day and is therefore somewhat questionable; it is clear, however, that the true water temperature is greater than 59 F.

Figure 28, C128. Scattered to broken clouds at about 4000 ft. This air had a trajectory over waters north of Cape Ann before reaching Massachusetts Bay. The trajectory of the air near the surface is somewhat doubtful because of the easterly surface wind at Rockport; however, it is probably not essentially different from that of the air aloft since the surface wind direction at Rockport was NNW until about 14^h. The height of modification is doubtful, but it is quite certainly at least 200 ft. Above this level, the characteristic curve is not a straight line, but the bend may be due to shear or to changing water temperature; the latter is a distinct possibility because of the colder water north of Cape Ann. The measurements below 200 ft lie along a straight line which intersects the saturation curve at a point corresponding to a water temperature of 61.5 F. At 18^h30^m water temperatures lying between 60 and 62.5 F were measured near the sounding point.

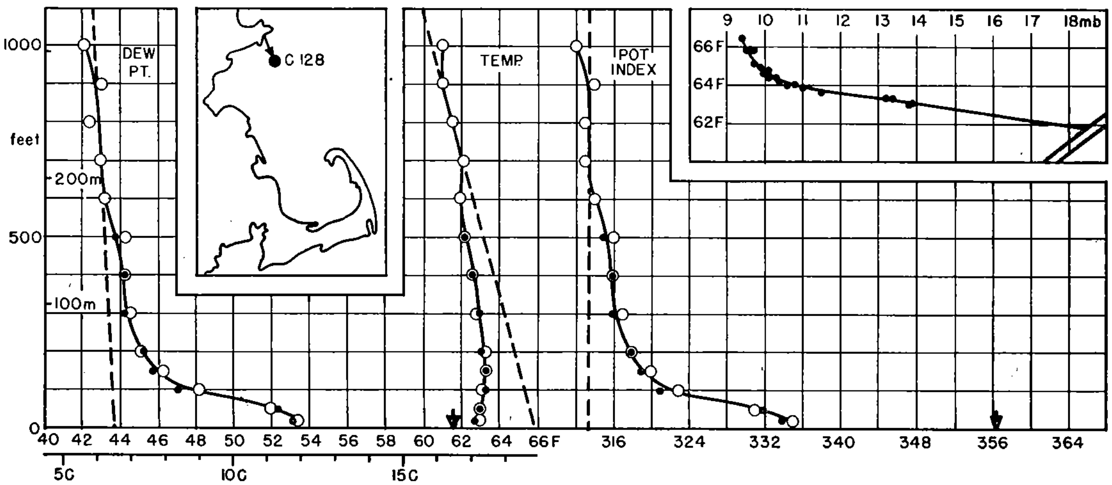

FIG. 28. C128; 70°36′W, 42°31′N; 25 August 1944; o ascent 14^h12^m–14^h22^m, • ascent 14^h25^m–14^h30^m; wind 340° 10 mph at 1000 ft, 2B (direction not observed) at surface (E 4 mph at Rockport); 1000-ft trajectory 8 mi, ½ hr, from Cape Ann.

Figure 29, C135. High scattered clouds.° The air in this sounding left land near Portland early in the morning and was not initially homogeneous. The surface temperature and dew point at Portland at 05^h30^m were 53 F and 51 F, so that this air must have been quite stable before leaving land. The nocturnally cooled air has been heated from below by progressively warmer water during its over-water travel from Portland. It is now

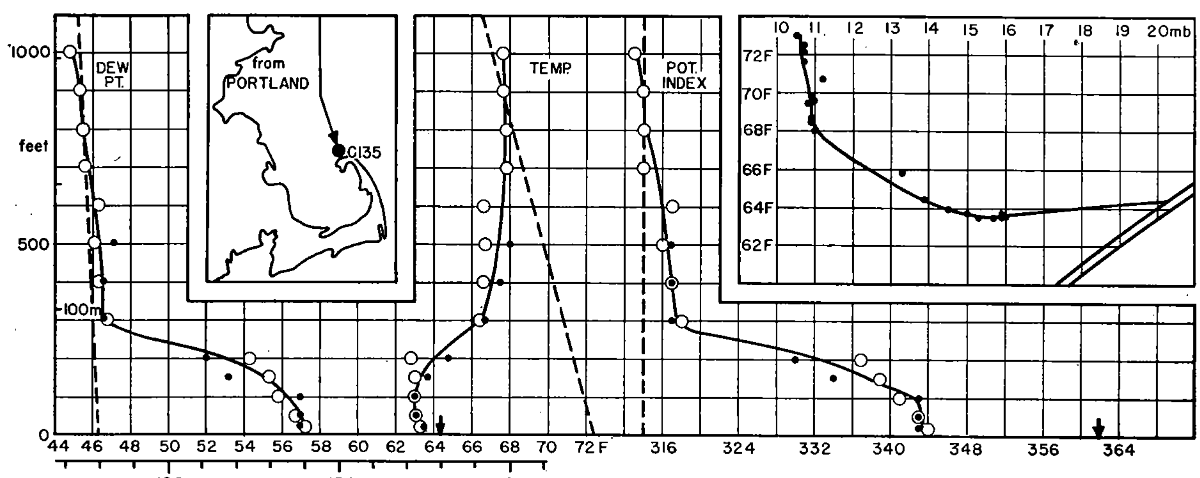

FIG. 29. C135; 70°16′W, 42°08′N; 28 August 1944; o ascent 15^h35^m–15^h45^m, • ascent 15^h49^m–15^h54^m; wind 340° 14 mph at 1000 ft, 2B (direction not observed) at surface (N at Race Point); 1000-ft trajectory about 120 mi, 9 hr, from near Portland, Maine.

over water of temperature 64–65 F as measured at 16^h30^m, 4 miles from the sounding point. The effect of the heating and moistening is confined to the lowest 200 ft, despite the long over-water trajectory; this, of course, is because the air above that level is potentially warmer than the water, so that there is a definite top to the convection.

Figure 30, C138. High scattered clouds. The radiosonde observation at Cambridge at 11^h14^m showed an adiabatic lapse rate of temperature up to 3000 ft, so that the air leaving land at Duxbury at about the same time was almost certainly homogeneous in

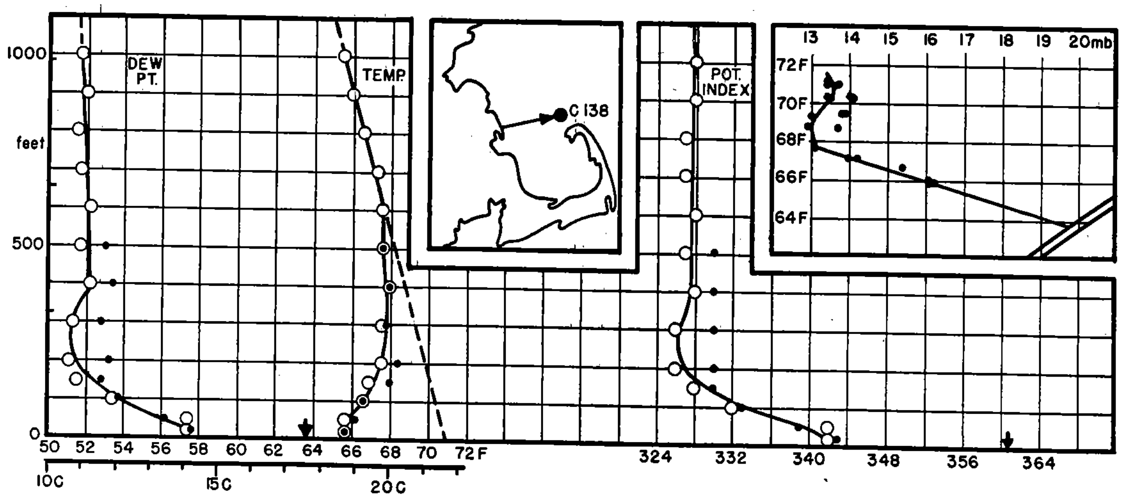

FIG. 30. C138; 70°16′W, 42°08′N; 29 August 1944; o ascent 12^h00^m–12^h10^m, • ascent 12^h13^m–12^h18^m; wind 260° 25 mph at 1000 ft, WSW 2B at surface; 1000-ft trajectory 20 mi, ⅘ hr, from Marshfield.

the lowest 1000 ft. Modification by the water extends no higher than 200 ft. It follows that variations from homogeneity above that level must be due to shearing stratification. The characteristic curve shows the effect of shear, but seems to be a straight line below 150 ft. When extended, it intersects the saturation curve at a point corresponding to a water temperature of about 64 F. The boat measured 62.5 F at 08^h00^m and 65 F at 16^h50^m at the position of the sounding.

Figure 31, C140. High scattered clouds. The air in this sounding was homogeneous when it left land near Marshfield at about 10^h30^m. During the 10-mile trajectory over the water, the air below about 250 ft has lost heat and gained water vapor, but the air above that level has been unaffected. The water temperature of 63 F follows from the characteristic diagram, the extrapolation in this case appearing to be quite reliable.

Figure 32, C143. Broken clouds at about 4000 ft. The air was homogeneous before leaving land, as shown by the 11^h11^m radiosonde at Cambridge and by the fact that convective clouds formed over land in the late morning. The air measured above 500 ft must have a somewhat different trajectory than the air below it, since it is slightly drier; the difference, however, is slight. The air in the lowest 200 ft has been cooled and moistened since leaving land, and the characteristic curve can be drawn as a straight line

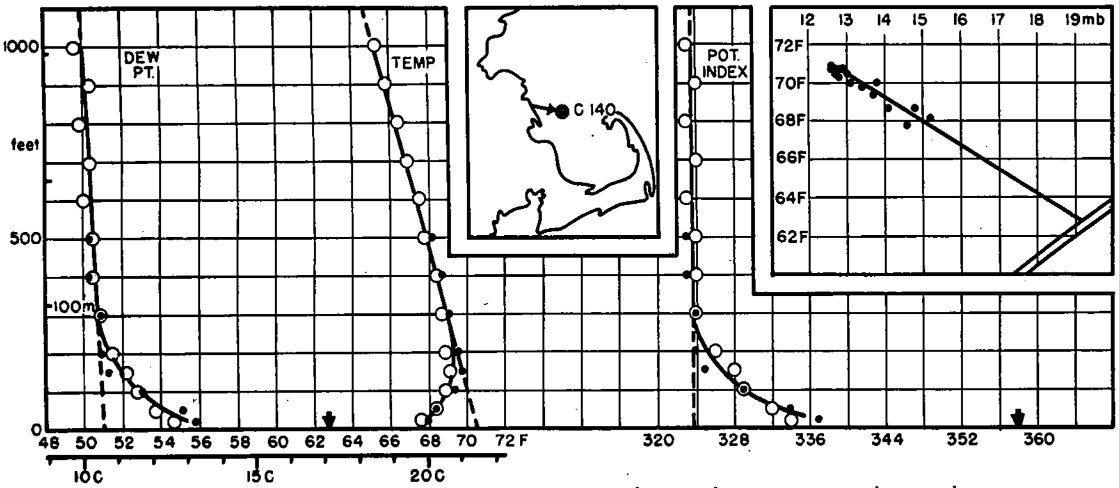

FIG. 31. C140; 70°28′W, 42°05′N; 30 August 1944; o ascent 10^h47^m–10^h57^m, • ascent 11^h01^m–11^h06^m; wind 280° 21 mph at 1000 ft, WNW 3B at surface; 1000-ft trajectory 10 mi, ½ hr, from Marshfield.

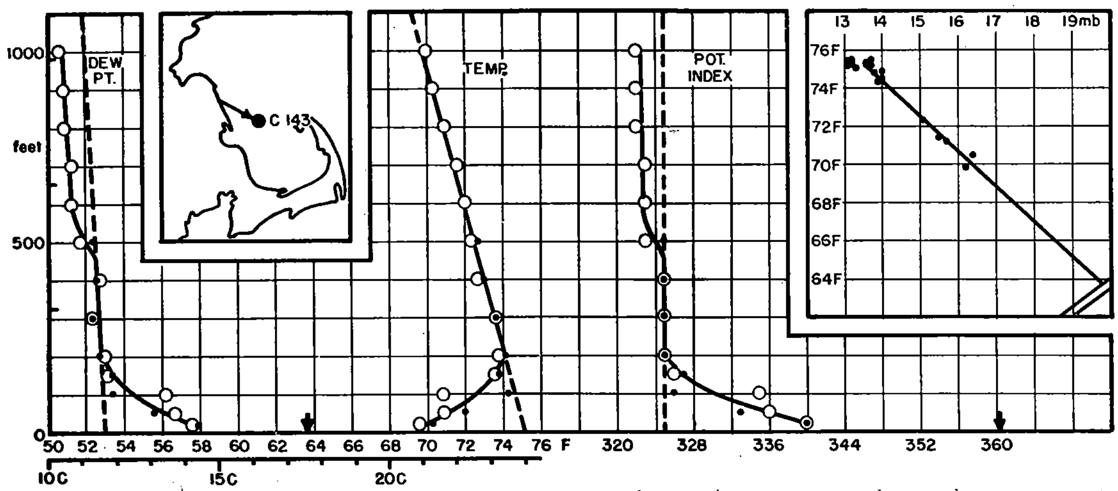

FIG. 32. C143; 70°28′W, 42°05′N; 30 August 1944; o ascent 15^h32^m–15^h42^m, • ascent 15^h45^m–15^h50^m; wind 290° 22 mph at 1000 ft, WNW 2B at surface; 1000-ft trajectory 14 mi, ⅔ hr, from Scituate.

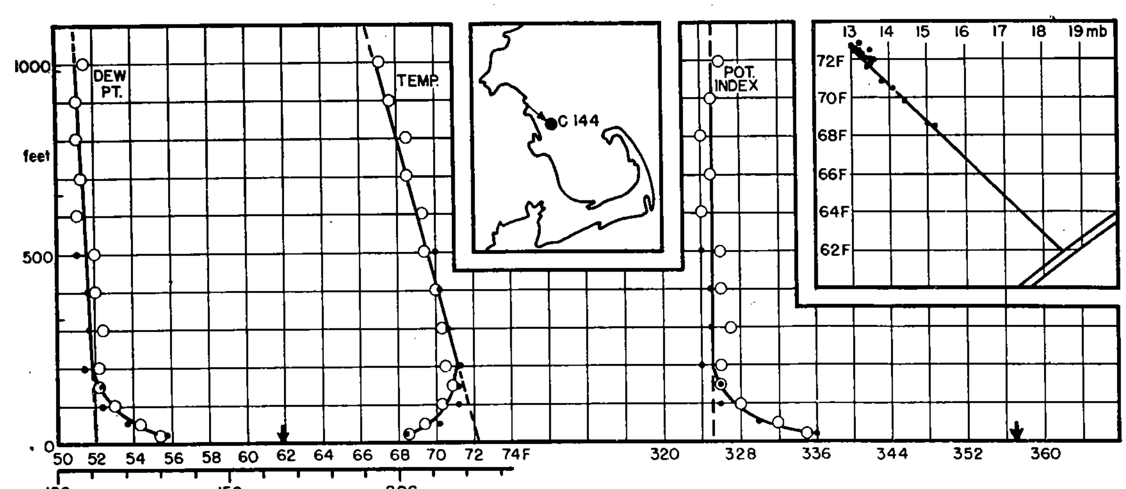

FIG. 33. C144; 70°36′W, 42°06′N; 31 August 1944; o ascent 10^h04^m–10^h14^m, • ascent 10^h17^m–10^h22^m; wind 310° 16 mph at 1000 ft, NW 1B at surface; 1000-ft trajectory 8 mi, ½ hr, from Scituate.

through the measurements in this layer. A water temperature slightly under 64 F is indicated by the intersection of this straight line with the saturation curve for salt water; no measurements are available for comparison with this value. Since the wind is nearly parallel to the coastline, there is some possibility that the air may have left land at Boston and traveled 35 miles over the water. However, pilot-balloon measurements at Boston and North Truro at $11^{h}00^{m}$ and $17^{h}00^{m}$ and at South Weymouth at $13^{h}30^{m}$ all substantiate the indicated trajectory, as does the observation of the surface wind at the time and place of the sounding.

Figure 33, C144. Clear skies. The air was initially homogeneous and has been modified in the lowest 200 ft during its trajectory over the water. The distributions of temperature, humidity, and potential index are similar, showing that mechanical mixing has been the principal process effecting the modification. The extrapolated water temperature is 62 F, somewhat lower than measurements of 63 F near by at $12^{h}30^{m}$. The discrepancy is small and can be at least partially accounted for by solar heating of the water during the time interval between the sounding and the measurements, with clear skies and light winds prevailing. The angle between the wind and the coastline is small, and, from a considerations of winds alone, it appears possible that the air may have left land at Boston at $08^{h}30^{m}$ rather than at Scituate at $09^{h}30^{m}$. However, the indicated trajectory is quite conclusively verified by a consideration of temperatures: The surface temperature at Boston at $08^{h}30^{m}$ was only 68 F, too low to account for the mixed layer in the sounding with potential temperature 72 F; on the other hand, the temperature at South Weymouth at $09^{h}30^{m}$ was 74 F, high enough to have produced this mixed layer.

Figure 34, C149. Overcast at about 6000 ft. The air in this sounding was not homogeneous before passing over Massachusetts Bay. It had a trajectory over warm water south of New England, when it gained considerable moisture in the layer below 500 ft, and then passed only a short distance over land before starting its present over-water trajectory. The surface air, at least, in view of the S or SSW surface winds reported all morning at Race Point and North Truro, appears to have crossed Cape Cod, and traveled a distance of only 10–15 miles over land. During its trajectory over Massachusetts Bay, it has been cooled and dried in about the lowest 200 ft. The water temperature appears from the sounding to be less than 64 F, but cannot be determined at all accurately by the extrapolation method because the characteristic curve is so nearly parallel to the saturation curve. The assumed water temperature of 62–63 F follows from measurements made in the region between $08^{h}30^{m}$ and $09^{h}30^{m}$. The combination of a substandard layer at the surface and a markedly superstandard layer aloft appears in this case to have resulted from large-scale variations in the temperature of the water over which the air has traveled.

Figure 35, C161. Broken clouds at 3000 ft, cold front approaching from the north. Although this sounding was made near shore and the air aloft has come directly from Duxbury, there is a strong likelihood that the surface air has come about 10 miles over water from Plymouth. This follows from the observed surface wind direction, which is verified by observations at Duxbury near by. Moreover, some shear is indicated by the drier air above 600 ft, since the air was homogeneous over land. The air has been modified up to 150 ft while passing over the water. Since the index deficit is zero, the potential-index distribution has remained unchanged. Despite the probability of shear and the scatter of points on the characteristic diagram, the extrapolated water temperature of 61 F agrees well with measurements of 60–62 F made in the vicinity at $20^{h}00^{m}$.

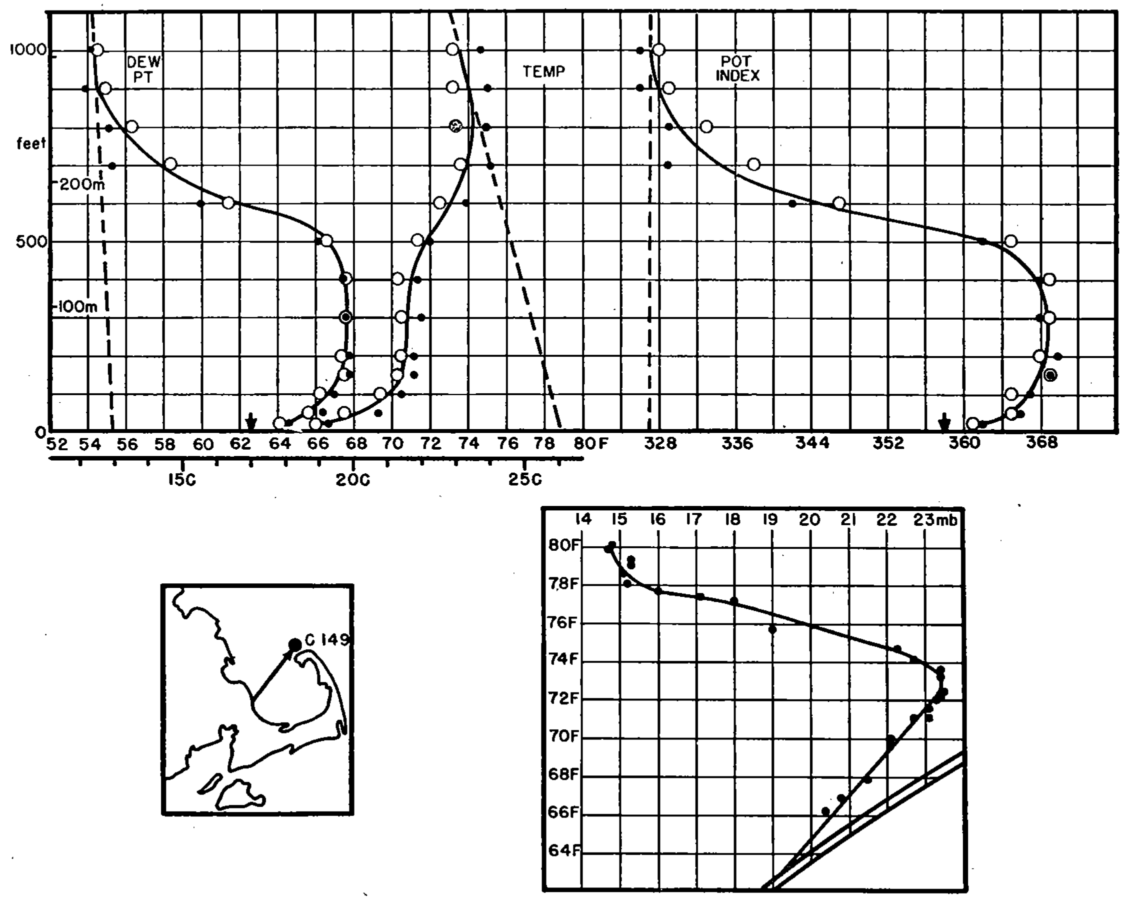

FIG. 34. C149; 70°16′W, 42°08′N; 1 September 1944; o ascent 11^h37^m–11^h47^m, • ascent 11^h59^m–12^h09^m; wind 210° 13 mph at 1000 ft, SW 2B at surface; 1000-ft trajectory, 24 mi, 2 hr, from Plymouth.

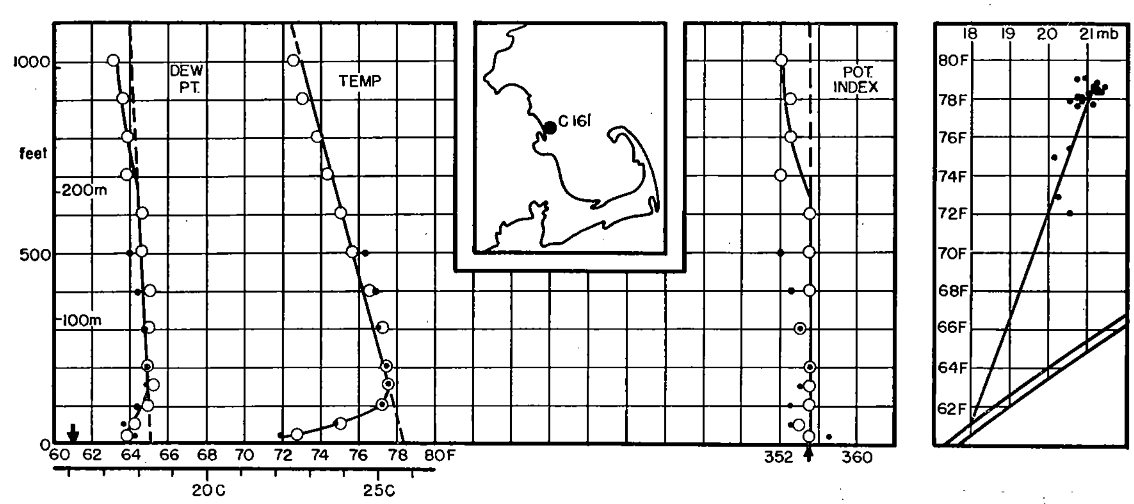

FIG. 35. C161; 70°36′W, 42°06′N; 7 September 1944; o ascent 15^h01^m–15^h11^m, • ascent 15^h16^m–15^h21^m; wind 230° 20 mph at 1000 ft, SSW 4B at surface; 1000-ft trajectory 3 mi, 1/7 hr, from Duxbury.

Figures 36, 37, A119, A120. High broken clouds. Both soundings were made in air which was convectively mixed before leaving land. Although the two air columns differed slightly in their times and points of departure from land, their potential temperatures and dew points over land were essentially the same, 70 F and 45 F. During the over-water trajectory, the surface air in both soundings has been cooled and moistened by contact with the water; this modification extends to about 150 ft in the case of A119 and to about 300 ft in the case of A120. The characteristic curves in both cases appear to be straight lines through the points representing measurements in the modified air, and the derived water temperatures are 59 F for A119 and 61 F for A120.

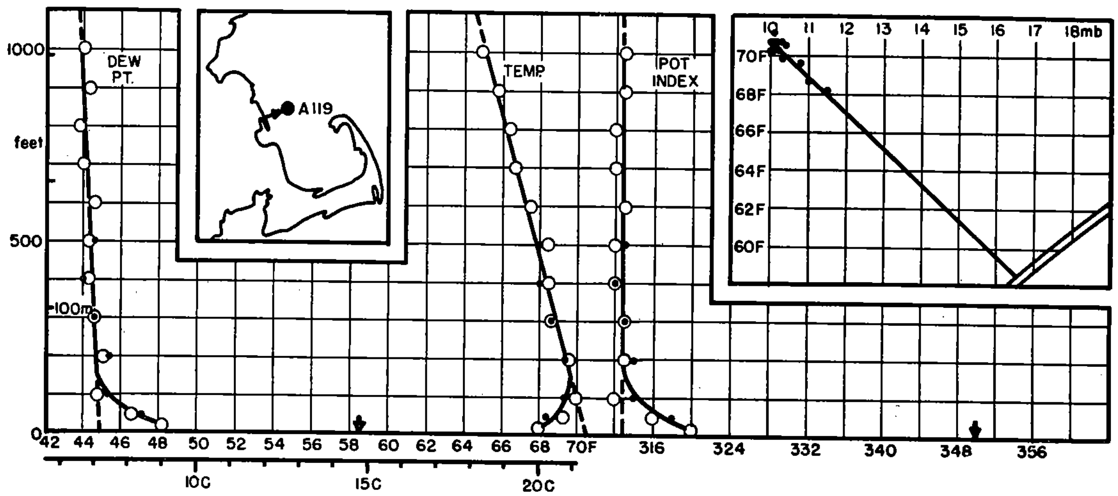

FIG. 36. A119; 70°32′W, 42°08′N; 8 September 1944; o descent 14^h56^m–15^h04^m, • ascent 15^h04^m–15^h08^m; wind 250° 20 mph at 1000 ft, W (force not observed) at surface (15 mph at Duxbury); 1000-ft trajectory 8 mi, ½ hr, from Marshfield.

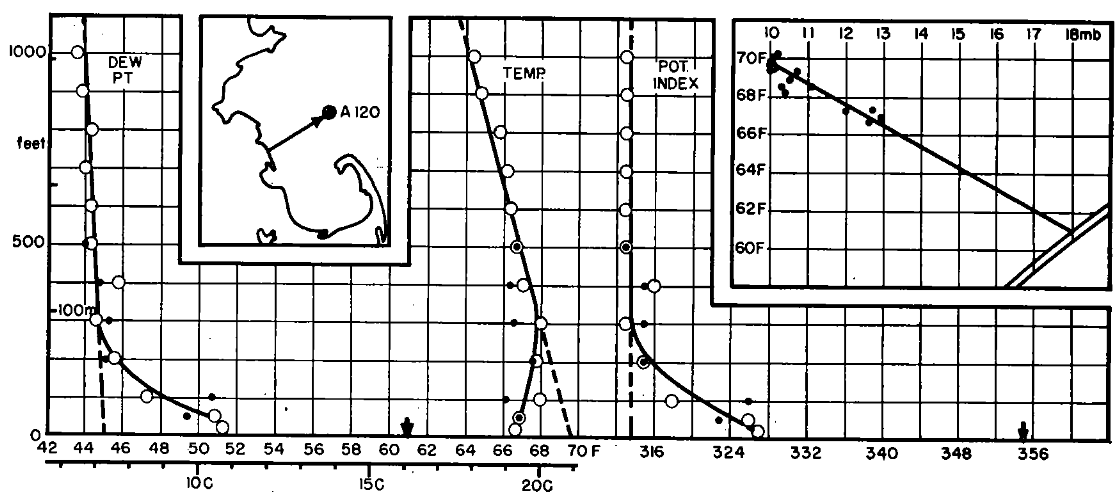

FIG. 37. A120; 70°16′W, 42°09′N; 8 September 1944; o descent 15^h16^m–15^h24^m, • ascent 15^h24^m–15^h28^m; wind 240° 22 mph at 1000 ft, W (force not observed) at surface (12 mph at Race Point); 1000-ft trajectory 24 mi, 1 hr, from Plymouth.

Figures 38, 39, A143, A144. Scattered clouds. These soundings are interesting chiefly because the temperature excess is smaller, the wind stronger, and the over-water trajectory longer than in most of the other soundings presented. It is not definitely indicated that the air in these two soundings was initially homogeneous, but there was probably no appreciable stability over land in the lowest 1000 ft in view of the reported surface wind speeds (18 mph at Bedford, 16 mph at Rockport) and the small increase of surface temperature due to solar heating during the morning. The height to which modification by the water extends is at least 400 ft in both cases, and is probably considerably higher. However, changes in temperature and humidity above 400 ft due to over-water modification have been quite small. Because of mechanical mixing, especially effective due to

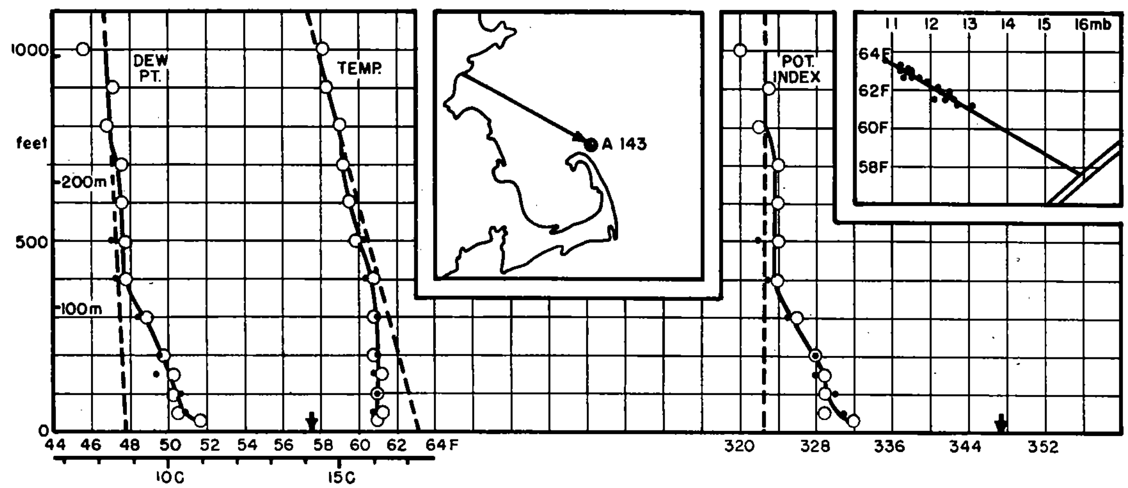

FIG. 38. A143; 70°05′W, 42°07′N; 22 September 1944; o descent 10^h31^m–10^h47^m, • ascent 10^h47^m–10^h55^m; wind 300° 25 mph at 1000 ft, W 4B at surface; 1000-ft trajectory 48 mi, 2 hr, from Lynn.

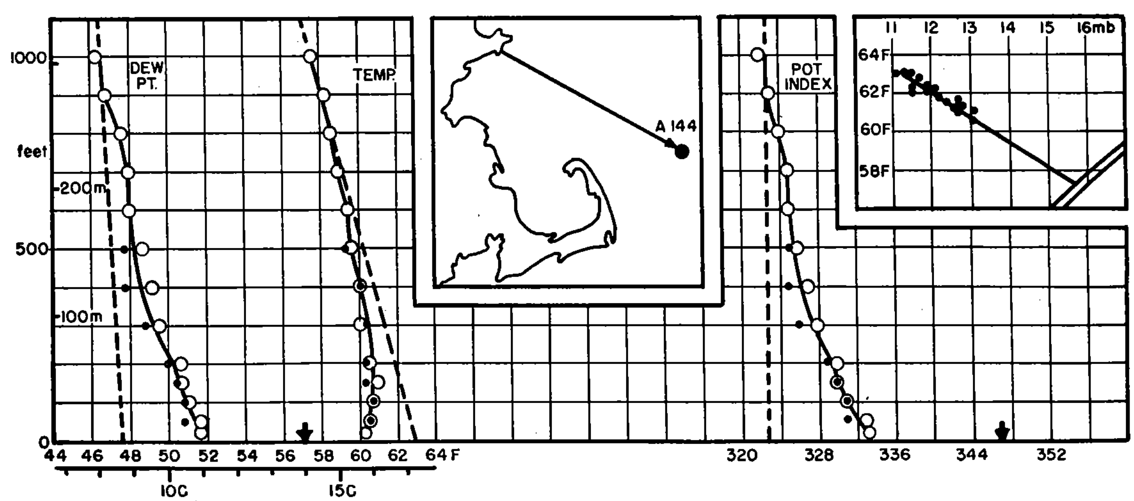

FIG. 39. A144; 69°30′W, 42°07′N; 22 September 1944; o descent 11^h04^m–11^h16^m, • ascent 11^h16^m–11^h22^m; wind 300° 25 mph at 1000 ft, W 4B at surface; 1000-ft trajectory 67 mi, $2\frac{1}{2}$ hr, from Gloucester.

the small temperature excess, there are no large vertical gradients above 50 ft in the modified layers. There are no measurements to verify the extrapolated water temperatures of 57.5 F for A143 and 57 F for A144, and they must be considered somewhat doubtful.

Figures 40, 41, C195, C196. Scattered to broken high clouds. The over-water trajectories of the air measured in these soundings are questionable since the 1000-ft wind has been light and variable. However, the wind has been generally from the northeast quadrant and there is little doubt that the air left land somewhere on the coast of Maine or Nova Scotia the previous day and has been heated from below during a comparatively

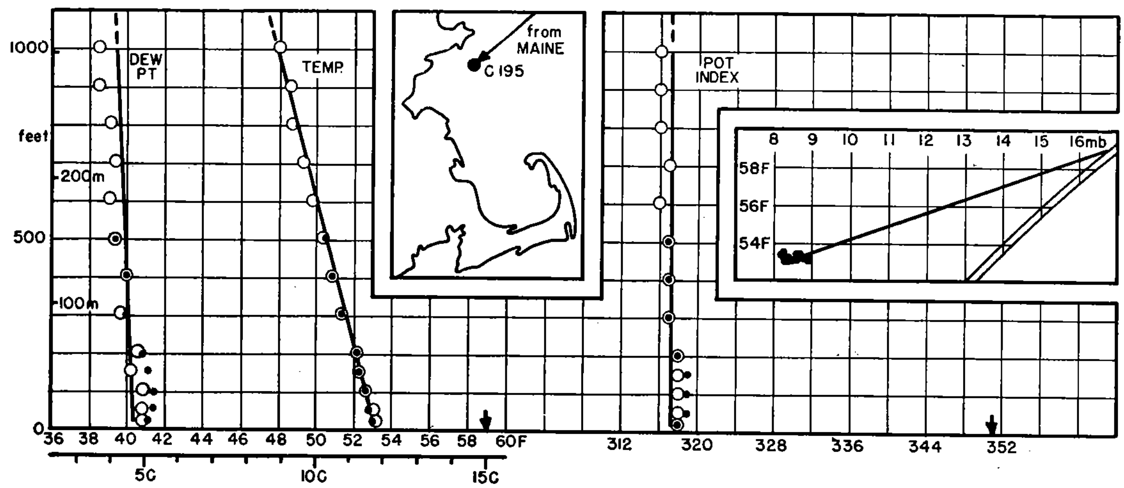

FIG. 40. C195; 70°36′W, 42°31′N; 25 September 1944; o ascent 09^h56^m–10^h06^m, • ascent 10^h11^m–10^h16^m; wind 50° 10 mph at 1000 ft, 2B (direction not observed) at surface (N at Rockport); 1000-ft trajectory > 100 mi, > 10 hr, from Maine or Nova Scotia.

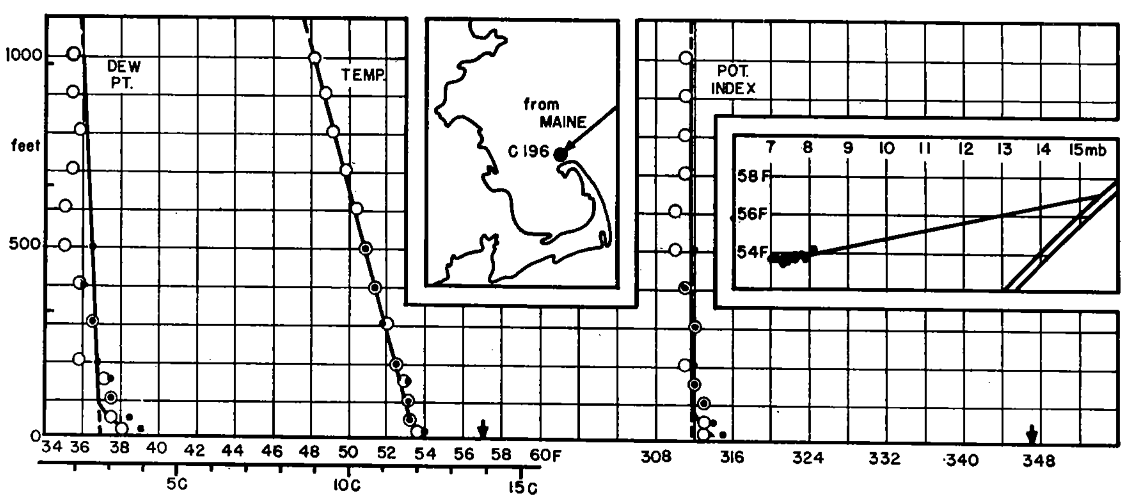

FIG. 41. C196; 70°16′W, 42°08′N; 25 September 1944; o ascent 10^h52^m–11^h02^m, • ascent 11^h05^m–11^h10^m; wind 50° 09 mph at 1000 ft, 2B (direction not observed) at surface (NE at Race Point); 1000-ft trajectory > 150 mi, > 15 hr, from Maine or Nova Scotia.

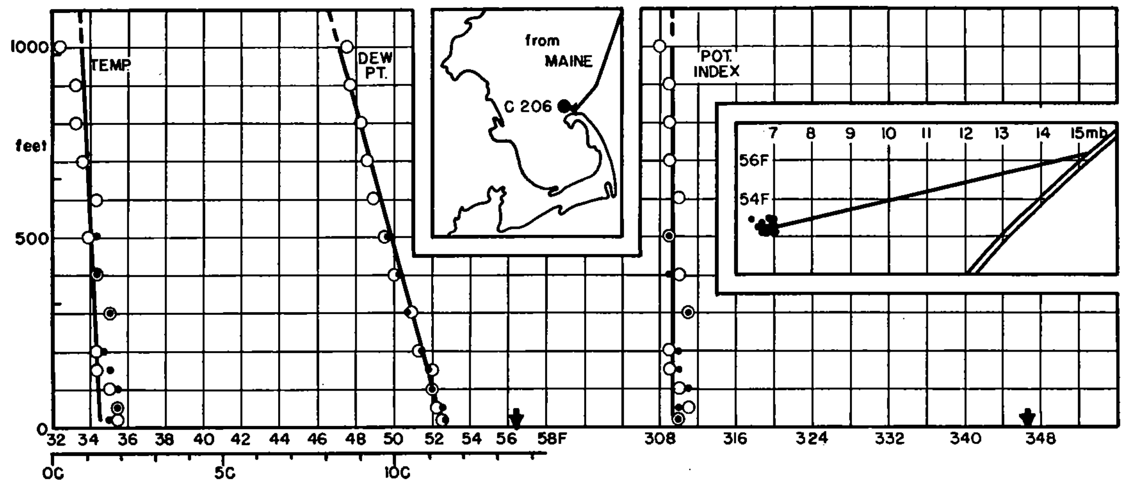

FIG. 45. C206; 70°16′W, 42°08′N; 4 October 1944; o ascent 11^h22^m–11^h32^m, • ascent 11^h39^m–11^h44^m; wind 130° 4 mph at 1000 ft, calm at surface; 1000-ft trajectory about 150 mi, 12 hr, from Maine (may have crossed tip of Cape Cod before reaching sounding point).

least 200 ft and possibly 500 ft; a closer estimate cannot be made because of the complications introduced by the shear. The water temperature extrapolated from the characteristic diagram is 56 F, about the same as values measured at the same place by the boat at intervals between 10^h and 12^h.

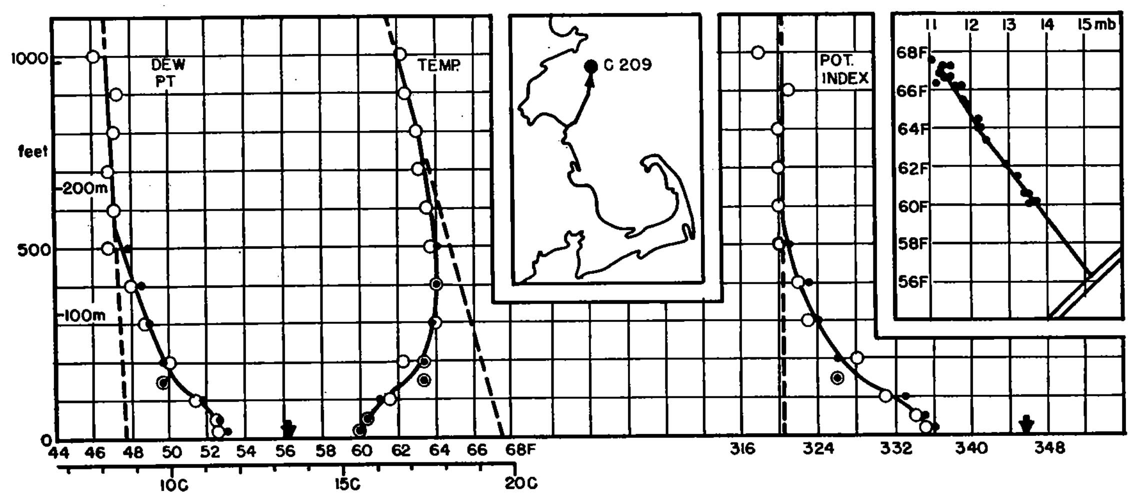

FIG. 46. C209; 70°36′W, 42°31′N; 5 October 1944; o ascent 17^h02^m–17^h12^m, • ascent 17^h15^m–17^h20^m; wind 190° 10 mph at 1000 ft, SSE 3B at surface; 1000-ft trajectory 22 mi, 2 hr, from Scituate.

Figures 47, 48, 49, C210, C211, C212. Clear skies, dense fog all morning on and south of Cape Cod, light fog at other stations. The surface temperature and dew point at 10^h30^m were 72 F and 65 F at Duxbury, 73 F and 64 F at South Weymouth. The stratification observed in the soundings above 200–300 ft therefore appears to reflect conditions over land, since the air could not have been convectively mixed above that level. Cooling

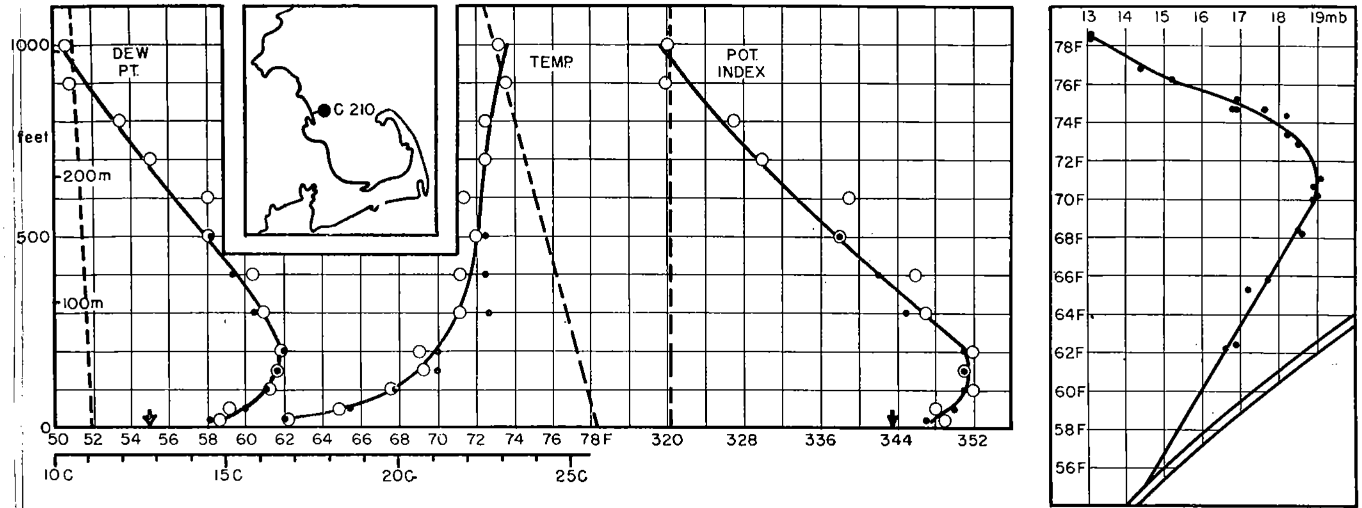

FIG. 47. C210; 70°36′W, 42°06′N; 7 October 1944; o ascent $10^{h}34^{m}$–$10^{h}44^{m}$, • ascent $10^{h}47^{m}$–$10^{h}52^{m}$; wind 250° 18 mph at 1000 ft, 1B (direction not observed) at surface (SSW 5 mph at Duxbury); 1000-ft trajectory 2 mi, 1/9 hr, from Duxbury.

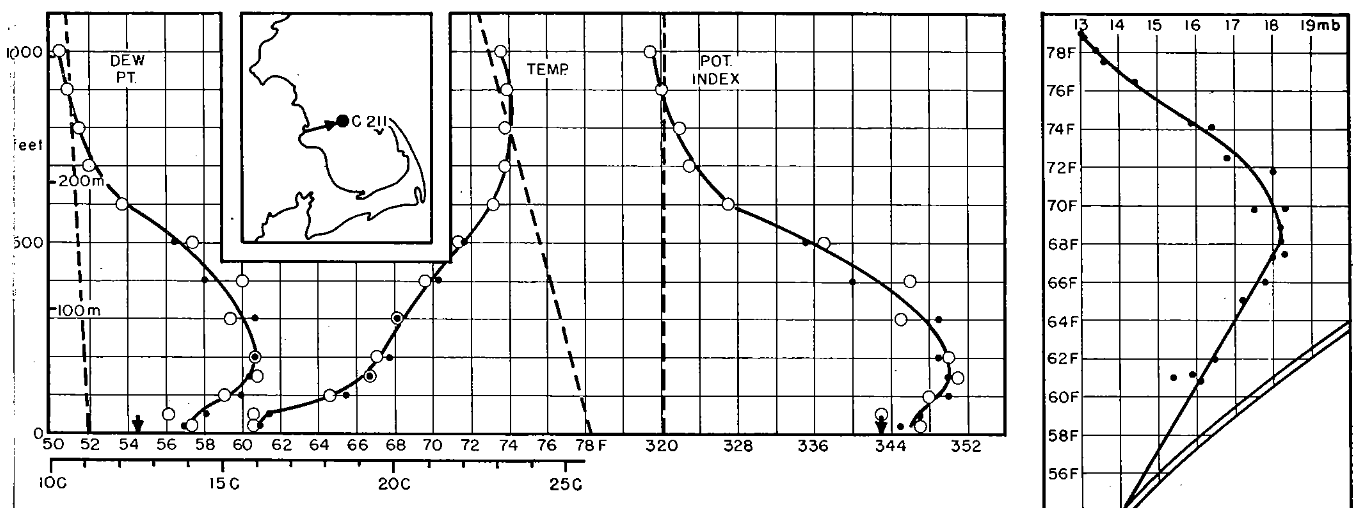

FIG. 48. C211; 70°28′W, 42°05′N; 7 October 1944; o ascent $10^{h}59^{m}$–$11^{h}09^{m}$, • ascent $11^{h}12^{m}$–$11^{h}17^{m}$; wind 250° 18 mph at 1000 ft, 1B (direction not observed) at surface; 1000-ft trajectory 10 mi, ½ hr, from Duxbury.

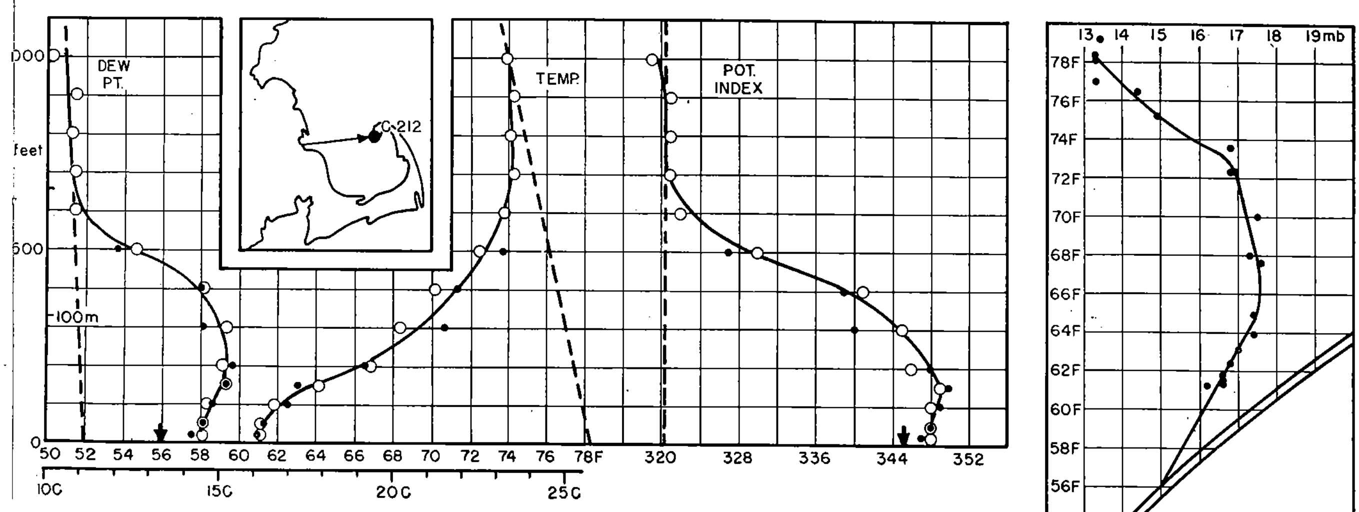

FIG. 49. C212; 70°16′W, 42°04′N; 7 October 1944; o ascent $11^{h}55^{m}$–$12^{h}05^{m}$, • ascent $12^{h}09^{m}$–$12^{h}14^{m}$; wind 260° 22 mph at 1000 ft, SW 3B at surface; 1000-ft trajectory 23 mi, 1 hr, from Plymouth.

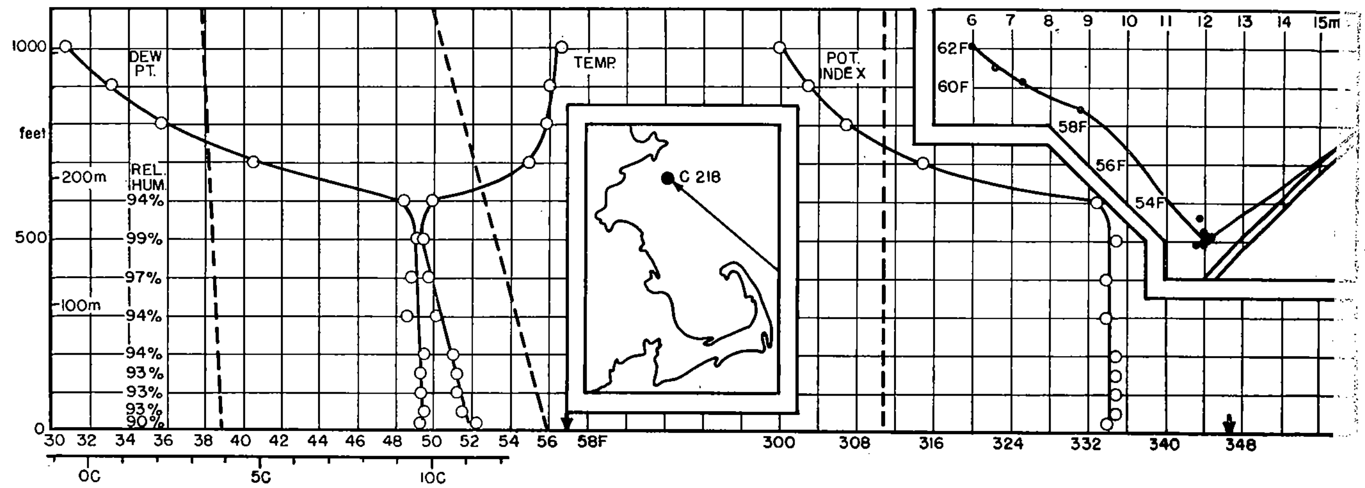

Fig. 50. C218; 70°36′W, 42°31′N; 12 October 1944; 0 ascent $13^{h}51^{m}$–$14^{h}01^{m}$; wind 130° 10 mph at 1000 ft, calm at surface (SE 10 mph at Rockport); 1000-ft trajectory >100 mi, >10 hr, land source not known.

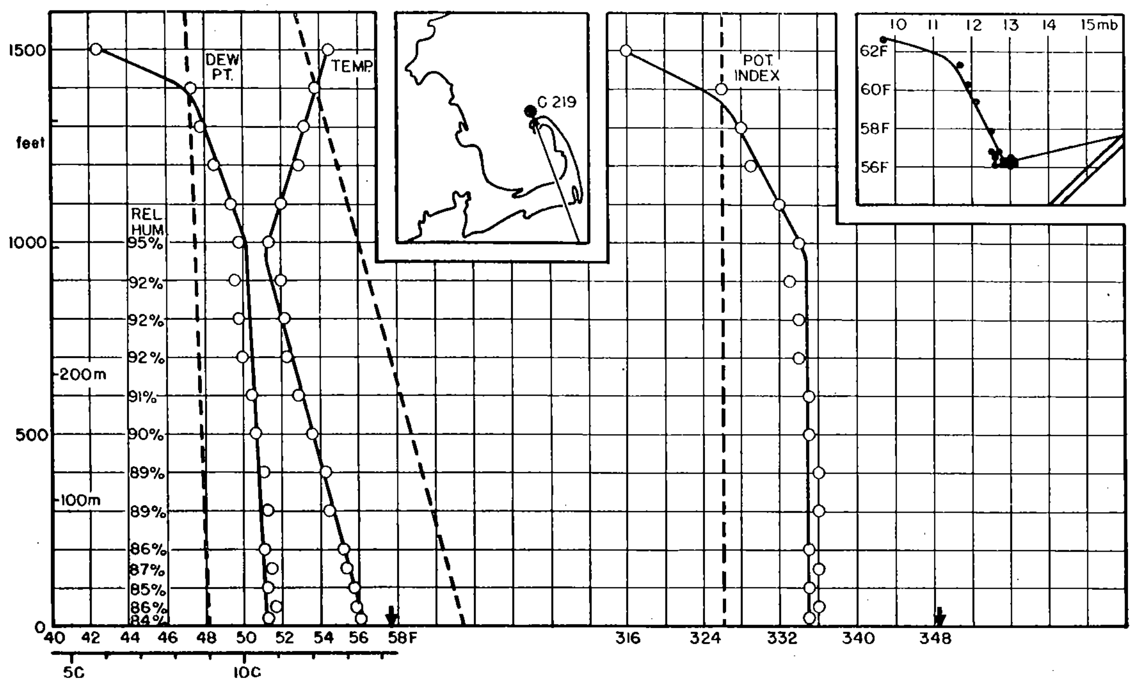

Fig. 51. C219; 70°16′W, 42°08′N; 12 October 1944; 0 ascent $14^{h}51^{m}$–$15^{h}02^{m}$; wind 160° 10 mph at 1000 ft, 1B (direction not observed) at surface (SSE 9 mph at Race Point); 1000-ft trajectory 5 mi, ½ hr, from Cape Cod.

and drying of the air during its over-water travel apparently does not extend above 200 ft in any of the three soundings. Radiation and shear may also have affected the distributions observed over water. Shearing stratification must be considered, since the wind speed is less at the surface than it is aloft in all three cases and the trajectory is probably longer with more southerly winds. Effects of radiation must be expected, since observations from the plane showed "fog next to water" in the case of C210, "hazy next to water"

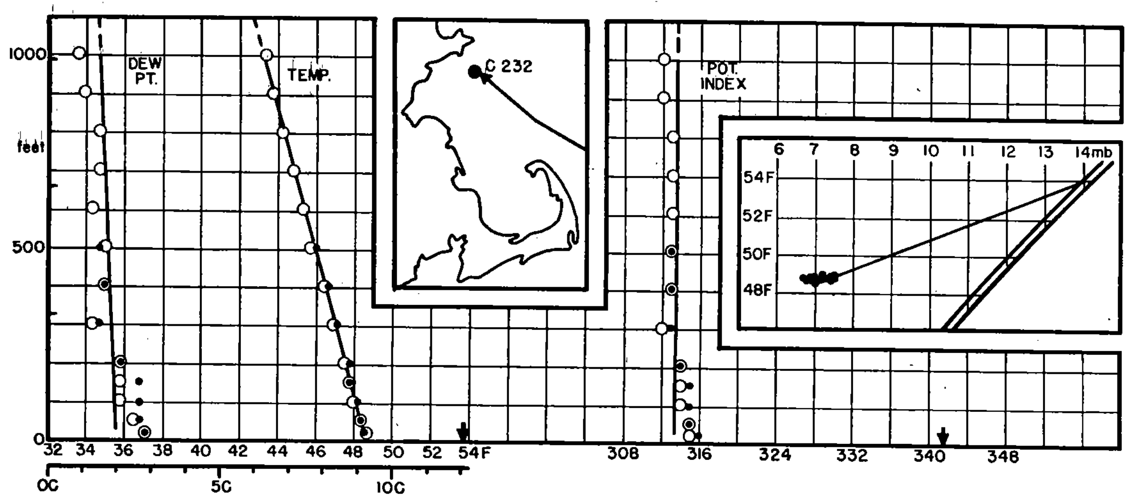

FIG. 52. C232; 70°36′W, 42°31′N; 20 October 1944; o ascent 14^h51^m–15^h01^m, • ascent 15^h04^m–15^h09^m; wind 130° 10 mph at 1000 ft, 1B (direction not observed) at surface (SE at Rockport); 1000-ft trajectory >100 mi, >10 hr, land source not known.

in the case of C211, and "fog up to about 200 ft" in the case of C212. Radiation from the top of a fog layer would tend to cool the layer from above and may explain the tendency toward homogeneity observed near the surface in C211 and C212. No measurements of water temperature were made during the day, and the extrapolated values are not reliable because of the small angle between the characteristic curve and the saturation curve.

Figures 50, 51, C218, C219. High broken clouds, haze near Rockport; broken to overcast clouds at 500–1000 ft near Race Point. Both soundings measure air which has traveled hundreds of miles over the open ocean, except that in the case of C219 there has probably been a recent, short over-land trajectory. In both cases the air is being heated from below. The indicated water temperatures, 57 F for C218 and 58 F for C219 are known quite accurately from measurements made near the sounding points at nearly the same time as the soundings. In both cases, the observer in the plane reported fog extending from the surface to 600 ft in C218 and to 1000 ft in C219; for this reason no check soundings were made and, in the case of C219, the ascent was made by means of a direct climb rather than the usual spiral ascent.

The presence of fog with heating from below and adiabatic lapse rates of temperature is most interesting. It seems likely that the fog formed during an earlier part of the trajectory and is at this time in the process of dissipation; this idea is supported by the presence of fog in the air arriving all day at Chatham, Nantucket, and North Truro and the lack of fog at Rockport after the air crossed Massachusetts Bay. At the time of the fog formation, the air may have been in stable equilibrium; convection would then have developed as the air passed over warmer water and the fog layer was cooled from above by radiation. The distributions of potential index are interesting in the light of the presence of the fog. In both cases there is a shallow superstandard layer and an overlying standard layer in the fog; there is no substandard layer present at any level. These and other soundings (Figs. 13, 34, 53) show that fog is neither a necessary nor a sufficient condition for the occurrence of substandard propagation conditions.

Figure 52, C232. High overcast. This air is arriving from a southeasterly direction and has passed over water for at least 100 miles. It is being heated from below, and this process has produced the dry-adiabatic lapse rate of temperature between 20 ft and 1000 ft. The humidity also has an essentially homogeneous distribution above 20 ft, so that the potential index above 20 ft has an approximately standard distribution. In contrast to conditions above 20 ft, there are large temperature and humidity lapses near the surface. Correspondingly, there is a shallow superstandard layer near the surface. Water temperatures between 53 F and 54 F were measured at about 17^h.

Figure 53, C245. High overcast, broken to overcast clouds at about 600 ft; at Rockport, overcast at 400 ft and light fog. From the surface to 400 ft, the measurements were

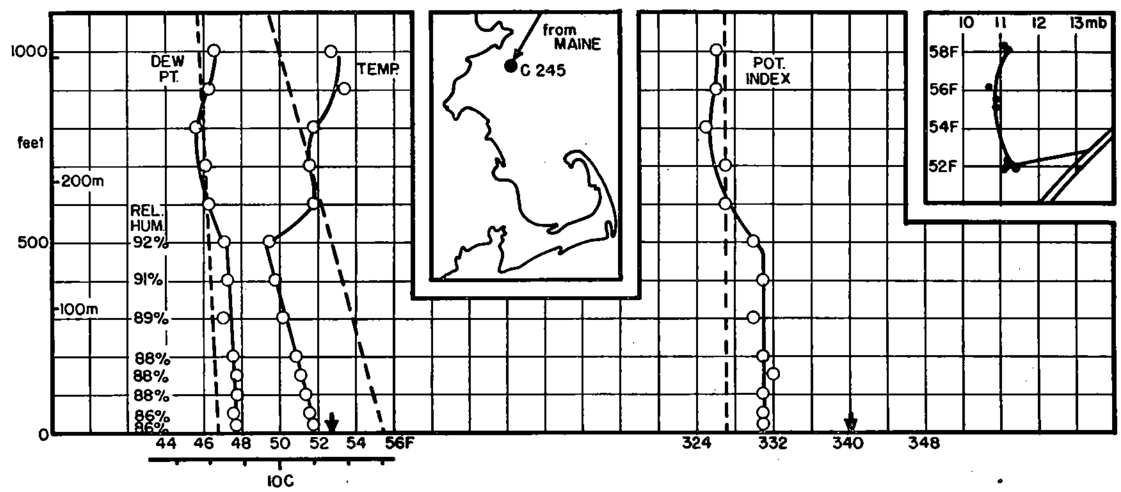

FIG. 53. C245; 70°36′W, 42°31′N; 26 October 1944; o ascent 16^h22^m–16^h32^m; wind 30° 14 mph at 1000 ft, NNE 3B at surface; 1000-ft trajectory 55 mi, 4 hr, from Kennebunk, Maine.

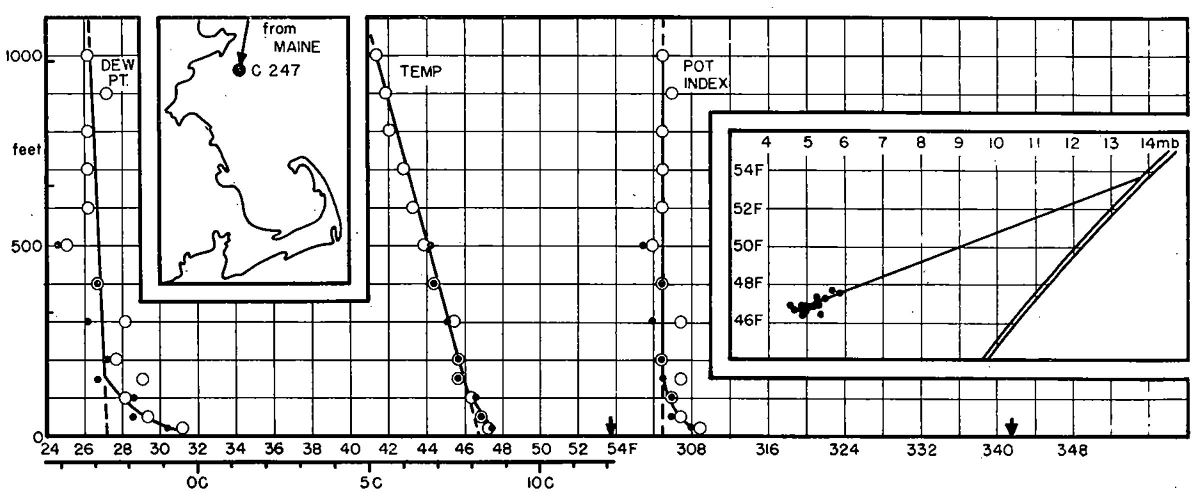

FIG. 54. C247; 70°16′W, 42°08′N; 27 October 1944; o ascent 15^h37^m–15^h47^m, • ascent 15^h50^m–15^h55^m; wind 10° 25 mph at 1000 ft, NNE 5B at surface; 1000-ft trajectory about 100 mi, 4 hr, from Portland, Maine.

made in a "hole in fog"; at 400 and 500 ft the plane was in fog or stratus. The air is being heated from below, as is shown by the homogeneity between 20 ft and 500 ft and by the warmer water, the temperature of which was measured at the sounding point at $16^{h}00^{m}$. As was pointed out in connection with Figures 50 and 51, the air may have been in stable equilibrium at the time when the fog formed. Because of the fog no check sounding was made.

Figure 54, C247. Broken clouds estimated at about 3500 ft. This air is being heated from below by warmer water. This sounding may be contrasted with other cases of heating from below which are presented in this paper, in that there is apparently a superadiabatic lapse rate of temperature extending slightly above 100 ft. In most of the Massachusetts Bay soundings made in air heated from below, the superadiabatic lapse rate of temperature was confined below 50 ft, and there was only one other case (not presented in this paper) where it clearly extended above 100 ft. The greater height of the superadiabatic layer is probably associated with the stronger wind.

Above 100–150 ft the air is essentially homogeneous. The water temperature is not known with any certainty, except that it must be greater than 47 F to produce the observed distributions; about 54 F was measured the previous day. The measurements at 20 ft and 50 ft, when plotted on the characteristic diagram, tend to lie along a straight line pointing to this water temperature.

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