

HARVARD METEOROLOGICAL STUDIES

No. 5

ECLIPSE METEOROLOGY

WITH SPECIAL REFERENCE TO
THE TOTAL SOLAR ECLIPSE OF
AUGUST 31, 1932

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MILTON, MASSACHUSETTS

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The contributions by the different authors are indicated by their initials after section headings. Portions uninitialed are mostly by C. F. B.

The program was developed chiefly by S. P. F. and C. F. B., and to S. P. F. fell the task of designing, building or directing the construction of the apparatus and setting up the special stations. He also read the automatic records and prepared the diagrams (Figs. 2, 15, 16, 18, 19) based on them.

Particular acknowledgment is due Mrs. Brooks for voluntary assistance. She summarized most of the data on temperature, humidity, clouds, and winds, and prepared most of the tables and much of the text for these sections. She also wrote most of the synopsis and edited the entire manuscript. We are indebted to Mr. H. Helm Clayton for collateral studies of our pressure and wind data and for constructive criticism, also to Dr. V. Conrad for a critical reading of the proof and several valuable suggestions.

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SYNOPSIS

A solar eclipse is a relatively quick shutting off and restoration of solar radiation, thereby causing not only a fall in temperature and a rise in humidity, but also changes in wind and clouds. The path of the eclipse of Aug. 31, 1932, across a well populated region in North America, provided an unusual opportunity to obtain considerable information.

Our program endeavored to investigate further the question of an eclipse cyclone by employing delicate open scale recording instruments at more than 30 special stations and by adding aerological observations, of which there have been few, to supplement those at the surface. Detailed observations from several hundred stations concentrated in New England but extending over a large part of the United States were obtained.

The radiant energy received from the sun during an eclipse can be assumed to be roughly proportional to the unobscured part of the sun. The radiation on a horizontal plane is dependent, in addition, on the zenith-distance of the sun. With an average atmospheric transmission coefficient of 0.6, good agreement was obtained in the 1932 eclipse between the observed and computed range of radiant energy.

A comparison of radiation with decrease of temperature in the 1932 eclipse indicated that for a decline of 0.1 g. cal./cm² the temperature decreased an average amount of 0.7 F° (0.4 C°), which is less than the 1.1 F° (0.6 C°) afternoon decrease for an equal fall in radiation at the same time of year. The rate of decrease of solar radiation during the first half of the eclipse was four times the usual afternoon rate of fall. On a cool day in a brisk wind the rate is less: in 1940 it was 0.45 F°/0.1 g. cal. on Blue Hill.

The temperature effect diminished quite regularly with distance from the path of totality, yet could be recognized with assurance as far as the zone of 40% obscuration. For stations having clear sky in the zone of totality it averaged about 6 F° (3 C°), with max. over 9 F° (5 C°); in the 40% zone it did not exceed 2 F° (1 C°) or 3 F° (1.5 C°).

This temperature effect was markedly decreased by cloudiness, water, and altitude. Thus the area of greatest eclipse cooling did not coincide with the path of totality, but occurred to the east, in Maine, where the skies were clear, in contrast with the cloudiness elsewhere in New England. At higher altitudes, the temperature fall was generally less apparent, though greater on mountains than in the free air, where it could not be traced with certainty above 500 m. Thermometers lying on

the ground in full sunlight fell at least 30 F° (17 C°) and in the shade or at cloudy stations, 3 to 7 F° (2-4 C°). On the ocean, no eclipse decrease (in excess of 0.1 F°) could be detected in either air or water temperature. A fairly consistent though slight contrast between inland and coastal stations was evident, coastal stations showing the smaller temperature change.

The pressure change ascribable to the eclipse of 1932 at 4 stations with open scale records in the zone of totality averaged a dip of 0.3 mb, with the minimum about 20 min. after totality. Among other variations, there was a very slight hump, of less than 0.1 mb, with maximum at totality. A similar dip in pressure, and a more pronounced hump in the middle of the eclipse, are typical of eclipses, and are of an order of magnitude reasonably expected theoretically. The dip can be due to the release of the free air from the surface drag, and consequent attenuation of the air over the shadow, as convection ceases; the hump should arise from inflow of air aloft owing to the downward bending of pressure surfaces during the eclipse cooling. The minimum of convection and of pressure should come a few minutes later than the minimum of temperature and maximum of accumulated air from inflow, thereby advancing to the time of totality the time when the pressure from the combination of the dip and the rise will be at its maximum.

The characteristic wind changes observed, namely, a decrease in velocity and gustiness and a decrease in azimuth, or turning to the left, could be adequately explained by the decrease in daytime convection resulting from eclipse cooling. An eclipse wind, being of lesser magnitude, may have been present, however. Such a wind is suggested by our new analysis of the Indian data of 1898.

The rise in relative humidity occasioned by a solar eclipse is largely a function of the temperature, since changes in absolute humidity are small. Thus the relative humidity in most cases was highest shortly after the maximum eclipse when the temperature was lowest, and, in general, the greater the temperature fall the greater the rise in relative humidity.

The changes in absolute humidity were small, irregular, and difficult to evaluate, being the resultant of opposing factors, evaporation and convection, possibly with settling from aloft, though aerological data seem to minimize this factor. In the first half of an eclipse in clear weather the vapor pressure is likely to fall, apparently because the rate at which the air is charged by evaporation decreases more rapidly than the rate of vapor concentration owing to decreasing convective exchange. Immediately after totality, however, the vapor pressure usually rises, probably because evaporation is then increasing while convection is still decreasing.

This reduction of convection was responsible also for the generally noted decrease in cumulus and even cumulonimbus clouds. Though observations in other

eclipses seem to point to an increase in the higher clouds, there were no significant changes apparent in the 1932 data on the middle- and high-level cloudiness which can be definitely attributed to the eclipse.

Data on shadow-bands, confirmed previous experience, indicating that the bands are parallel to the solar crescent and that they move with the wind that carries an optically disturbed layer. A definite correspondence was noted between the direction and velocity of motion of shadow-bands at Rockport and of a disturbed layer aloft marked by altocumulus clouds. Sky illumination at totality was marked by darkness overhead with a rich orange sunlit atmosphere all about the horizon.

The cloud motions observed in 1932, while inadequate to prove the existence or absence of an eclipse circulation, offer at two inland stations possibly a faint corroboration of a tendency down the temperature-change gradient suggested by the more accurate and detailed results obtained from the pilot-balloon runs at the two inland aerological stations. Balloon runs at the coastal stations do not show such a flow. As evidence is divided, more cases are needed to establish this point.

Data from four airplane flights indicate a temperature effect decreasing geometrically from 5 F° (3 C°) at the ground to little change at 500 m. There are, perhaps, falls of 0.4 C° at 1000 m, and 0°.3 at 3000 m, due to loss of heating by direct solar radiation. There is fairly definite evidence, in unchanged haze-layer heights, cloud heights, wind-boundary heights and a lack of consistent decrease in vapor pressure, that no circulatory subsidence of any consequence could have taken place. This confirms the evidence from cloud motions and pilot balloon runs that while a slight inflow above and outflow below may have occurred in some instances it was not enough to produce what might be called even a weak cyclone.

Conclusion. We have found that though large changes in temperature took place at the earth's surface during the eclipse of 1932: the increase in wind aloft when released from convection was too small to lower the pressure more than an average of 0.3 mb and the layer of air appreciably cooled was too shallow to effect an observable sinking of pressure surfaces aloft. Therefore, little redistribution of air could be expected, and we have found little evidence of pressure rise at the surface attributable to inflow aloft. Any systematic wind changes observed may be adequately explained by the decrease in daytime convection resulting from eclipse cooling, which, in the eclipse of 1932, obscured eclipse-wind tendencies.

Further data on changes in solar and atmospheric radiation and of related surface and air temperatures seem desirable. More knowledge of the vertical extent of appreciable cooling would permit a closer theoretical check on changes in pressure and circulation that more refined barometric and aerological observations may reveal. Shadow-bands also seem deserving of closer study, especially in connection with the presence and movement of optically disturbed layers.

ECLIPSE METEOROLOGY

WITH SPECIAL REFERENCE TO THE TOTAL SOLAR ECLIPSE OF AUGUST 31, 1932

INTRODUCTION

The solar eclipse presents an opportunity to observe the consequence of a rapid shutting off and restoration of insolation, like a quick, brief night interrupting the normal course of the day's weather. The North American total eclipse of August 31, 1932, crossed a well-populated region of considerable physical diversity at a time when the sun was high in the sky (Fig. 1).

Problems of eclipse meteorology. The main controversial point in eclipse meteorology seems to be the 'eclipse cyclone'. Does a definite system of pressure and winds develop around the chilled and contracted air of the eclipse shadow or are the changes involved too small and the time too short? Although theoretical considerations make the development of an eclipse cyclone seem unlikely, we wished to test this theory again, as previous investigators had disagreed in their conclusions.

Past studies have agreed fairly well about the fall in temperature, and decreases in wind velocity, which have been quite regularly reported; while there was difference of opinion about wind direction and pressure changes. A rise in relative humidity has been undisputed, while the course of absolute humidity has been variously described. Little has been done with cloud motions or upper air observations.

The extent of observational data in eclipse meteorology. The meteorology of eclipses has been observed intensively during more than a dozen eclipses, widely scattered over the earth. In several of these, considerable networks of stations have made simultaneous observations. E. W. Barlow, 1927a, has compiled a bibliography of 162 titles of papers from which he prepared a summary of "The meteorology of eclipses", as background for a study of the total eclipse that passed over England June 29, 1927. There are 25 general works, and from one to 50 papers on each of 24 eclipses. That of August 30, 1905, which crossed Europe, received the most attention. It is, obviously, unnecessary to reprint Barlow's bibliography or to summarize in detail again what he has done so well. Some of the observations of previous eclipses serve our purposes nearly as well as our own data in making new analyses

of wind changes which are still in an unsatisfactory state. We have used published data of the following eclipses—

Jan. 22, 1898	Central India (Eliot, 1899)	154 stations
May 28, 1900	SE and E U.S.A. (Clayton, 1901, Bigelow, 1902)	73 stations
May 18, 1901	Sumatra and Java (van Bemmelen, 1903)	36 stations
June 8, 1918	NW to SE U.S.A. (Kimball and Fergusson, 1918, 1919, Brooks, 1919)	87 stations
Jan. 24, 1925	NE U.S.A. (Varney, 1925; Fergusson, 1925)	13 stations

Our own records comprise 3 eclipses —

Aug. 31, 1932	U.S.A.	300 stations
Feb. 3, 1935	Partial, U.S.A.	19 stations
Apr. 7, 1940	Partial, U.S.A.	1 station

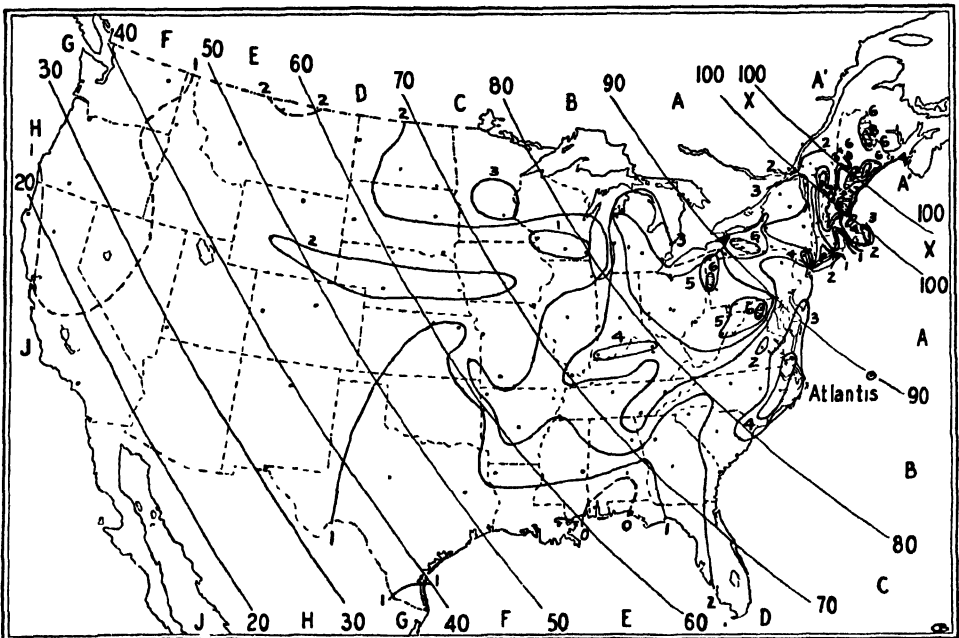


FIG. 1. Path of the total solar eclipse and 10% zones of maximum of partial eclipse, August 31, 1932 (Plotted from data in "Total eclipse of the sun August 31, 1932", Suppl. to the American Ephemeris, 1932, U. S. Naval Obsy., Washington, D. C., 1931, 31 pp.) and effect of the eclipse on temperature throughout the United States and nearby Canada. (Dots show locations of stations, mostly U. S. Weather Bureau.)

I. PROGRAM, METHOD, STATIONS AND THE WEATHER FOR THE ECLIPSE OF AUGUST 31, 1932

Our program endeavored to investigate further the question of an eclipse cyclone by employing delicate open scale recording instruments at special stations and by adding aerological observations, of which there have been few, to supplement those at the surface. Detailed and numerous observations concentrated in New England, but extending over a large part of the United States, have added considerably to the available data on all the meteorological elements.

A. *Meteorological instruments for eclipses.*¹ While ordinary apparatus can measure changes of radiation and temperature caused by an eclipse, instruments of more than usual sensitivity would be necessary to detect any consequent variations in pressure. So small are any changes of pressure that it seems futile to hope to detect them except by means of a barograph having a scale of at least 3 to 1.² If an aneroid is used, compensation for temperature change becomes important; if a mercurial, the bore must be sufficiently large (20–25 mm) to minimize the effects of capillarity. Variations in wind direction are best recorded by an anemoscope of the Draper pattern, the record of which can be read to 1°. Non-recording “hand” anemometers and vanes are satisfactory and economical, but in view of the attention needed by other instruments during the eclipse, light recorders with scales open enough for readings to 0.1 m/s are preferable. A Draper anemoscope combined with a cup-anemometer into a single instrument recording direction and velocity has proved to be very satisfactory. Also, because of the rapidity with which changes occur, the thermograph and hygrograph should be sensitive, permitting changes of 0.1 F° and 1% relative humidity to be detected, and they should be more freely exposed than is customary; an open shelter of the French or Russian type is recommended, though, along with the freer air movement, there is some disadvantage from the exposure to radiation from the ground, and it may raise problems with the local police, as at Provincetown, who thought that a hot-dog stand was being erected in a park! A sling or other ventilated type of psychrometer is best for temperature and humidity, having less lag and greater accuracy than the recording instruments.

For the study of the eclipse of 1932, 9 of the special stations of the Blue Hill Observatory were equipped with barographs, anemographs or thermohygrographs designed by S. P. Fergusson according to experience derived from studies of earlier eclipses. All had time-scales of 40 mm/hr., permitting readings every two minutes,

¹ For details see Fergusson, S. P.; *Sensitive open-scale instruments for the detection of minor disturbances of the atmosphere*. Am. Met. Soc., Bull., v. 20, pp. 135–141, Apr. 1939.

² I. e., 3 times as great as the change in height of a mercury column.

ECLIPSE METEOROLOGY

and with as open scales for the various elements as seemed practicable. Fig. 2 shows sample records. Six thermo-hygrographs and parts for seven anemographs were constructed by the Mann Instrument Company; the anemographs were completed by Frank B. and Philip A. Towle. Three aneroids and two Draper weighing mercurial barographs with scales of 5 or 5.5 to 1 were constructed and one Richard aneroid rebuilt with a 3 to 1 scale. The mercurial barographs had tubes of 23 mm internal diameter. Estimates to 0.01 mb were possible from the records of both types. Six black-glass nephoscopes were built to order by the Mann Instrument Company, and some 30 sling psychrometers, by Henry J. Green, were borrowed from the Harvard students' meteorological laboratory. These psychrometers had long cords, which permitted them to swing on a radius of about one meter, thereby insuring ample ventilation.

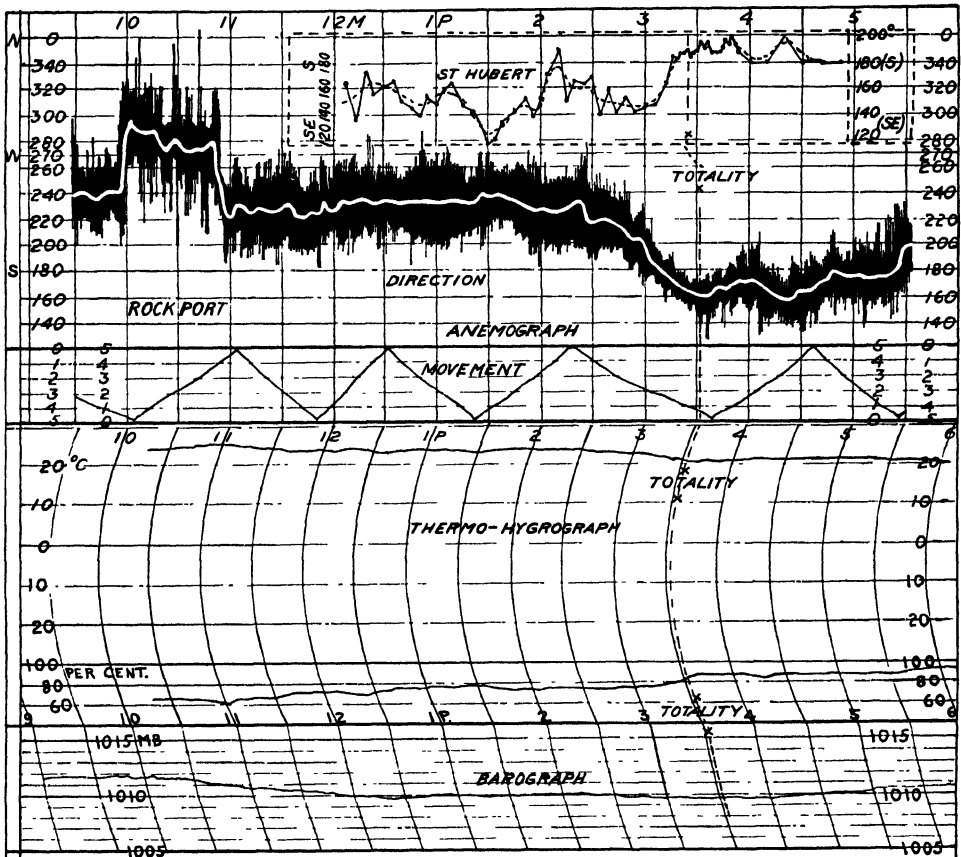


FIG. 2. Records from specially designed instruments at Rockport during the eclipse and the wind direction from a Draper anemoscope at St. Hubert (Montreal).

B. *The special meteorological stations.* To offset local adverse weather, to minimize the effect of local differences on the conclusions to be reached, and to permit comparisons on opposite sides of the path of totality, a network of 44 stations was equipped or maintained,— 39 by Blue Hill Observatory and experienced coöperating observers and 5 by the Canadian weather service. Ten were mountain-summit or hill-top stations, 7 were other mountain stations, 5 were valley stations in the mountain region, 13 were lowland stations at least 35 mi (60 km) inland, and 9 were coastal stations, within 10 mi (16 km) of the coast. Forty were in the zone of totality, 11 of them very near the central line; and 4 were in the zone of 90–100% of maximum obscuration, one, Concord, only a mile or two outside the shadow. Aerological data were obtained by airplane at two stations and by pilot balloon at five. Practical considerations made the distribution unsymmetrical relative to the path of the center of totality. The locations are shown in Fig. 11 (p. 41, below).

C. *The country-wide network of stations.* An attempt was made to gather extensive information on temperature, wind, humidity and cloudiness changes over a wide enough area to include a great variety of weather under different degrees of eclipse. So great was the generous response to our request for special observations that the most extensive body of data ever gathered during a solar eclipse was received. Our printed circular soliciting coöperation was as follows:

WANTED: WEATHER OBSERVATIONS DURING THE ECLIPSE OF AUGUST 31, 1932

THE BLUE HILL OBSERVATORY will investigate both intensively and extensively, the effect of the solar eclipse of August 31, on the weather. About thirty stations in New England are being specially equipped with apparatus, a number of interested observers in New England, New York and Quebec have already indicated their desire to coöperate, and now a closer network of stations in this region and a general network throughout the United States, all of which will have at least a partial eclipse, are sought. This circular is being sent to several hundred coöperative observers and to all the regular stations of the Weather Bureau in the 48 States. If, after reading the following program, you wish to help by making any observations whatever, kindly send a copy of your observations to the undersigned, for our study.

PROGRAM OF OBSERVATIONS

Duration and Frequency: Every fifteen minutes, beginning at 1:30 P.M. and ending at 6:30 P.M., 75th Meridian (Eastern Standard) Time, or 2:30 to 7:30 P.M. Daylight-Saving Time, August 31, 1932. In New England, New York and Quebec, also every five minutes from 3:15 to 4:00 P.M., Eastern Standard Time.

Elements to be Observed. Air Temperature (and if psychrometer is available) temperature of the wet-bulb. Direction of the Wind: As accurately as possible (to nearest five degrees, if nephoscope is available, in which the average position of the reflected image of the wind-vane can be measured by means of a ruler or straight-edge).

Atmospheric Pressure, provided a large-bore mercurial barometer, an open-scale aneroid barometer or micro-barograph is available. The readings should be made in thousandths of an inch.

High and Middle-level Cloudiness: The Total Amount of Cirrus, Cirro-stratus, Cirro-cumulus, Alto-stratus, Alto-cumulus and high Strato-cumulus, actually visible, estimated in tenths of the entire sky. The international abbreviations of these names are, respectively, Ci, Cist, Cicu, Ast, Acu, high Stcu.

Amount of Cumulus Clouds (Cu) estimated in tenths of the entire sky.

Amount of Stratus Clouds (St) estimated in tenths of the entire sky.

Motions of Clouds: Direction, in Degrees of Azimuth, from which they move, and angular velocity, separately, for each level (High, Middle or Low) at which clouds are visible. These observations to a useful degree of accuracy can hardly be made without a nephoscope.

Form for Recording Observations: Each observer can rule a form that will include whatever observations he cares to make.

CHARLES F. BROOKS, *Director*
Blue Hill Observatory, Hyde Park, Massachusetts

AUGUST 18, 1932

A line calling for wind velocity was overlooked in copying. Many observers sent velocities anyway. The rest were subsequently asked, but it proved generally impracticable to obtain all the detail desired.

162 observers, chiefly in New England and New York, sent useful observations, and 129 regular airport and special stations of the U. S. Weather Bureau throughout the country made detailed frequent observations on the afternoon of the eclipse (locations on Fig. 1). The locations of those stations in the northeastern States that sent temperature data from which the effect of the eclipse on the air temperature could be derived are shown by the dots on Fig. 11.

D. *The weather of August 31, 1932 (S. P. F.)*¹ proved somewhat unfavorable for the eclipse. At 2 P.M. (Fig. 3) a Canadian cyclone of considerable intensity, central at The Pas at 8 A.M., had moved northeastward to northern Ontario and decreased in intensity, a weak secondary was central over New Jersey, and the Atlantic anticyclone had moved northward over West Virginia. Cloudiness had increased over the entire region east of the Mississippi Valley and temperatures were abnormally high. Contrasts of pressure were very small and winds continued light and variable.

By 5 P.M. (Fig. 3) the New Jersey cyclone had not increased in intensity but had expanded, covering the region between North Carolina and the St. Lawrence Valley; the Atlantic anticyclone was nearly stationary, covering West Virginia, western Pennsylvania, and Kentucky. The contrasts of pressure continued small, temperatures were high, and winds were light and variable throughout the eastern half of the country. The sky was cloudy or partly cloudy over New England and the coast as far south as Norfolk and west of the Mississippi Valley, where an anticyclone of slight intensity was moving from the west. Clear weather prevailed only over Maine, the Ohio Valley, and western Pennsylvania.

¹ Letters following a section heading are initials of the author(s) mainly responsible.

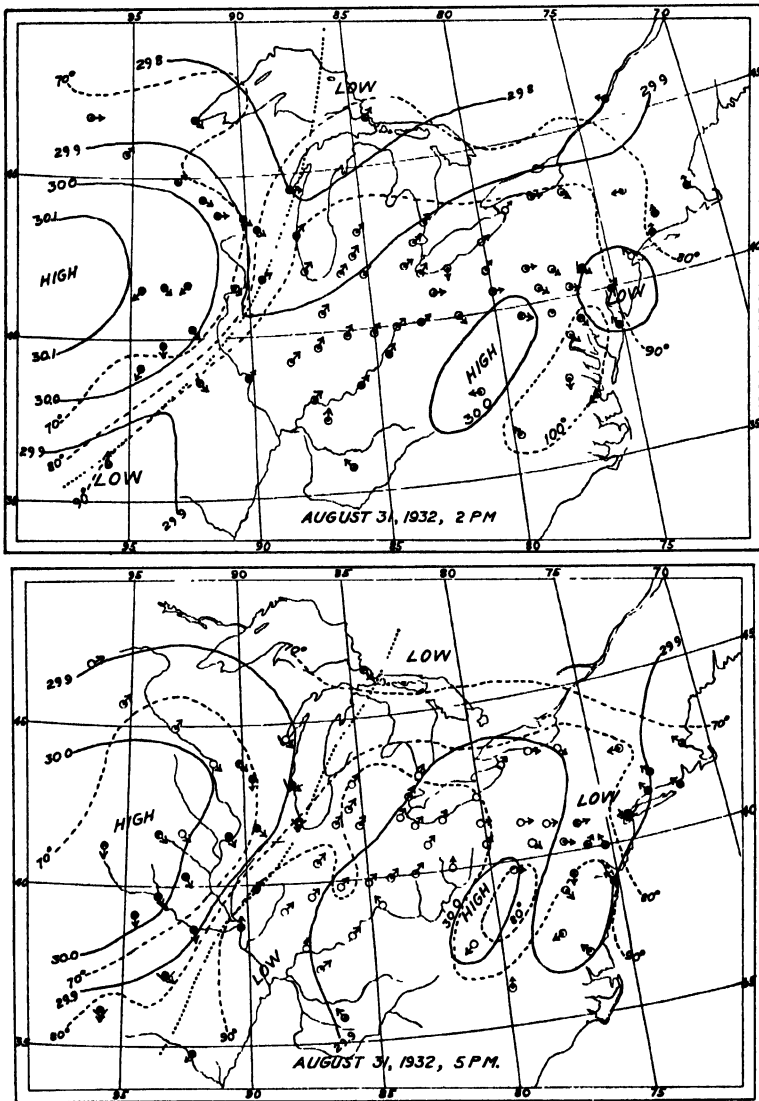


FIG. 3. Weather maps for 2 and 5 P.M. August 31, 1932. Courtesy, U. S. Weather Bureau.

II. SOLAR RADIATION AND ITS IMMEDIATE EFFECT ON TEMPERATURE DURING AN ECLIPSE

The effects of a solar eclipse vary with the degree of obscuration, the duration, the height of the sun, the time of day, the transparency of the atmosphere, and the state of the weather. The most pronounced effect is, of course, the drop in solar and sky radiation, which causes appreciable variations in temperature, relative humidity, and wind velocity at the surface, and in convectional cloudiness. The responses of the other elements are generally so small that they are difficult to detect.

A. *Results of previous studies* (B. H. & C. F. B.). The drop in solar radiation, as might be expected, is roughly proportional to the percentage of the solar disc obscured by the moon, as shown by Buchanan, 1900, Kimball and Fergusson, 1919, Dörr, 1922, Lindholm and Bergsten, 1923, Dorno, 1925, Lipp, 1929, Albrecht, 1934, Predescu, 1937, Stenz, 1937, and Wirtz, 1937. Aside from the negligible radiation received from the uneclipsed corona and the insignificantly larger or smaller amounts of sky radiation from those portions of the sky having a different percentage of obscuration from that of the observing station, three factors prevent the drop in total solar and sky radiation on a horizontal surface from being proportional to obscuration: decreasing intensity of radiation toward the sun's limb, changes in atmospheric transparency, and changes in the altitude of the sun. These will be considered seriatim in the following paragraphs.

If the intensity of solar radiation on a surface perpendicular to the sun's rays outside the atmosphere, computed from the percentage of the sun obscured, without taking into account the decreasing intensity of radiation toward the sun's limb, is G'_0 and if G is the radiation on a surface perpendicular to the sun's rays at the ground, G'_0/G has a maximum around totality according to Albrecht's measurements. From these observations Albrecht computed a reduction factor which gives the influence of the decreasing brightness toward the solar limb. His figures agree well with the measurements by Abbot¹ of the distribution of radiation intensity over the solar disc. Similarly Kalitin, 1928, and Stenz, 1929, 1937, found satisfactory correspondence to the observations by using Abbot's material.

Albrecht also determined the turbidity factor, as defined by Linke. A certain difficulty arises here since the constants for the computation of the turbidity factor are given for the ordinary spectral distribution of solar intensity. This distribution, however, is different for the outer parts of the solar disc; consequently the turbidity factors determined during a solar eclipse will be erroneous to a certain degree if the

¹ ABBOT, C. G.: *On the distribution of radiation over the sun's disk*. *Smiths. Inst., Astrophys. Obsy., Annals*, v. 3, ch. 7, pp. 155-165, Washington, 1913; *ibid.*, v. 4, ch. 7, pp. 217-257, 1922. *The distribution of energy over the sun's disk*. *Smithsonian Misc. Colls.*, v. 78, no. 5, 12 p., Washington, 1926.

ordinary constants for the computation of turbidity factors are used. The range of the turbidity factor during the eclipse seems to indicate an initial stage of condensation, but according to Albrecht our knowledge about the relation between condensation and radiation processes is still too limited to allow any definite conclusions. That condensation phenomena actually take place during the eclipse seems also to be indicated by the sky radiation. The ratio of solar radiation on a horizontal plane to sky radiation, which should be a smooth curve under ordinary circumstances, shows considerable changes, particularly around totality, which seems to indicate condensation phenomena, since the intensity of the sky radiation increases.

Wirtz, 1935, 1937, measured turbidity during two partial eclipses in the early morning, and found no effect in a 23% eclipse (1933) but a distinct reducing effect, relative to the usual morning increase, in a 50% eclipse (1936). This effect may have been due to reduced convection, which carried the nocturnal turbidity of surface air more slowly to levels above the 62-meter height of the observation point.

The changes in the altitude of the sun affect the direct sunlight both by varying the amount of air through which the rays must pass and also by altering the amount of spread of a unit cross-section of the rays when they impinge on a horizontal surface. With increasing solar altitude the intensity of the direct sunshine on a horizontal surface increases closely as the square of the sine of the altitude, since the amount of air traversed and the area of spread of the rays each decrease as the sine of the altitude. While this statement is strictly true for the spread of the rays, it is not exact for the air traversed, which, owing to the curvature of the atmosphere, does not decrease quite as rapidly as the sine of the altitude increases. The light scattered by the molecules of atmospheric gases, dust and condensed water vapor in the air does not increase nearly so rapidly as the direct sunshine with increasing altitude of the sun. (Cf. Fig. 5, below, in which are shown for several stations the percentage of maximum obscuration and the total solar and sky radiation on a horizontal surface; and, for Wells, Me., the course of total radiation on a horizontal surface computed with reference to obscuration and solar altitude combined; see Fig. 4 and discussion, pp. 20-22, below.)

The net outgoing long-wave radiation was measured by Kimball and Fergusson, 1919. They found that this radiation was markedly higher during the time of totality than before or after. A similar result was obtained by Albrecht in 1927 (Süring, . . . , 1934). On the other hand, Aldrich, 1919, found rapidly decreasing net long-wave radiation during totality, though the values were considerably higher than during the night. Abbot and Moore, 1920, at a very high elevation (4120 m) and early in the morning, found values during totality about the same as those during the night preceding.

B. *Theoretical relations — obscuration, solar radiation, temperature* (B. H.): The radiant energy can be assumed as roughly proportional to the unobscured part of the sun, whereby, of course, such influences as decreasing brightness towards the solar limb¹ and changes of atmospheric turbidity are neglected (V line Fig. 4).

The radiant energy which a horizontal plane receives from the sun during an eclipse is

$$E = I_0 f \cos z p^{\sec z}$$

where I_0 is the solar radiation energy outside the atmosphere, z the zenith distance, p the coefficient of transmission, f the expression for the unobscured part of the sun given by tables, E is a function of the time t , since f and z are functions of t .

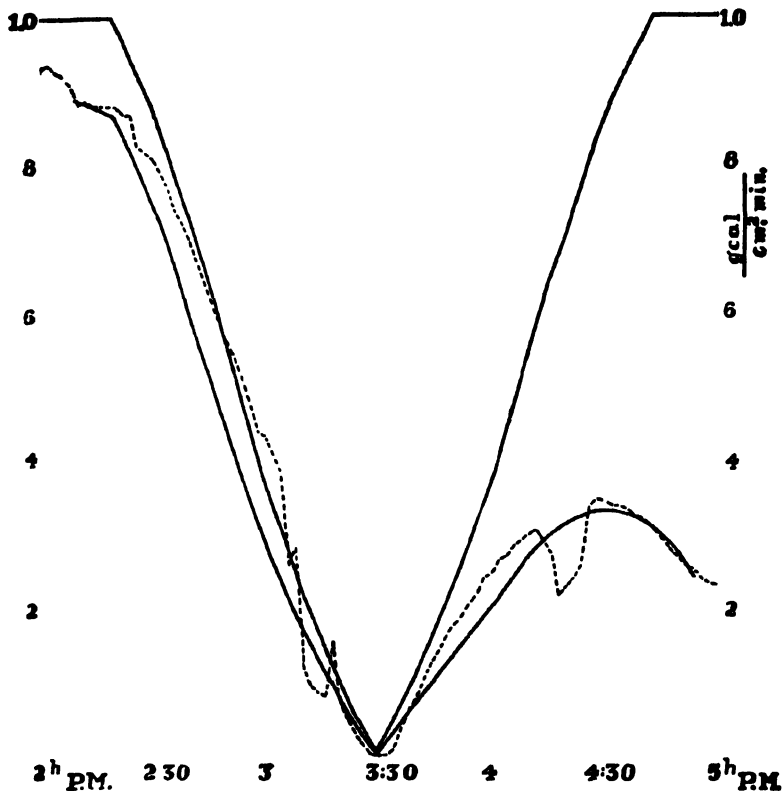


FIG. 4. Computed and observed course of solar radiation on August 31, 1932, at Wells, Me.

The lower full curve in Fig. 4 is the course of the solar radiation according to the preceding formula for E . The average transmission coefficient was assumed as $p=0.6$ for the wavelengths recorded. The total radiation from the sun and

¹ Ibid.

sky on a horizontal plane (dotted) obtained by Dr. P. R. Gast at Wells, Me. is given. The trend of both curves is the same but the radiation from the sun and sky is always greater except when clouds are before the sun. It will be seen from Fig. 4 that the radiation begins to decrease again before the fourth contact, since the influence of the decreasing altitude of the sun then becomes greater than the effect of the increase in visible area of the solar disc.

To derive the temperature changes caused by a solar eclipse we have first to compute the change in surface temperature caused by the change in solar radiation and convection. Problems closely related to these were treated by Milankovitch¹, W. Schmidt², Brunt³ and others. Here again, however, our observational material is deficient, since we do not have any ground temperatures and very scanty data about temperatures above and below the standard thermometer level. Aside from the lack of sufficient observational material our knowledge of the thermal constants of the ground and of absorption constant is quite inaccurate. Nevertheless, with plausible values for the constants we find satisfactory agreement between our scanty observations and theory.

In the computation of the temperature of the earth's surface we can follow Milankovitch's method.⁴ The expression for the solar radiation energy E given above should be developed in a Fourier series, but for the sake of simplicity we shall assume that E can be represented by

$$E = \frac{a_0}{2} \left(1 + \cos \frac{2\pi}{T} t \right)$$

where we assume the total variation of solar radiation during the eclipse to be $a_0 = 1$ g. cal/cm² and the duration of the eclipse $T = 144$ min. The time, t , is counted from the middle of totality, negative for the instances before, positive for instances afterwards. If the appropriate boundary conditions are introduced, the expression of the surface temperature will be, according to Milankovitch

$$\vartheta = \text{const} + B \cos \left(\frac{2\pi}{T} t - \epsilon \right)$$

where B is the fall in air temperature.

The phase retardation ϵ is given by

$$\text{tg } \epsilon = \frac{1}{1 - \frac{m}{R} \sqrt{\frac{T}{\pi}}}$$

¹ Milankovitch, M.: *Math. Klimalehre*. Köppen-Geiger, Handbuch der Klimatologie, v. 1, pt. A.

² Schmidt, W.: *Der Massenaustausch in freier Luft und verwandte Erscheinungen*. Hamburg, Henri Grand, 1925.

³ Brunt, D.: *Transfer of heat by radiation and turbulence in the lower atmosphere*. London, Roy. Soc., Proc., A, v. 124, pp 201-218, 1929.

⁴ Milankovitch, M.: loc. cit., p. 90.

where

$$m^2 = \frac{K}{c\rho}$$

K is the coefficient of heat conductivity, c the specific heat, ρ the density of the ground.

Further

$$R = \frac{K}{a \cdot 4\sigma\vartheta_0^3}$$

a the absorption coefficient of the ground, $\sigma = 8.26 \cdot 10^{11}$ g. cal./cm², min., the Boltzmann constant, ϑ_0 the mean ground temperature. The amplitude B is given by

$$B^2 = \frac{A^2}{\left(1 + \frac{R}{m} \sqrt{\frac{\pi}{T}}\right) + \frac{R^2}{m^2} \frac{\pi}{T}}$$

where

$$A = \frac{a_0}{8\sigma\vartheta_0^3}$$

To apply these formulæ to the eclipse let us assume the following constants which hold for a rocky ground according to Milankovitch: $K = .5$, $C = c\rho = .5$; therefore $m^2 = 1$, the absorption coefficient $a = .92$, $\vartheta_0 = 285^0$; therefore $R = 71$.

This gives $\epsilon = 42,5^0$ and thus for the retardation of the minimum of the surface temperature 17 minutes. For B we obtain 3.6 C^o (6.5 F^o). Unfortunately, we have no observations of the surface temperatures. From the observations of air temperature at Wells, Me. the minimum of the air temperatures can not be determined very accurately since the air temperature was the same at 3:30, 3:35 and 3:40 P.M. Thus the lag is about 6 to 16 minutes behind totality. We should expect the lag of the air temperature to be greater than the computed lag of the ground temperature. However, the agreement is rather satisfactory if we consider our many simplifying assumptions. If we had chosen values corresponding to a sandy ground, namely, $K = 0.16$, $m = 0.72$, and left every other constant unchanged, we should have obtained for the retardation of the minimum 15.6 min. and $B = 8$ C^o (14.4 F^o). Since the total observed temperature fall at Wells was 8 F^o, the first set of constants seems more satisfactory.

3. *Summary* (B. II.). The radiant energy received from the sun during an eclipse can be assumed to be roughly proportional to the unobscured part of the sun. Since only the total radiation from sun and sky on a horizontal surface was measured, it does not seem necessary to take into account the decreasing brightness towards the solar limb and possible changes of atmospheric turbidity during the time of the eclipse. The radiation on a horizontal plane is further dependent on the zenith-distance of the sun. With an atmospheric transmission-coefficient of 0.6,

good agreement is obtained between the observed and computed range of the radiant energy (Fig. 4). The radiation begins to fall off again before the fourth contact, since the increase of the zenith-distance of the sun then becomes more influential than the increase in visible area of the sun.

The decrease of solar radiation during totality causes a temperature drop. The time of the minimum of temperature occurs nearest the time of totality at the surface of the earth. Higher up the time of minimum temperature is retarded further and the amount of the temperature drop decreases according to the theory of eddy conductivity. With plausible values for the conduction coefficients we obtain a time lag of 15 minutes and a temperature drop of 3.6 C°, in fair agreement with the observations.

C. *Solar radiation observations, 1932* (H. H. K., C. F. B.). Observations of radiation or illumination during the eclipse of 1932 were made at 10 stations. Seven were equipped with Eppley Laboratory 10-junction thermoelectric pyrheliometers¹ with Leeds & Northrup "Micromax" millivoltmeters, recording the total radiation from sun and sky on a horizontal surface. At Lancaster, N. H., the records from the Leeds and Northrup recorder were supplemented by eye readings on a high sensitivity microvoltmeter, in connection with a separate Eppley pyrheliometer.

Other records were obtained from a Weston photronic cell (Buffalo, N. Y.), a Weston illuminometer (Seabrook, N. H.) and black bulbs in vacuo.

Evaluation of the solar records. (H. H. K. & C. F. B.) The automatic records and eye readings were evaluated for intervals of five minutes by H. H. Kimball for all stations. That for Wells, Me., was read for each two minutes by Wendell F. Smith, who assisted Prof. P. R. Gast at Wells. The Douglas Hill record gave zero radiation intensity from ten minutes before totality of the eclipse began until thirty minutes after totality had ended, which was obviously too long. At Lancaster, N. H., for example, through a continuous sheet of stratocumulus clouds, zero intensity was indicated for only three minutes. Not enough current was generated by the radiation falling upon the thermopile during totality to cause the slightest tremor in the highly sensitive microvoltmeter in circuit with it. This was also the case at Goldendale, Wash., with the sun unobscured by clouds during totality of the solar eclipse of June, 1918, but only during the short interval of totality (Kimball and Fergusson, 1919). Thus it appears that the zero of the recorder at Douglas Hill was set too high. An extrapolation of the curve plotted from the actual record indicates that the zero should have been between 0.10 and 0.15 gr. cal. lower. A value of 0.12 has been chosen as the closest approximation and this amount has been added to all the Douglas Hill readings.

¹ Cf. Kimball, H. H. and H. E. Hobbs. *A new form of thermoelectric recording pyrheliometer.* Mon. Weather Rev., v. 51, pp. 239-242, 1923.

In reducing the instrumental readings to heat units, reduction factors furnished for each instrument by the Eppley Laboratory have been employed, which depend upon standardization tests of an Eppley pyrheliometer by the U. S. Weather Bureau in 1931. This standard, in turn, ties up with the Smithsonian Scale of Pyrheliometry of 1913, through comparison of Weather Bureau and Smithsonian pyrheliometers.

There is some doubt as to the value of the factor necessary to reduce the illumination intensities measured at Seabrook and Buffalo to heat units.

Kimball¹, has shown that for air mass 2 (solar altitude 30°) a radiation intensity of 1 g. cal. is represented by approximately 6470 foot candles (fc.). In Table 1, the illumination values for Seabrook, by A. T. Sampson have been divided by 6470 to obtain the roughly-equivalent radiation values

The problem of equivalent radiation for the Buffalo illumination observations by L. A. Harding, is more difficult. The relative values for Buffalo are hundredths of milliamperes at normal incidence of the sun produced by a Weston photonic cell (at approx 1.4 microamperes per fc.) and indicated on a Weston milliammeter, neither of which Mr Harding had calibrated, though he had no reason to doubt their accuracy. The relative values have been converted to fc. (Table 1). To convert, now, to illumination on a horizontal surface we may use measurements by Kimball and Hand², in which the illumination intensities for direct sunshine at normal incidence and on a horizontal surface are presented for Washington and 2 stations in Chicago and for skylight illumination on horizontal and vertical surfaces for Washington alone. These data are given for solar altitudes of 42° for Washington and 41° for Chicago, which are suitable for the Buffalo reduction, where the sun's altitude averaged about 40° in the first half of the eclipse. The illumination on a horizontal surface is found to average 66% of that on a normal surface. Some account should, perhaps, be taken of the effect of the small changes in the altitude of the sun on the reduction to a horizontal surface, but since this would decrease the factor by only a few percent in the course of the fall in illumination, this refinement seems unwarranted. The 66% may therefore be applied with moderate confidence to all the Buffalo values. The illumination values for a horizontal surface derived by taking 66% of the values at normal incidence are presented in Table 1. These are then converted to gram calories as was done for Seabrook, except that the conversion factor is for air mass 1.6, namely 6690 (interpolated³), on account of the higher altitude of the sun at Buffalo. The gram calories derived thus are shown in the last column for Buffalo. Obviously, they are to be taken as only very rough values.

The solar radiation intensities as determined above are given, in Table 1, for five-minute intervals from 2.00 P.M. to 5.00 P.M., inclusive, 75th meridian time. The percentage of the solar disc not eclipsed by the moon was kindly furnished by the Nautical Almanac Office of the U. S. Naval Observatory, for each of the stations, except Montreal, New York and Pittsburgh, for the same five-minute intervals at which the radiation intensity was determined.

Black-bulb-in-vacuo records were submitted by the Central Park Observatory, New York City and Prof. Guy-Harold Smith, Ohio State Univ., Columbus, Ohio. These are also included in Table 1.

The observations of air temperature (H. H. K. & C. F. B.) included in Table 1 and

¹ Kimball, H. H.; *Records of total solar radiation and their relation to daylight intensity* Mon. Wea. Rev., v. 52, pp 475-479, Oct. 1924. Ref. to Table 2.

² Kimball, H. H. and Irving F. Hand; *Sky-brightness and daylight-illumination measurements* Mon. Wea. Rev., v. 49, pp. 481-488, Sept. 1921. Ref. to Table 1.

³ Kimball, loc. cit., Table 3.

Figs. 5 and 7 for comparison with the solar radiation were obtained at all stations by means of slung or whirled psychrometers, except at Conway. At Lancaster the psychrometer was slung in the open on the roof of a three story building; at Montreal, Douglas Hill, Wells, Seabrook, and Columbus the psychrometer was slung in open fields at a height of 3 or 4 feet from the ground; at Center Conway the thermometer was exposed in the open but not ventilated before being read; at New York and Buffalo the thermometer was whirled in a latticed shelter standing on the ground, and at Pittsburgh in a shelter atop a high office building. No temperature observations having been made in the immediate vicinity of the solar apparatus at Conway or Seabrook, the temperatures from Center Conway, 4 miles east of Conway, and from Seabrook Beach, 3 miles SE of the Seabrook station, were used. Center Conway was slightly less cloudy than Conway; and Seabrook Beach was partly cloudy to clear, like Seabrook.

D. *The Fall in Air Temperature.* (C.F.B.) 1. *Eclipse falls.* With both solar radiation and air temperature varying up and down with passing clouds or convectional gusts before the beginning of the eclipse, it is obviously necessary to take a mean pre-eclipse value of each if we are to arrive at any valid comparison of the effect of the fall in solar radiation on the temperature. For obtaining a mean of the solar radiation, the seven 5-min. values from 2:00 to 2:30 p.m., inclusive, were used; since, however, the eclipse began near 2:20 p.m. at all our stations, the last two or three values were first divided by the as yet uncovered percentage of the sun's disc. The pre-eclipse temperature was taken as the mean of all values from 2:00 to 2:45 p.m., by which time the effect of reduced radiation was just beginning to be felt.

The declines in solar radiation and temperature are presented in figs. 5, 6, and 7, and with the ratio of the latter to the former, in Table 2.

It is to be seen that at all stations within the zone of totality, and one outside, whether clear, partly cloudy or cloudy, the fall in temperature from the mean of 2-2:45 p.m. was from 0.65 to 0.85 F° per 0.1 gr. cal/min., cm² decrease in radiation from the mean of 2-2:30 p.m. to the eclipse minimum. It is probably accidental that the three out of line were all outside the zone of totality; it is surprising that there is not more diversity, in view of the diversity of local surroundings and the unmeasured, though undoubtedly considerable, difference in return radiation from the sky, a factor in the net radiation and consequently a temperature control. At all three stations the temperature observations were made inside the shelters, which would give less of a fall, in contrast to observations outside at the other stations, except Buffalo. The temperature fall at Central Park, New York City was extremely small for practically clear, though hazy, weather in the 90% zone. Possible special factors involved were radiation from the but slowly cooling buildings and streets

TABLE 1. SOLAR ILLUMINATION AND RADIATION INTENSITY MEASUREMENTS, AND SYNCHRONOUS AIR TEMPERATURE READINGS DURING THE SOLAR ECLIPSE OF AUGUST 31, 1932

TIME	SEABROOK, N. H. ¹				BUFFALO, N. Y.				CONWAY, N. H.				DOUGLAS HILL, ME.				
	EST*	eclip	illu	radn	tem	eclip	illu	radn	t(bg)	tem	eclip	radn	sk.ra	tem	eclip	radn	tem
p.m.		%	fc.	g. cal.	°F	%	fc.	g. cal.	°F	°F	%	g cal	g cal	°F	%	g. cal.	°F
2:00		100	..	..	75.2	100	..	..	77.0	85 0	100	0.829	0.243	81.0	100	0.597	80.0
05		100	..	..	..	100	..	..	..	..	100	1.120	0.227	..	100	0.551	..
10		100	..	..	..	100	..	..	..	..	100	1.130	0.248	..	100	0.927	82.5
15		100	..	..	74.2	99.8	(5090)	(0.76)	77.9	85.0	100	0.480	0.303	81.0	100	0.820	..
20		100	..	..	..	97.2	(4780)	(0.72)	..	..	100	0.866	0.366	..	100	1.017	81.0
23		100	9700	(1.50)	..	..	..	..	..	..	..	..	..	..	..	..	..
24		..	9400	(1.45)	..	..	..	..	..	..	..	..	..	..	..	..	..
25		98.8	1500	(0.23)	..	98.1	(4750)	(0.71)	..	..	97.4	0.989	0.318	..	97.8	0.868	..
2:30		95.4	6100	(0.94)	72.8	88.1	(4460)	(0.67)	77.3	85 0	95.2	1.120	0.329	81.5	93.8	0.951	79.0
35		90.5	7400	(1.14)	..	82.3	(4160)	(0.62)	..	..	88.0	0.835	0.329	..	88.6	0.894	..
40		84.8	6150	(0.95)	..	75.9	(3830)	(0.57)	..	..	81.8	0.414	0.314	..	82.6	0.431	78.5
45		78.3	5000	(0.77)	73.4	69.0	(3500)	(0.52)	77.0	84.1	75.0	0.568	0.299	82 0	75.8	0.749	..
50		71.2	4200	(0.65)	..	61.6	(3070)	(0.46)	..	..	67.7	0.353	0.251	..	65.8	0.220	78.0
55		63.6	3300	(0.51)	..	53.5	(2670)	(0.40)	..	..	59.7	0.348	0.235	..	60.7	0.154	..
3:00		55.5	2560	(0.40)	70.5	45.8	(2140)	(0.32)	76.3	83.5	51.4	0.241	0.220	81.0	52.3	0.146	78.0
05		47.0	1920	(0.30)	..	37.4	(1680)	(0.25)	..	..	42.8	0.187	0.163	..	43.7	0.130	..
10		38.1	1470	(0.23)	..	29.3	(1250)	(0.19)	..	..	33.7	0.134	0.126	..	34.7	0.277	78.0
15		28.9	1050	(0.16)	69.4	21.3	(880)	(0.14)	75.5	82.1	24.5	0.102	0.079	78.0	25.6	0.182	..
20		19.5	610	(0.09)	..	14.2	(590)	(0.09)	75 2	81.1	15.2	0.066	0.048	77.0	15.9	..	77.0
25		10.2	224	(0.03)	..	10.1	(460)	(0.07)	75.0	80.4	5.6	0.010	0.010	76.0	06.5	..	..
26		(450)	(0.07)	..	..	..	..	..	..	..	..	..
3:30		0.9	10	(0.002)	66.5	11.8	(560)	(0.08)	74.8	80.0	0.0	0.000	0.000	..	0.0	0.000?	76.0
31		0	0.55 ³	(0.0001)	..	..	..	..	..	..	..	..	..	..	..	..	..
35		4.8	310	(0.05)	..	18.3	(850)	(0.14)	74.7	80.0	9.5	0.000	0.000	75.0	08.1	..	..
40		15.4	..	..	..	26.3	(1380)	(0.21)	74.7	..	19.0	0.028	0.028	75.0	18.0	..	74.5
45		24.2	..	..	66.8	34.3	..	..	74.7	79.0	28.7	0.078	0.050	74.0	27.9	..	..
50		33.9	..	..	..	43.4	..	..	74.9	..	38.3	0.082	0.075	..	37.4	..	74.0
55		43.4	..	..	..	52.0	..	..	74.9	..	47.7	0.092	0.088	..	46.9	..	..
4:00		52.6	..	..	67.2	60.6	..	..	75.0	79.4	56.7	0.168	0.098	74.0	56.0	..	74.0
05		61.5	..	..	..	68.9	..	..	..	..	65.4	0.134	0.107	..	64.7	0.176	..
10		70.0	..	..	..	76.3	..	..	..	..	78.7	0.138	0.119	..	73.1	0.171	74.0
15		77.9	..	..	67.0	83.4	..	..	75 3	80.1	81.3	0.148	0.121	77.5	80.8	0.180	..
20		85.2	..	..	..	89.7	..	..	..	..	88.2	0.159	0.122	..	87.8	0.181	74.0
25		91.6	..	..	..	93.0	..	..	..	..	94.0	0.152	0.122	..	93.7	0.156	..
4:30		96.7	..	..	..	99.0	..	..	75.8	82.0	98.4	0.152	0.122	77.5	98.2	0.160	73.5
35		99.9	..	..	..	100	..	..	..	..	100	0.134	0.113	..	100	0.156	..
40		100	..	..	..	100	..	..	..	..	100	0.115	0.107	..	100	0.169	73.0
45		100	..	..	66.3	100	..	..	76.2	..	100	0.115	0.098	77.5	100	0.180	..
50		100	..	..	..	100	..	..	..	..	100	0.107	0.080	..	100	0.182	72.5
55		100	..	..	..	100	..	..	..	..	100	0.088	0.079	..	100	0.177	..
5:00		100	..	..	66.0	100	..	..	76.2	82.0	100	0.082	0.067	77.0	100	0.162	72.0

* Meanings of abbreviations. "hbt," black-bulb temp.; "cu," cumulus cloudiness; "eclip," solar disk exposed, "EST," 75th Mer. Time, "illu," illumination on horizontal surface; "radn," total solar and sky radiation on horizontal surface, "sk.ra," sky rad. on hor. surf., "tem," air temp.; "t(bg)," air temp on high bldg.

¹In order to have the time of minimum recorded illumination agree with the time the minimum of solar disk was exposed, as given by the Nautical Almanac Office, it has been necessary, with the concurrence of Mr. Sampson, to set back the curve of

TABLE 1. SOLAR RADIATION INTENSITY MEASUREMENTS AND SYNCHRONOUS AIR TEMPERATURE READINGS DURING THE SOLAR ECLIPSE OF AUGUST 31, 1932 (Concluded)

TIME EST	WELLS, ME.			COLUMBUS, O.		NEW YORK CITY			PITTSBURGH, PA.			LANCASTER, N. H.			MONTREAL, Q.U.E.	
	eclip	radn	tem	bbt	tem	radn	bbt	tem	radn	tem	cu	eclip	radn	tem	radn	tem
p.m.	%	g. cal.	°F	°F	°F	g. cal.	°F	°F	g. cal.	°F	1-10	%	g. cal.	°F	g. cal.	°F
2:00	100	0.932	72.5	.	.	0.857	122	81.1	0.785	93.1	7	100	.	.	.	76.7
05	100	0.924	.	.	.	0.810	.	.	100	.	.	100	.	79.4	0.230	.
10	100	0.883	.	.	.	0.666	.	.	100	.	.	100	.	.	.	77.2
15	100	0.884	72.7	(155)	96	0.716	119.5	82.4	1.021	92.7	6	100	0.416	77.9	0.230	.
20	100	0.877	.	(154)	.	0.720	.	.	.	.	.	99.5	0.444	.	0.217	76.8
23	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
24	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
25	98.5	0.848	.	(150)	95	0.693	.	.	.	.	.	96.3	0.491	.	.	.
2:30	95.2	0.801	72.3	(146)	(95)	0.718	118.5	82.5	0.455	93.8	5	91.8	0.563	79.1	0.184	76.8
35	90.1	0.754	.	142	(95)	0.668	.	.	.	.	.	86.3	0.443	.	0.184	.
40	84.0	0.698	.	137	(95)	0.576	.	.	.	.	.	80.0	0.366	77.6	0.184	76.6
45	77.4	0.624	70.3	132	(95)	0.522	116	82.5	0.722	93.1	5	73.0	0.314	.	0.184	.
50	70.3	0.561	.	(121)	(95)	0.468	.	.	.	.	.	65.5	0.288	.	0.104	76.2
55	62.5	0.495	.	121	(94.8)	0.405	.	.	.	.	.	51.4	0.253	78.7	0.080	76.0
3:00	54.4	0.435	69.5	118	94.5	0.342	116.5	82.8	0.424	94.4	4	49.2	0.186	.	0.046	75.8
05	45.8	0.322	68.0	115	(94.1)	0.288	.	.	.	.	.	40.2	0.125	77.1	0.046	75.6
10	36.8	0.124?	66.5	(111)	(93.7)	0.216	.	.	.	.	.	31.4	0.074	.	0.034	75.6
15	27.7	0.084?	66.0	(107)	(93.1)	0.162	96	82.5	0.063	92.7	4	23.1	0.044	.	0.020	75.0
20	18.1	0.074?	65.9	104	(92.3)	0.117	93	81.9	0.157	92.5	4	12.6	0.016	76.9	0.000	75.1
25	8.6	0.020	64.9	(101)	(91.8)	0.063	89	82.0	.	92.4	3	3.1	0.003	.	0.000	75.1
26	.	.	.	.	.	.	.	.	.	.	.	0.0	0.000	.	.	.
3:30	0.0	0.000	64.5	100	(91.1)	0.023	87	82.0	0.079	92.3	3	2.1	0.003	75.5	0.008	75.0
33	.	.	.	99	90.5	.	.	.	.	.	.	.	.	.	.	.
35	6.1	0.023	64.5	(99.5)	(90.5)	0.009	85	81.4	0.094	92.1	.	11.8	0.020	75.2	0.039	75.0
40	15.9	0.080	64.5	100.5	(90.5)	0.036	84	81.0	0.141	92.0	2	21.4	0.045	.	0.060	75.0
45	25.6	0.134	65.0	103	(90.9)	0.071	85	80.4	0.173	92.1	2	31.0	0.075	75.2	0.074	75.0
50	35.3	0.177	.	105	(91.5)	0.099	87.5	80.5	0.298	92.0	2	41.6	0.107	.	0.094	75.0
55	44.8	0.214	65.6	(107)	(92.0)	0.081	88	80.9	0.298	92.1	2	49.4	0.130	76.0	0.102	75.0
4:00	54.0	0.248	.	109	92.5	0.198	88.5	80.5	0.361	92.2	2	58.9	0.145	.	0.133	75.2
05	62.8	0.279	.	114	93.5	0.238	.	.	.	.	.	67.4	0.160	.	0.097	75.4
10	71.3	0.302	(67.0)	120	93.5	0.207	.	.	.	.	.	75.5	0.175	.	.	75.5
15	79.2	0.285?	.	125	(93.8)	0.169	91	79.9	0.455	92.3	1	82.5	0.190	76.0	.	.
20	86.3	0.233	.	128	94.0	0.108	.	.	.	.	.	89.6	0.200	.	.	75.4
25	92.5	0.301	.	131	(94.0)	0.070	.	.	.	.	.	95.2	0.197	.	.	.
4:30	97.4	0.347	67.5	135	94.0	0.050	83	79.0	0.455	92.7	few	99.1	0.195	77.0	.	75.5
35	100	0.340	.	135	(94.3)	0.032	.	.	.	.	.	100	0.188	.	.	.
40	100	0.325	.	(132)	(94.5)	0.027	.	.	.	.	.	100	0.181	.	.	75.5
45	100	0.298	67.5	(132)	(94.7)	0.018	80	78.5	0.345	92.2	few	100	0.180	.	.	.
50	100	0.270	.	131.5	95.0	0.009	.	.	.	.	.	100	0.184	.	.	75.5
55	100	0.247	.	131	95.0	0.004	.	.	.	.	.	100	0.186	.	.	.
5:00	100	0.234	66.3	(129.5)	.	0.002	78	79.0	0.314	92.3	2	100	0.196	77.0	.	75.5

illumination intensity, as given, by three minutes, the amount by which his watch appears to have been faster than 75th Mer Time.

² To correct for an error of the zero of the scale, 0.120 has been added to all recorded values at Douglas Hill

³ This corresponds almost exactly to Kahtun's, 1928a, minimum of 0.6 ft. in the eclipse of 1927.

ECLIPSE METEOROLOGY

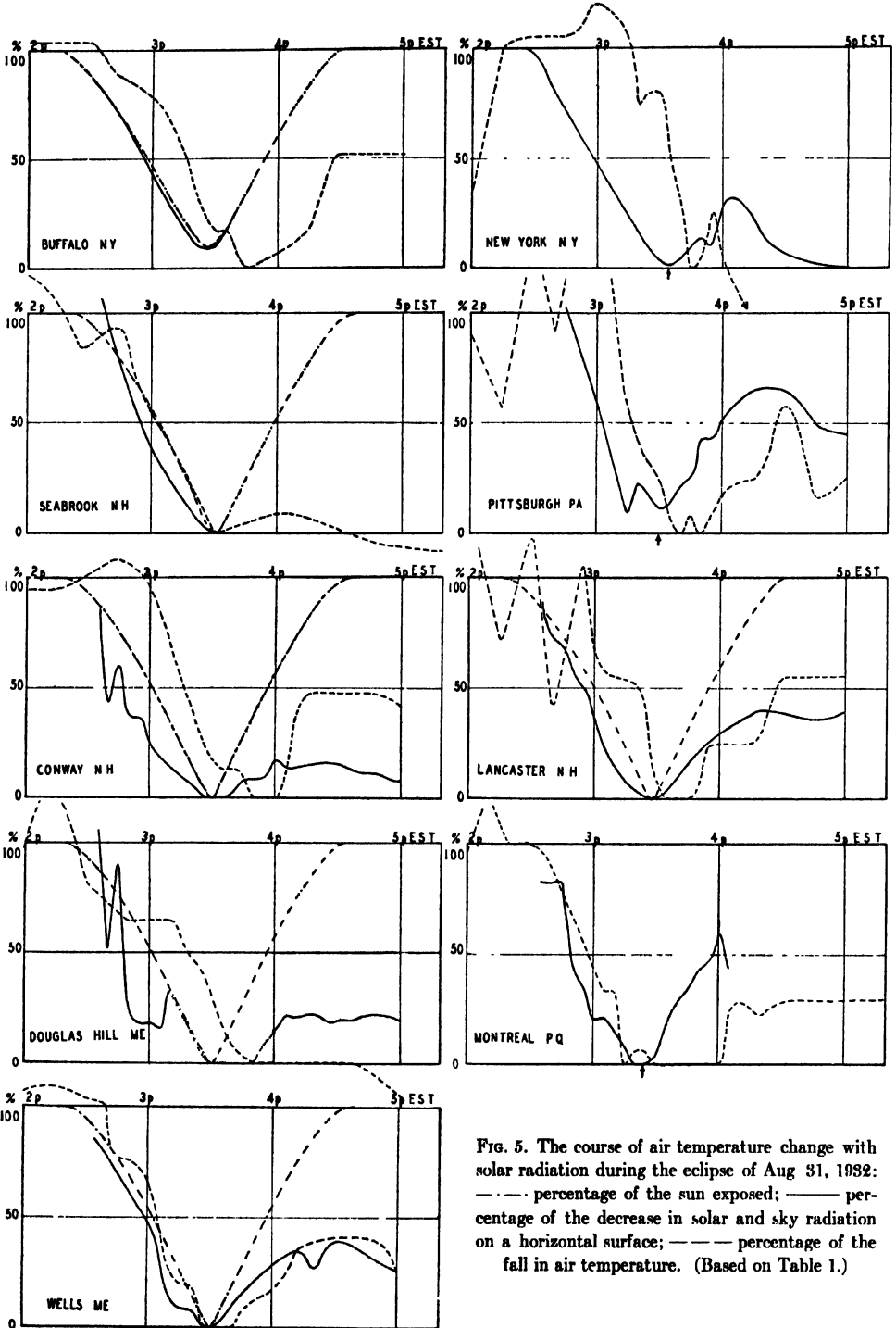


FIG. 5. The course of air temperature change with solar radiation during the eclipse of Aug 31, 1932: - - - percentage of the sun exposed; ——— percentage of the decrease in solar and sky radiation on a horizontal surface; — — — percentage of the fall in air temperature. (Based on Table 1.)

and the temperature steadying effect of a 10-mile wind off Long Island Sound, $1\frac{1}{2}$ miles up-wind.

2. *Eclipse vs. diurnal falls.* To compare the daily slow decrease in temperature with declining radiation in the afternoon of a normal day with the foregoing eclipse values, observations at Blue Hill Observatory on five clear and five cloudy days between Aug. 20 and Sept. 11 in 1933, 1934, 1935, and 1936 are presented in Table 2 and Fig. 7. Starting with the time the 1932 eclipse began (about 2:15 p.m.), the solar radiation on these non-eclipse days decreased till sunset at about 6:20, four hours later, at a rate, therefore, a little less than four times as slow as during the eclipse.

Correspondingly, if we take four times the approximately $1\frac{1}{2}$ hrs from the beginning to the end of the eclipse temperature fall, we should run from 2 to 8 p.m. for the non-eclipse temperature fall to compare with the decrease in solar radiation, except for the fact that in the last quarter hour of the eclipse fall it is being rapidly slowed by increasing insolation. As a compromise, therefore, the temperature at 7 p.m. (about 40 min. after sunset) is taken to compare with the eclipse minimum temperature.

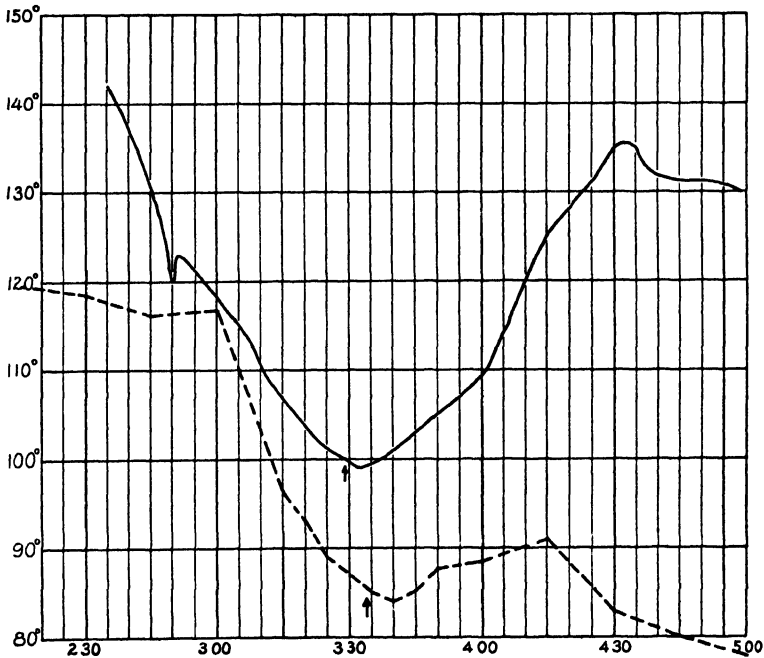


FIG. 6. Black bulb in vacuo temperatures during the eclipse of Aug. 31, 1932. — at Columbus, Ohio (Prof. Guy-Harold Smith); - - - at New York City (Central Park Obsy, U.S. Weather Bureau). (From Table 1.)

The maximum temperature is, presumably, related to the maximum radiation even though the maximum temperature usually occurs some two hours after the maximum radiation. Therefore, we have made several different comparisons, combining variously the maximum of radiation or radiation at 2:00-2:30 as starting points of decrease, and, similarly, using both maximum temperature and temperature at 2:15 p.m. From Table 2 and Fig. 7, showing one of these comparisons, it is evident, as would be expected, that, given more time, there is a somewhat greater fall per unit decline in solar radiation. The afternoon fall is thus from 22% to 63% greater than the eclipse fall, depending upon the method of calculation employed.

A rough relationship between solar radiation and air temperature changes appears also when a comparison is made between the air temperature and the black bulb in vacuo temperature at the same station during the eclipse. (See Table 3.)

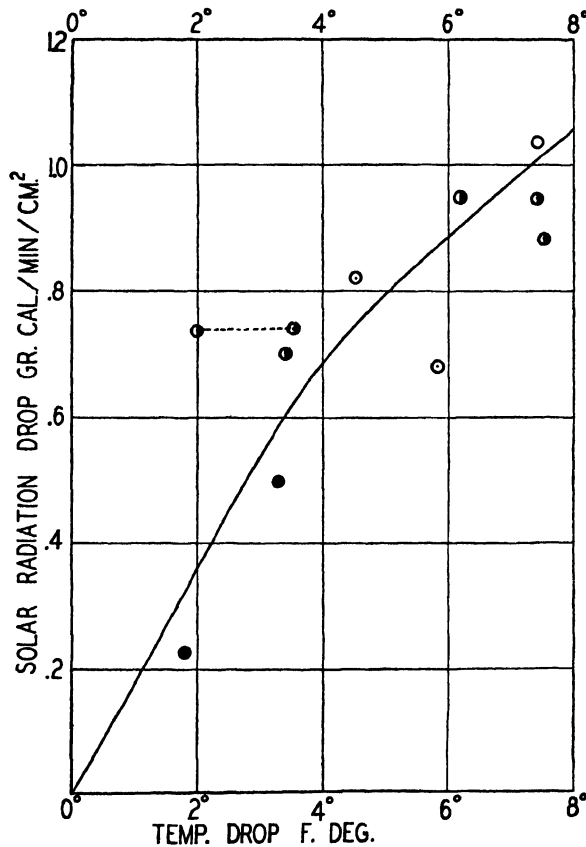


FIG. 7. Fall in air temperature from about 2 p.m. to eclipse minimum, Aug. 31, 1932, with reduced solar and sky radiation on horizontal surface from 2:15 p.m. Open circles represent conditions in clear weather; half black, partly cloudy; solid black, cloudy. (From Table 2.)

TABLE 2 RELATION OF FALL IN TEMPERATURE TO DECREASE IN TOTAL SOLAR AND SKY RADIATION ON A HORIZONTAL SURFACE AFTER 2:15 p.m., ESPECIALLY DURING THE ECLIPSE OF AUGUST 31, 1932.

ECLIPSE FALLS, AUG 31, 1932							BLUE HILL NON-ECLIPSE AFTERNOON FALLS AUG. AND SEPT., 1933-1936					
Station	ecl*	radn	t.fl	t.f/r	cld	vp	Date	radn	t.fl	t.f/r	cld	vp
	%	g cal/min.cm ²	F°	F°		mm		g cal/min.cm ²	F°	F°		mm
Seabrook, N H.	100	(1.040) ¹	7.4	(0.71)	cr	15	Aug. 21 1934	1.050	6.2	1.0	cr	6
Conway, N H.	100	0.951	(7.4)	(0.78)	pc	—	Aug. 24 1936	1.050	4.6	0.4	cr	13
Douglas, Hill, Me.	100	(0.950) ²	6.2	(0.65)	pc	—	Sept. 11 1935	1.010	9.9	1.0	cr	9
Wells, Me.	100	0.886	7.5	0.85	cr—pc	15	Sept. 6 1936	0.950	12.4	1.3	cr	12
Columbus, Ohio	83	(0.822) ³	4.5	(0.55)	cr	19	Aug. 30 1933	0.833	3.7	0.4	cr	10
New York:												
Central Park	95	0.738	2.0	0.27	hz & pc	19	Sept. 4 1934	0.423	5.9	1.4	cy	15
Battery ⁴	95	—	(3.5)	0.39	hz & pc	19	Sept. 8 1935	0.413	3.8	0.9	cy	12
Pittsburgh, Pa.	88	0.702	1.2 3.4 ⁵	(0.47)	pc-cr	15	Sept. 10 1936	0.338	2.6	0.8	cy	13
Buffalo, N Y.	91	(0.686) ⁴	5.8	(0.85)	cr	20	Aug. 27 1935	0.260	3.5	1.3	cy	18
Lancaster, N H.	100	0.497	3.3	0.66	oc	15	Sept. 5 1935	0.253	4.9	2.4	cy	15
Montreal, Que.	100	0.223	1.8	0.81	oc	19						
Mean ⁷				0.67			Mean			1.09		

* Abbreviations are as follows

cld — cloudiness: cr, clear, pc, partly cloudy, cy, cloudy, oc, dense overcast, hz, hazy.

ecl — maximum obscuration

radn — mean value of total solar and sky radiation 2-2.30 p.m. on Aug. 31, 1932; actual at 2.15 p.m., 1933-1936.

t.fl — fall in air temperature from mean of 2-2.45 p.m. to minimum during eclipse, from 2-7 p.m. 1933-1936.

t.f/r — t.fl/radn × 10, i.e. fall in temperature per 0.1 gr cal. decrease in radiation.

vp — vapor pressure at 2 p.m.

¹ From illumination values () enclose computed, extrapolated or otherwise uncertain data.

² 0.120 added to all values for approximate zero displacement.

³ From black bulb thermometer in vacuo

⁴ Downtown office building

⁵ Value from formula, $e = orb$, in which e is the value given, o the observed eclipse effect on temperature (1.2 F°) on the roof of the office building (353 ft. high), r the ratio of eclipse effects on office buildings to those at ground exposures per 100 ft. (the difference in eclipse effect at Buffalo and Columbus having been found to average 0.8 F°/100 ft.), and h the height of the building in hundreds of feet, here, 3.53

⁶ From unstandardized illumination values on normal surface converted to horizontal.

⁷ New York counted as one station, with Central Park given twice the weight of the Battery. If the values in () are given only half the weight the means are the same within 0.03°.

TABLE 3. COMPARISON OF BLACK BULB IN VACUO AND AIR TEMPERATURE CHANGES DURING ECLIPSES.

Year	Place	Weather	Maximum obscuration	Temperature fall or rise		Ratio
				Blk.b.	Air	Bb/Air
1887 ¹	Chlamostino, Russia	Cloudy	%	F°	F°	
1889 ²	Willows, Calif.	Pt. cldy. to clear	100	14	4	4
1898 ³	Six stas in India	Mostly clear	100	62	6.3	10
1932	New York City	Lt. haze to pt.cldy.	85-100	50	3.8	13
1932 ⁴	Columbus, Ohio	Clear	95	36	2.0, 3.5	18, 10
1936 ⁵	Le Lycabette, Greece	Clear	83	43	4.5	10
			100	32	3.2	10

¹Upton and Rotch, 1888. ²Upton, 1892. ³Ehot, 1899. ⁴Prof.G.-H Smith. ⁵Livathnos and Cariapieria, 1937.

E. *Data from the Partial Solar Eclipse of April 7, 1940 at Blue Hill. (C.F.B.)*
 During the late afternoon eclipse of April 7, 1940, the Blue Hill Observatory obtained open scale records of the direct and screened solar radiation shining normally on a thermopile at the bottom of a tube 10 times as long as its diameter and of the total solar and sky radiation on a horizontal surface. The pyrheliometers were both Eppley; the recorders, a Leeds and Northrup "Micromax" potentiometer and an Engelhard microammeter. The atmosphere was remarkably clear and dry all day. Another such day occurred 3 days later, providing an excellent basis for evaluating the effect of the eclipse.

In Fig. 8, the afternoon record of the intensity of direct sunshine at normal incidence is folded back at local noon on to the morning record. At the time of maximum eclipse the intensity was 63% less than at the same time in the morning. But just before the eclipse began the intensity was running 2 to 4% below the corresponding morning values. To take this into account the afternoon values of April 10 were increased by 5%, the amount by which the noon radiation on the 7th was in excess of that on the 10th, and the mid-eclipse value was then found to be 54% below what it would have been at the same time on the 10th, had the afternoon of the 10th been as bright as the 7th. This corresponds well to the maximum obscuration of "approximately 53%" kindly computed for Blue Hill by W. J. Eckert, Director, Nautical Almanac, U. S. Naval Observatory. Similarly, Dörr, Dorno, and Lipp, found reductions of 63, 73, and 80% in eclipses of 63, 66, and 82%, respectively.

There was a 5% greater intensity of the yellow and shorter wave-lengths (cut off by Schott filter OG1) relative to the total and 0.5% lesser intensity of the longer wave-lengths transmitted by RG2 (longer wave-lengths of red, and infrared), during the eclipse than at the same time on April 10, whereas, the values on both

days were identical at the time of day when the eclipse began (see Table 4). The reverse might have been expected, and, indeed, was observed by Dörr, Dorno and Lipp since the moon covers a larger percentage of the hotter central portion of the sun's disk than of the limb. At about 33% eclipse, 28 min. before the maximum, when the total radiation was cut 33%, the ultraviolet (UV) was only 28% below non-eclipse values at the same hour. In fact, the UV had declined only 54% from the beginning of the eclipse, whereas on the 10th the decrease in the same time had been 48%. This, like the short-wave filtered radiation, is less of a reduction than expected. Albrecht, 1934, found a 49% decrease at 40% eclipse and 60% decrease at 50% eclipse. In both cases, however, the amounts we are dealing with are so small as to be appreciably affected by observational error, especially in the case of the ultraviolet measures by dosimeter. Sub-visible Ac clouds would have had an effect, as in Albrecht's measurements. A rapid reduction of ultraviolet to zero at totality and subsequent rapid rise are presented by H. Slouka, 1937; but not compared with eclipse percentage.

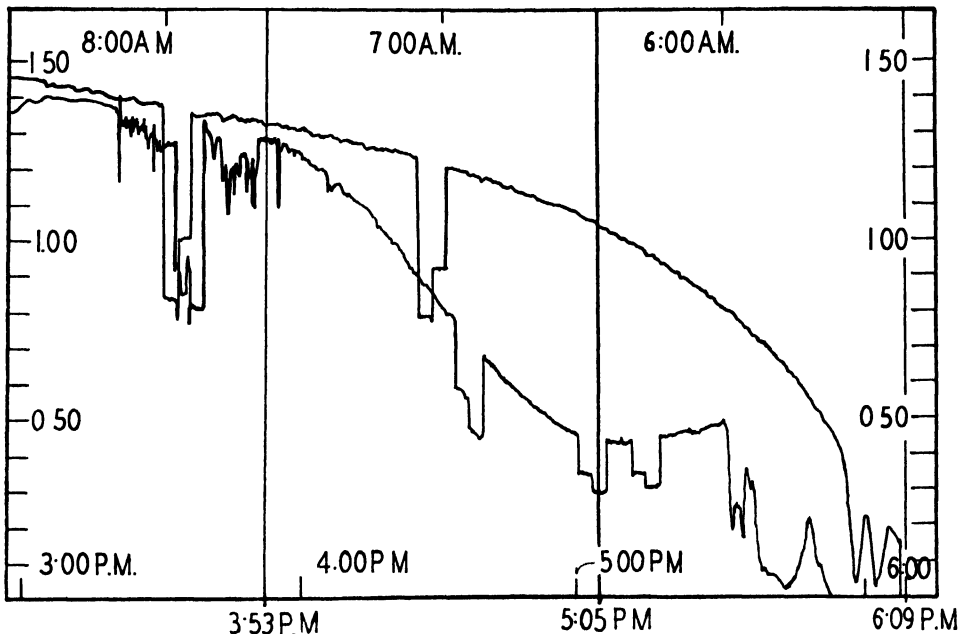


FIG. 8. Solar radiation at normal incidence, on Eppley thermopile in tube having aperture 1/10 its length, April 7, 1940, at Blue Hill Observatory. The upper curve is a record of the morning radiation; the lower curve the afternoon radiation at the same local times as the morning record. An eclipse of the sun occurred from 3:53 to 6:09 p.m., with a maximum obscuration of 53% at 5:05. The vertical walled depressions in the curves are from screenings with yellow and red filters, OG1 and RG2. The deep irregularities in the lines are due to cirrus clouds. The values in the vertical scale are gram cal. per min per sq. cm., converted from microvolts recorded on Leeds and Northrup "Micromax" potentiometer

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TABLE 4. SPECTRAL INTENSITIES OF DIRECT SOLAR RADIATION ON APRIL 7 (eclipse day) AND APRIL 10, 1940, AT BLUE HILL OBSERVATORY.

Local time from noon ¹		Ultraviolet				Short-wave radiation ³ (< 524 mμ)		Long-wave radiation ⁴ (> 633 mμ)		Intensity of unscreened solar rad. at normal incidence ⁵	
		Dosimeter units ²		Rel. to noon intens.		% of total		% of total			
Ap. 7	Ap. 10	Ap. 7	Ap. 10	Ap. 7	Ap. 10	Ap. 7	Ap. 10	Ap. 7	Ap. 10	Ap. 7	Ap. 10
				%	%	%	%	%	%	g. cal.	g. cal.
4:45a	4:42a	.	..	27	28	23.6	23.4	.	..	1.18	1.03
4:43	4:40a	.	..	.	.	..	.	64.3	64.1	1.19	1.05
3:50a	4:10a	...	...	40	40	26.0	27.2	..	..	1.32	1.16
3:48a	4:08a	..	..	...	.	...	.	61.2	60.8	1.33	1.16
1:48a	1:42a	..	..	..	..	28.6	28.8	..	..	1.48	1.37
1:46a	1:39a	..	..	96	93	.	..	59.2	59.0	1.47	1.39
0:04p	0:04p	11.1	9.0	100	100	29.0	29.0	..	..	1.47	1.40
0:06p	0:06p	..	.	.	..	.	..	58.2	58.2	1.48	1.40
3:48p	3:47p	..	...	.	..	26.8	26.8	..	..	1.26	1.25
3:51p	3:50p	..	...	50	61	..	...	62.5	62.0	1.27	1.24
4:49p	4:50p	..	...	.	..	24.2	22.8	..	..	0.73	1.04
4:51p	4:52p	..	...	23	32	..	..	65.4	66.1	0.68	1.01
5:15p	5:11p	...	..	...	.	23.4	22.3	..	...	0.44	0.95
5:18p	5:13p	...	...	13	..	..	...	66.4	66.4	0.43	0.93
5:27p	5:27p	...	..	.	...	20.6	15.4	..	..	0.43	0.85
5:20p	5:29p	..	...	..	..	..	..	69.2	69.1	0.44	0.82

¹ 14 min. before noon E S T.

² Measured by German chemical dosimeter (cf Trans Am Geophys U, 1938, p 141).

³ Total minus radiation transmitted by Schott yellow filter OG1, with cutoff at about 524 mμ (cf Met Z, 1932, pp 242-244)

⁴ Total minus radiation transmitted by Schott red filter RG2, with cutoff at about 633 mμ (cf ibid)

⁵ From circle of sky including sun whose diameter is the angle having a tangent of 0.1, the same as the Smithsonian Silver-disk Pyrheliometer, in g cal/min, cm².

The total radiation on a horizontal surface fell with great rapidity, 0.529 g. cal./min, cm² during the first half of the eclipse, owing to the combination of decreasing sunshine, decreasing solar altitude, and decreasing (Ci.) clouds. The decline was nearly stopped, however, when the sun began to come out again, the rate of fall becoming only one-tenth of what it had been. But decreasing altitude, and then clouds near the horizon prevented radiation from again reaching the value at maximum eclipse.

The effect on air temperature was small. The micro-changes in temperature characteristic of a sunny afternoon virtually died out early in the eclipse, and the temperature started downward slowly instead of flattening out at the end of the slow afternoon rise as usual. The temperature decline definitely ascribable to the

eclipse could not have been more than 2 F°. The temperature fell from 51.2°F at 4 p.m. to 48.8°F at 5:20 p.m., or 2.4 F°. This is only 0.45 F° per 0.1 gr. cal. decrease in solar and sky radiation, or 2/3 the average of the warmer and less windy eclipse of 1932.

Summary: solar radiation and air temperature, 1932. A comparison of radiation with decrease of temperature in the 1932 eclipse indicated that for a decline of 0.1 g. cal./min, cm² the temperature decreased an average of 0.7 F° (0.4 C°), which is somewhat less than the 1.1 F° (0.6 C°) daily decrease for an equal fall in radiation on non-eclipse days at the same time of year. The rate of decrease of solar radiation during the first half of the eclipse was four times the usual afternoon rate of fall. On a cool day in a brisk wind the rate is less: in 1940 it was 0.45 F°/0.1 gr. cal. on Blue Hill, a rate only 2/3 the warm day, light wind value.

III. THE TEMPERATURE CHANGES DURING AN ECLIPSE

A. Introduction. (B. H.) The meteorological element most closely affected by the deficit in solar radiation during an eclipse is, naturally, the temperature. Clayton, 1905, summarizes the behavior of temperature during solar eclipses from 1878 to 1905 finding, *inter alia*, on the basis of the limited data available: that the fall does not begin until about 15 to 20 min. after first contact, that the time of minimum temperature lags behind totality from 2 or 3 to 20 min.

The lag of temperature relative to radiation is caused as follows. Near the surface the air is heated mainly by convection from the ground and therefore the difference in phase between solar radiation and temperature is simply due to the convective heat transfer and turbulent exchange. At greater heights, on the other hand, the range of temperature is determined by radiation in addition, as shown, e.g., by W. Schmidt¹. The duration of a solar eclipse is too short for convection to make the cooling of the earth's surface felt at such heights, except that convective transfer of heat upwards is reduced. So here the drop in temperature is caused only by the diminishing admixture of warm convective columns or bubbles, and decreasing direct solar heating of the air, and, therefore, is small. In some cases the greater amplitude of the temperature variation near the ground leads to a slight inversion in the lowest layers, as was shown, for instance, by Süring, 1912.

*B. Determining the Eclipse Effect on Temperature.*² (E. S. B., C. F. B.) The eclipse effect on temperature may be defined as the departure of the observed temperature

¹ Schmidt, *loc. cit.*, footnote 2, p. 21, above.

² It should be noted that the temperature drop discussed in connection with solar data in the preceding section (II) is the entire fall in temperature from the pre-eclipse value to the minimum shortly following totality or the maximum obscuration and is not the same as the eclipse effect on temperature discussed in this section (III), which subtracts normal afternoon decrease from the total drop to obtain the eclipse effect.

from that which would have occurred had there been no eclipse. How can the "would have occurred" temperature curve be approximated? If the weather of the eclipse day is practically the same as that of the day or two before or after, the diurnal curve of one of these non-eclipse days may be used for reference. Or, if there has been a record kept at this station before, the mean diurnal curve of several similar days at the same time of year in past years may be used, or even the normal curve of diurnal course of temperature for the month. Nevertheless, it must be borne in mind that every day would show a considerable deviation, not alone a day disturbed by an eclipse.

In studying the Indian eclipse of 1898 Eliot, 1900, used normal curves for reference, applying an appropriate correction to allow for the difference between the normal temperature and the actual temperature at the beginning of the eclipse. He estimated that the temperature did not return to its usual course until $11\frac{1}{4}$ hours after last contact. Apparently, the actual temperature record obtained after the eclipse was disregarded in drawing the theoretical temperature curve, which lead to a few inconsistencies. This method, however, proved relatively satisfactory for the calm, clear weather typical of India in January.

In Russia and in the United States, Upton and Rotch, 1888, 1892, used a similar method, but considered the departure from normal both at the beginning and end of the eclipse, applying a uniform change in the correction between beginning and end. This method was employed by Clayton, 1908, but, as he points out, it fails to allow for the fact that the temperature at last contact is lower than it would have been without the eclipse.

Bigelow, 1902, reporting on the eclipse of 1900, also did not attempt to allow for this delay in recovery, but drew his reference curve between the temperatures observed at first and last contact. Bigelow judged that recovery was not complete until two hours after totality (or about one hour after last contact).

In the 1932 eclipse a large number of stations was employed, many without permanent records. Moreover, the diversity of temperature, cloudiness, and time of day during the eclipse in different portions of the United States added to the difficulty of making detailed comparisons with normals. It appeared best to try to draw from the trends of temperatures observed before and after the eclipse at each station a curve which might reasonably represent the smoothed course the temperature would have taken had there been no eclipse, bearing in mind that at some stations the highest temperature of the day would have occurred during the eclipse period and that the hypothetical curve should not merge with the actual temperature curve until at least an hour after the end of the eclipse (generally 5:30 E. S. T.). (See Fig. 9.) A great many of our stations observed temperatures until 6:30 E. S. T.,

thus indicating the late afternoon trend. The eclipse effect was assumed to be the maximum difference within about $\frac{1}{2}$ hour after maximum obscuration between the non-eclipse curve and the observed temperature; though at a few stations the curve of observed temperatures was roughly smoothed and this curve used for comparison with the non-eclipse smoothed curve. Allowances were made or records discarded when recognized or reported fronts, sea-breezes, rapidly changing cloudiness, or showers disturbed the course of temperature. A number of stations, mostly far western, for which the evaluation of an eclipse effect was uncertain, were omitted from our study.

We have compared results from our completed-curve method with estimates from a normal curve, applying a correction based on the initial temperature. This is the method used in the Indian eclipse (Eliot, 1899), which furnishes the most extensive temperature data prior to 1932. The reference curve is an average of the mean diurnal curves for August and September at 15 eclipse stations for which this information was available. In spite of wide departures of individual stations, + 3.0 to - 2.5 F°, the difference exceeded 1.0 F° at only one third of the stations, and the average difference in eclipse effect obtained by the two methods was but 0.15 F°, the normal diurnal curve (Indian) method giving the larger values for the eclipse temperature departure.

The relation between the eclipse-temperature effect estimated from the completed curve method and (1) the actual temperature fall and (2) the mean of fall and subsequent rise was also determined at 43 stations. (1) In this midafternoon occurrence (1932) the eclipse-temperature effect, curve method, averaged 87% of the actual fall in the 90-100% zone (23 stas.) ranging from 55 to 112%, with half the cases between 83 and 94%. In the 80-90% zone (20 stas.) the average was 91%. (2) The eclipse-temperature effect from the curve method was 120% of the mean of the fall and subsequent rise, being the same in both zones.

As a further check on the completed-curve method, the theoretical amount of temperature fall due to the reduction of sunshine caused by the eclipse may be roughly estimated for comparison. For example, at Wells, Maine, the insolation was 0.88 g. cal/min., cm² at the beginning of the eclipse. It would have been approximately 0.70 at 3:30 had there been no eclipse, a decline of 0.18 g. cal. At the clear weather rate found at Blue Hill (Table 2) from a comparison of solar and temperature records on non-eclipse days, namely, 0.82 F° per 0.1 g. cal/min., cm², this fall of 0.18 g. cal would have caused a drop of 1.5 F°. Subtracting, this normal fall from the 7.5° fall observed, we have 6.0° as the eclipse effect. The amount derived from the completed-curve method was 6.0° and from the mean of fall and subsequent rise 5.5°.

C. *Temperature Data, 1932* (E.S.B.). 1. *Sources*. This study of temperature changes during the eclipse is based on more than 300 reports, for which we are indebted to many services, organizations and individuals. More than 125 Weather Bureau stations throughout the United States sent detailed temperature reports based on readings of the wet and dry bulb thermometers whirled in the shelter. In most cases readings to 0.1 F° were taken every 15 minutes from 1:30 to 6:30 p.m. E. S. T. The stations equipped by Blue Hill Observatory were practically all in the totality zone in New England. Most of them were provided with sling psychrometers, six had thermographs in addition. Psychrometer readings to 0.1 F° were made every 15 minutes from 1:30 to 6:30 and also at 5-minute intervals from 3:15 to 4:00 E. S. T. In addition, 163 miscellaneous reports came mostly from the totality and 90% zones, with a few scattering westward. These differed widely in nature, on account of the variety of equipment, exposures, and readings. Eleven automatic temperature records were received (Fig. 10), and some readings from sling psychrometers and precision thermometers exposed in the shade. Some reports had to be omitted because poor exposure or crude readings made comparisons of little value. One original observer explained that he hung his thermometer carefully upside down in a pine tree!

2. *Reduction*. The data for each station were plotted on coordinate paper and the temperature curve drawn. In order to compute the fall in temperature probably due to the eclipse, the hypothetical curve described above was constructed, showing as nearly as possible the probable diurnal course of temperature, had there been no eclipse. The greatest dip of the actual curve below this hypothetical curve was taken to indicate the temperature fall due to the eclipse, provided the record was not spoiled by a marked local factor such as a thunderstorm or striking windshift. The majority of temperature readings received were not taken at sufficiently frequent intervals to determine accurately the time of beginning of temperature fall or the time of minimum. Those with readings at 5-minute intervals or less showed the time of minimum fairly well, however, and have been averaged.

For 9 Weather Bureau stations with clear weather, obscuration 70–90%, the average delay of minimum temperature after maximum obscuration was 14 min. For 13 Blue Hill stations, mostly in the zone of totality and with varied weather, the lag averaged 4 min. The lag tended to be larger at Weather Bureau stations chiefly because of greater elevation above the ground, but also because of urban location, and because observations were taken in a shelter instead of in the open. The Indian eclipse of 1898 showed an average eclipse lag of 15 minutes in minimum temperature as shown by observations made in shelters.

Factors influencing the amount of the eclipse-effect on temperature at any

station include the percentage of the sun obscured, the cloudiness, changes in wind direction or velocity, altitude, relation to land and water bodies, and solar altitude (a function of the latitude and local time — not studied). Initial air temperature is also a factor, but negligible.

The zone map of the eclipse presented in Fig. 1 shows the path of totality over New England and the percentage of the sun obscured at the time of maximum eclipse in other parts of the United States.

Fig. 9 shows typical temperature curves for stations in the various eclipse zones from totality to 15% obscuration. The curves are chosen chiefly from stations

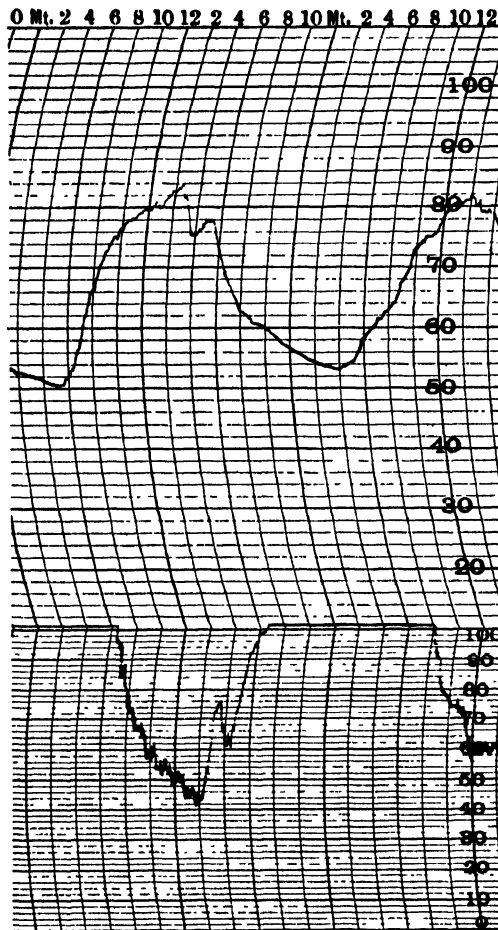


FIG. 10. Thermohygrograph record at Macwahoc, Me. (Courtesy, U. S. Weather Bureau) Note that the small variations in temperature and humidity ceased during the cooling period, and began again with the return of bright sunshine.

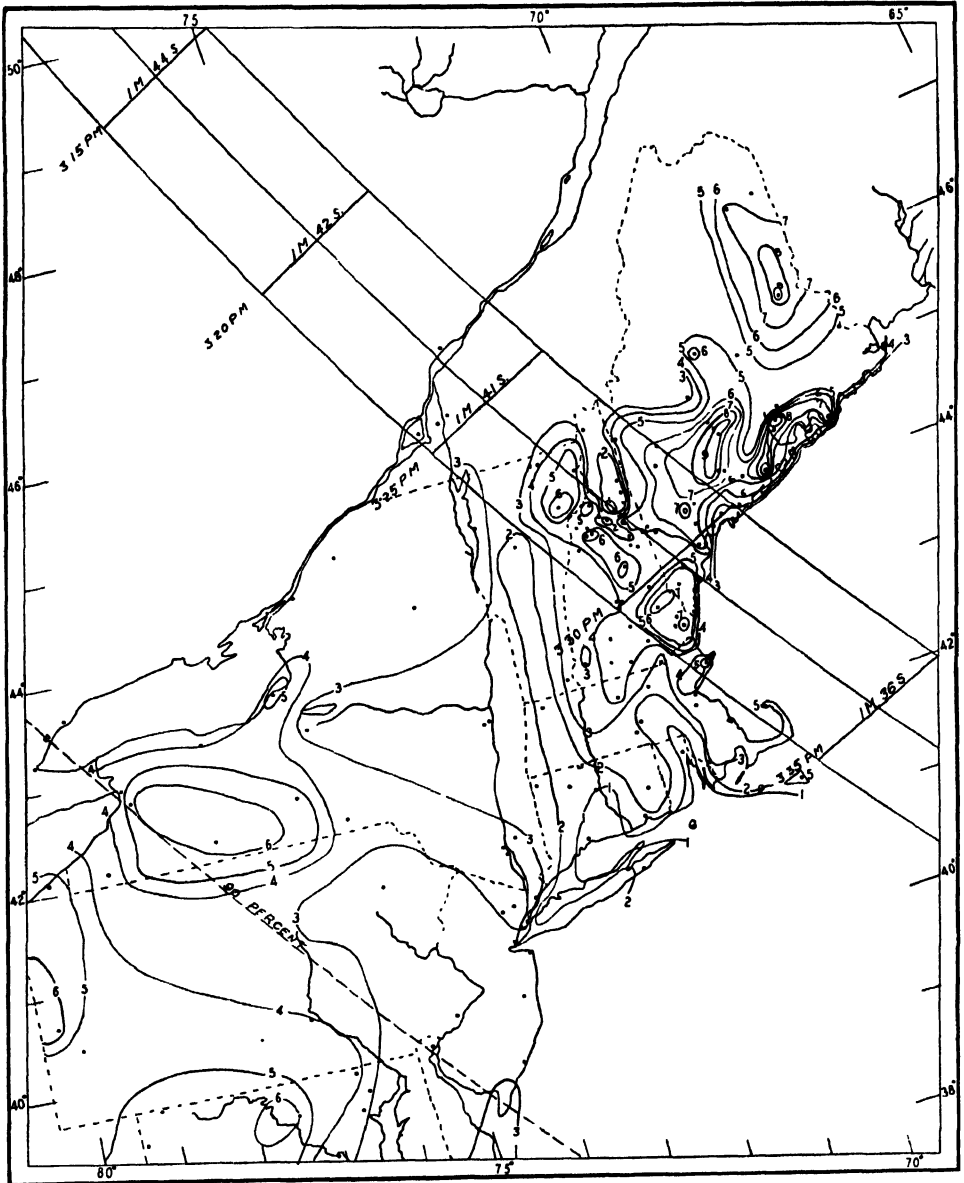


FIG. 11. Eclipse effect on temperature in the northeastern United States and part of Quebec, Aug. 31, 1932. Locations of 148 stations from which temperature data were used for this map are shown by dots. The path, times and durations of totality and the limit of 90% eclipse are from same source as in Fig. 1.

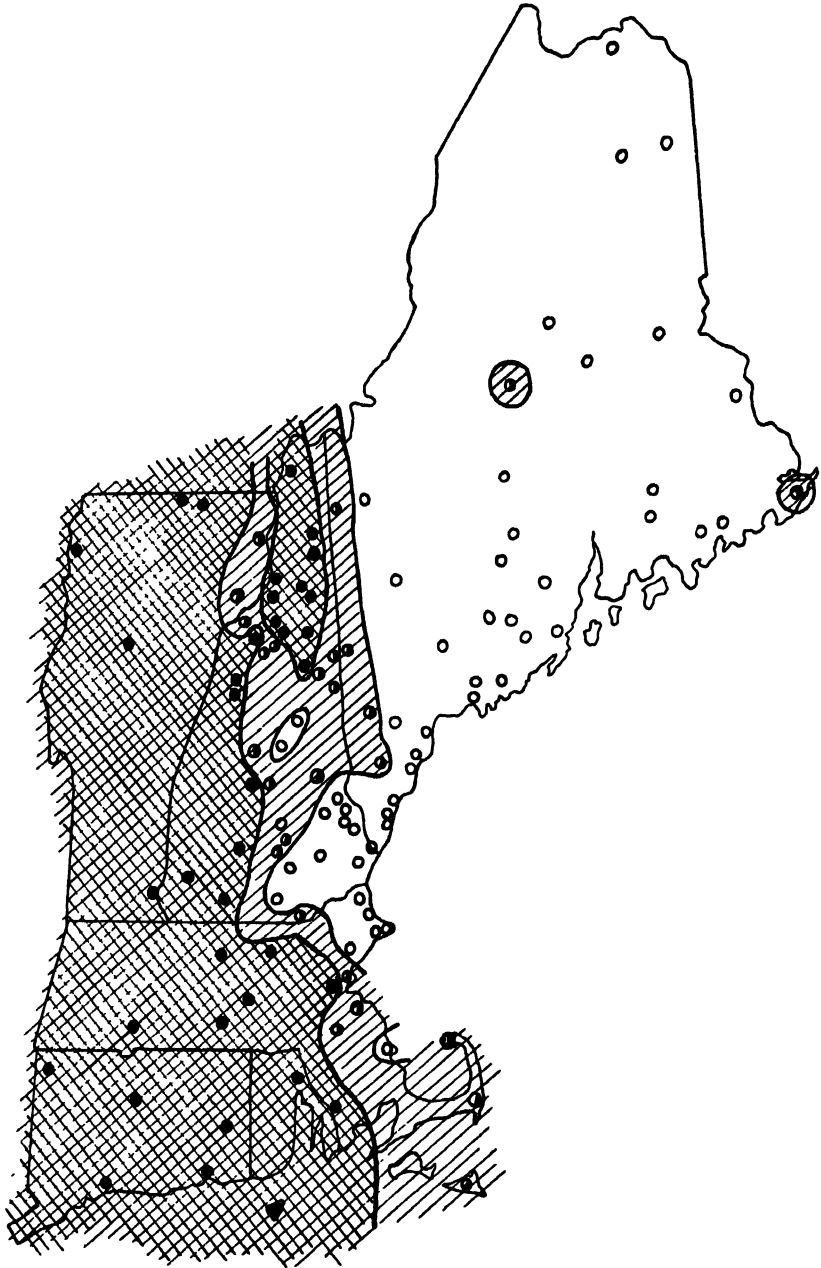


FIG. 12. Cloudiness in New England at the beginning of the eclipse of Aug. 31, 1932. Open circles — clear; half filled — partly cloudy; filled — cloudy.

having clear, calm weather in order that the eclipse effect may be most apparent.

Fig. 1 is a map of eclipse temperature falls throughout the U. S. and nearby Canada. Compare Fig. 1 with Fig. 3, and note how the cloudy low pressure troughs of the East and mid-west curtailed the fall in temperature. Fig. 11 presents more detail for the northeast; and Fig. 12 the concurrent cloudiness there.

D. *Zone and Cloudiness.* (F. S. B.) Of the total of nearly 300 temperature reports, 233 were used in computing the zone averages, the others not being employed on account of poor exposure, incompleteness, obvious inaccuracies, or because they represented special local conditions. For instance, the higher mountain stations and those having thunderstorms in progress were omitted from the general averages.

Table 5 gives the averages and absolute maximum of the eclipse effect by zones and by cloudiness for selected stations. The figures for zones in the far West where the sun was less than 40% obscured are doubtful because of the small number of stations and the questionable character of the results obtained. The eclipse occurred before the time of daily maximum temperature and so the effects usually were a reduction in the rate of rise of temperature and a lowered maximum temperature, both difficult to estimate. It may be noted that the 90-100% zone, A', in Maine, because of exceptionally favorable weather, shows both a higher average than the totality zone and nearly as large a maximum temperature effect.

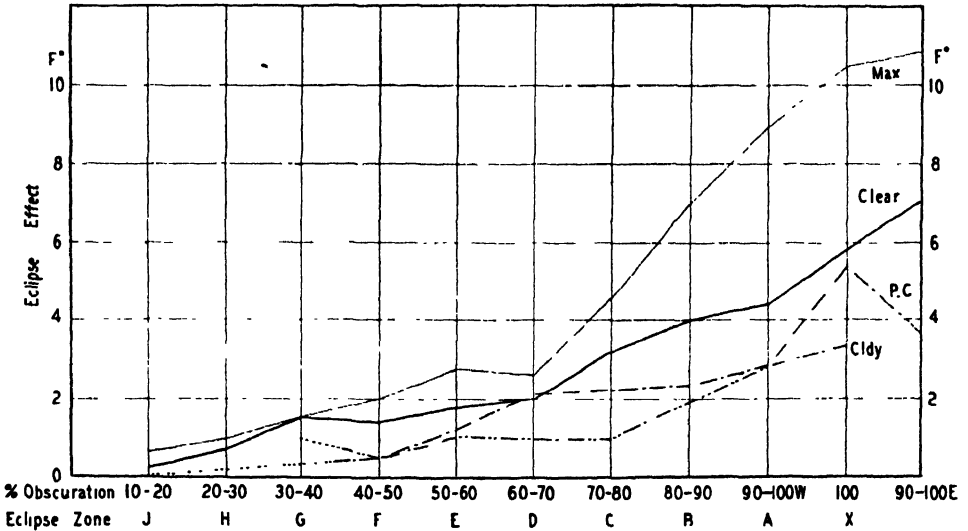


FIG. 13 Effect of the solar eclipse of Aug. 31, 1932 on air temperature according to percentage of maximum obscuration and amount of cloudiness. (Based on the data from 233 selected stations, summarized in Table 5)

TABLE 5. EFFECT OF SOLAR ECLIPSES ON AIR TEMPERATURE (See Fig 13)

ZONE	MAXIMUM OBSCURATION	REDUCTION IN AIR TEMPERATURE DUE TO THE ECLIPSE						
		MAXIMUM IN ZONE	AVERAGES ACCORDING TO CLOUDINESS					
			Clear	Partly Cloudy		Cloudy		
	%	F°	F°	stas.	F°	stas.	F°	stas.
a. Total eclipse of Aug 31, 1932. (Eleanor S Brooks.) (233 stas)								
A'	90-100 NE	10.8	7.1	(19)	2.7	(1)		(0)
X	100	10.5	5.7	(27)	5.3	(12)	3.3	(17)
A	90-100 SW	9.0	4.4	(19)	2.8	(11)	2.8	(24)
B	80-90	7.0 (10.0?)	4.0	(27)	2.4	(2)		(0)
C	70-80	4.5 (6.0?)	3.2	(11)	2.2	(10)	1.0	(2)
D	60-70	2.6	2.0	(5)	2.1	(8)	1.0	(9)
E	50-60	2.8	1.8	(5)	1.2	(4)	1.1	(2)
F	40-50	2.0	1.4	(5)	0.5	(1)	0.5	(1)
G	30-40	1.5	1.5	(2)	..	(0)	1.0	(1)
H	20-30	1.0	0.7	(3)		(0)	.	(0)
J	10-20	0.7 (?)	0.3	(4)	0	(1)	..	(0)
Maxima and totals		10.8	7.1	(127)	5.3	(50)	3.3	(56)
b Partial eclipse of Feb 3, 1935 (Edward M Brooks.) (19 stas)								
D	60-70	1.3	1.3	(1)		(0)	0.4	(1/2)
E	50-60	1.2		(0)	0.7	(1)	0.3	(1 1/2)
F	40-50	2.0 (?)	0.8	(2)	1.6	(2)	1.0	(6 1/2)
G	30-40	2.7 (?)		(0)	.	(0)	0.9	(4 1/2)
Maxima and totals		2.7 (?)	1.3	(3)	1.6	(3)	1.0	(13)

It is possible that the maxima in the upper part of this table are too large, for some are derived from the miscellaneous stations, which may not have employed standard practice in observing. The 10 F° maximum for zone A', however, is based on a reading of a sling psychrometer. The highest two values for the totality zone were 10.5° at Nauset Beach, Orleans, Mass., and 9.5° at York Beach, Me. At Nauset the thermometer (a \$1 store thermometer after a good one was broken) was whirled on a string about four ft. above the sand at the top of a sand dune. At York a precision thermometer was hung in the shade in a moderate wind. In both cases, the wind was at such an angle to the shore as to traverse about twice as much

sand as the width of the beach, which would favor unusually high temperatures before and after the eclipse. Theoretically (see p. 22, above), the temperature fall over sand might well have been more than 14°. The initial temperatures at Wells and Ogunquit, where sling psychrometer readings showed a 6.0° eclipse effect, were not so high, not being influenced by wind passing so far over sand. Table 5 and Fig. 13 show clearly that the amount of the eclipse temperature effect depends largely upon the degree of obscuration but is reduced by cloudiness.

On the other hand, the morning mid-winter eclipse of Feb. 3, 1935 showed very little eclipse effect and little contrast between zones or stations having different cloudiness (Table 5). But conditions were not favorable, for although 19 Weather Bureau stations kindly made detailed observations at the request of Edward M. Brooks only 4 had an obscuration of 50% or more and all but 6 experienced cloudy weather.

The eclipse effect was also small in the eclipse of Jan. 24, 1925, even though it was total and the weather more favorable. At all 12 stations it occurred very soon after sunrise and over a snow-covered terrain, (Varney, 1925, Fergusson, 1925). Observations were not made long enough before or after the eclipse to permit a truly satisfactory estimate of the eclipse effect by the curve method. The mean of fall and rise in temperature observed was taken as the eclipse effect. Even if we should raise our mean of these 8 stations having clear or partly cloudy skies from 2.6 to 3.0 F° to allow for this, the effect was hardly more than half that observed in the zone of totality in 1932.

Turning to the other extreme, it is interesting to compare the 1932 data with those from the Indian eclipse of Jan. 22, 1898, Table 6. Here a higher sun, with consequent direct solar radiation more than twice as intense on a horizontal surface as at totality in 1932, a longer duration of totality, and lack of artificial ventilation of the thermometers, should have favored the larger temperature falls shown.

TABLE 6. FALLS IN TEMPERATURE DUE TO THE ECLIPSE OF JANUARY 22, 1898, IN INDIA AND U S A
Compiled by Eleanor S. Brooks

OBSCURATION	REDUCTION IN AIR TEMPERATURE DUE TO ECLIPSE IN CLEAR WEATHER			
	India 1898		Eastern America 1932	
%	F°	cases	F°	cases
100	7.1	5	5.7	27
90-100	7.0	42	5.8	38
80-90	5.8	47	4.0	27
70-80	4.3	15	3.2	11

In the total eclipse of May, 1900, Clayton, 1901, found a mean temperature effect of 7.2 F° at three Blue Hill stations with Assmann or sling psychrometers, and Bigelow, 1902, obtained a temperature effect of 2 F° inside of shelters, averaging 60 stations. His 6 stations in the totality zone averaged 4 F° . Our curve method would have probably given figures 20% higher than Bigelow's mean of rise and fall. Bauer, 1919, in Liberia observed an eclipse effect of 3 F° in temperature and 10% in relative humidity at midday in a humid tropical climate: which suggests that the temperature effect is a function of atmospheric moisture as well as cloudiness. Wyatt, 1915, in Honolulu noted a 3.3 F° effect (mean of fall and rise), also at midday, but from a $2/3$ eclipse. Math, 1930, in Montana, found an 8 F° effect of a 95% eclipse at midday, and W. C. Jacobs¹ at Okanogan, Wash., Apr. 19, 1939, a 9 F° effect of an approximately 60% 8 a.m. eclipse, both in clear weather, which gives the contrast for a dry climate. A. E. Benfield,² at Ak-Bulak, and Orlov, Tretiakov, and Garkin, 1936, at Tomsk, U.S.S.R., observed a 5 F° effect of the total eclipse the morning of June 19, 1936 in partly cloudy weather. Lukachenko, 1940, at Svobodny, in clear weather, observed a drop of 11.5 F° from the beginning of the same eclipse at 2:40 p.m. to the minimum after totality.

E. Altitude; ground- and water-surface temperatures. (E. S. B., C. F. B.) 1. *Altitude.* Barlow, 1927a, states that "The temperature is confined to a very shallow layer not exceeding 300 or 400 meters above the earth's surface. At hill stations the fall is usually less than at low level stations, but the comparisons are not always consistent."

Towers, masts, and buildings may be counted on for a fairly accurate representation of the upward decrease in eclipse effect on temperature within 300 feet of the ground, though the structures themselves must have the effect of increasing the change in temperature during the eclipse. Seven sets of observations are presented in Table 7, and all but Fryeburg in Fig. 14.

These altitude comparisons show a considerable diversity. In most of these samples, the eclipse effect decreases 20 to 90% on buildings, towers, and masts. Other local factors besides altitude are involved. The Provincetown and Lakehurst towers, several miles down wind from the ocean, might be expected to present the least complicated contrast in altitude; however, at the top of the Pilgrim monument there was a peculiar dip in temperature at totality, and at Lakehurst a sea-breeze arrived 5 minutes after the maximum eclipse, and pushed the temperature at 10 ft. down about 1.6 F° while it was still falling as a result of the eclipse,—the eclipse minimum apparently coming 10 minutes later. At Seabrook Beach the

¹ Automatic record submitted in personal communication.

² Psychrometric record submitted in personal communication.

TABLE 7. ECLIPSE EFFECTS ON TEMPERATURE AT DIFFERENT HEIGHTS ON STRUCTURES, 1932

Place and cloudiness	Maximum obscuration	Structure	Height	Eclipse temp. effect
			above grd.	
	%		Ft.	F°
Seabrook Beach, N. H. ¹ Clear	100	Wood tower	40	2.8 ²
		Beach	4	5.8 ³
Fryeburg, Me. ⁴ Partly cloudy	100	Wood mast	100	2.0 ⁵
			75	2.7 ⁶
			50	2.0 ⁵
			25	6.1 ⁵
			5	7.1 ⁵
Lakehurst, N. J. ⁶ Partly cloudy	94	Steel mast	180	0.3 ⁷
			90	0.3 ⁷
			10	2.9 ⁷
Columbus, O. Clear	88	Office bldg. ⁸	216	2.8 ⁹
		Campus ¹⁰	4	4.5 ³
Buffalo, N. Y. ⁸ Clear	91	Office bldg.	248	3.0 ⁹
		Airport	185	5.0 ¹¹
Provincetown, Mass. ¹ Partly cloudy	100	Stone mon't.	250	3.8 ²
		Dune	4	4.7 ²
New York, N. Y. (Battery) (Central Park) (Sandy Hook, N. J.) Clear	95	Office bldg.	420	3.3 ⁹
		Lawn	6	2.0 ⁹
		Lawn	10	2.0 ⁹

¹ Blue Hill station
² Stationary thermometer in shelter
³ Sling psychrometer
⁴ Lee and Bryant, 1933 for data, eclipse effect by C.F.B.
⁵ Stationary thermometer in open shelter Probably 2.0 F° should be subtracted for long-wave radiation cooling effect, for observations at Fryeburg with a ventilated (Assmann) psychrometer (Milham, 1933), indicated an eclipse effect of 5.1 F° at 4 ft
⁶ Courtesy C J Maguire, U S Naval Air Station
⁷ Recording electrical resistance thermometer
⁸ U. S. Weather Bureau
⁹ Whirling psychrometer in shelter.
¹⁰ Obs. by Prof. Guy-Harold Smith
¹¹ Fanned thermometer in shelter.

observation tower stood so close to the shore that the air heated by the beach could not reach a height of 40 ft. before being blown inland. At New York, while both Central Park and Sandy Hook were rather directly affected by sea air, coming to the former from a long distance over the Sound, the Whitehall Building (south tip of Manhattan), 3.3 F° warmer than Sandy Hook, got air heated and then cooled over Long Island, from which direction its wind was coming.

Airplane observations indicate that in the free air the temperature effect may have reached more than 500 m (1600 ft.) but could not be traced any higher with certainty. See pp. 94-102, below.

Mountains. In the Indian eclipse a comparison of 4 hill stations with 5 neighboring plains stations showed a greater temperature effect at the hill stations, perhaps owing to more direct insolation. All had calm, clear weather.

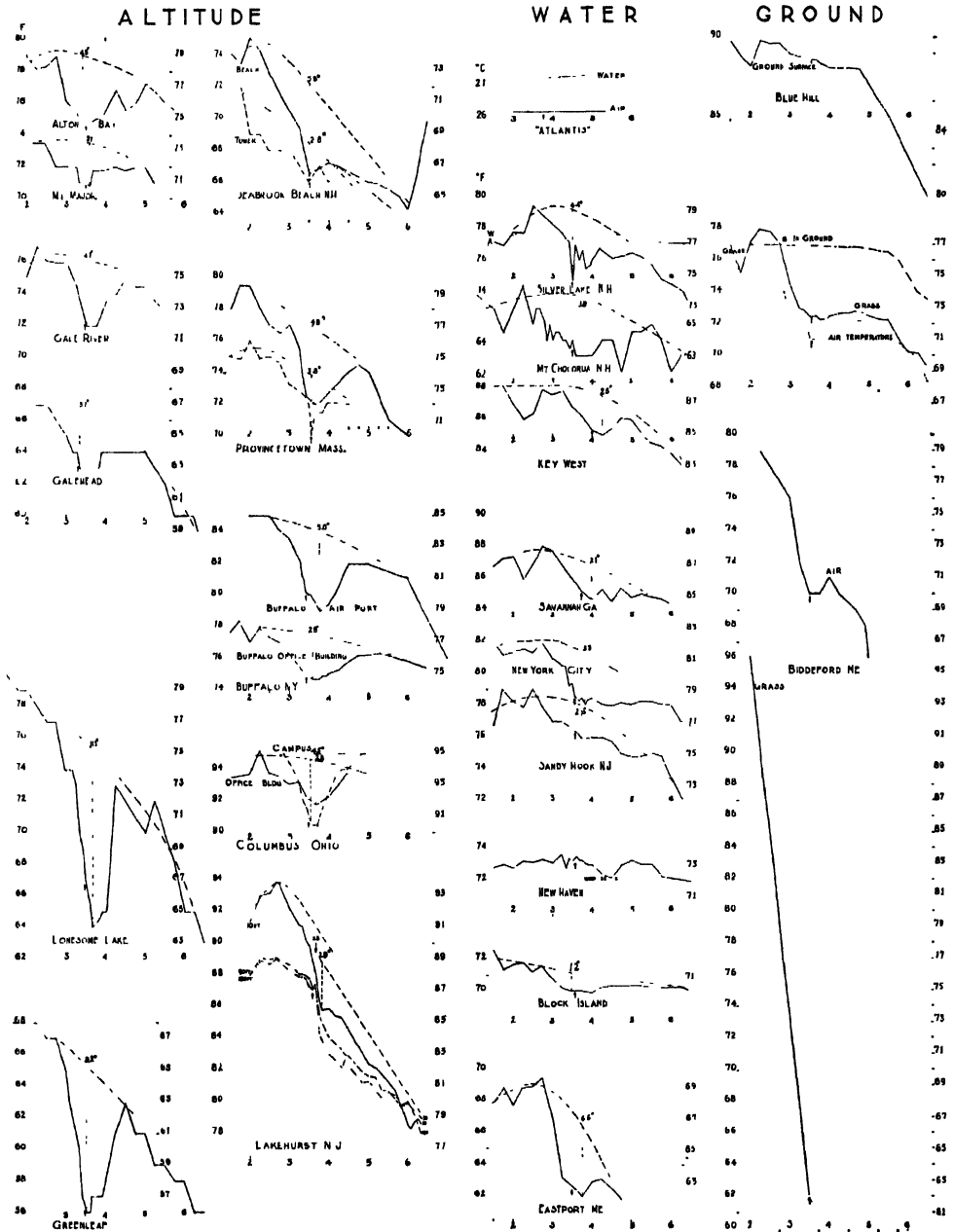


FIG 14 Altitude, water vs. land, and ground temperature contrasts in temperature effects of the eclipse of Aug. 31, 1932. "S.B." at Lakehurst indicates arrival of a sea-breeze. "W" and "A" at Silver Lake indicate water temp. at depth of 1 ft. and air temp. at 3-4 ft. above the surface, resp. See Table 7 and text. Small drop at New Haven and Block Island may be due principally to cloudiness

An altitude control is apparently exhibited in the eclipse data of 1932 by the several mountain stations, although the results in the White Mountains were impaired by cloudiness, making it impossible to distinguish between the effects of cloudiness and altitude. In general, the denser cloudiness occurred at the higher elevations, both controls thus operating to make the eclipse temperature-effect smaller there than on the lowlands (Table 8).

TABLE 8. TEMPERATURE EFFECT OF THE TOTAL ECLIPSE OF AUG. 31, 1932 AT DIFFERENT ALTITUDES, WHITE MTS., N. H.

STATION	BY ALTITUDE			STATION	ADJACENT PAIRS ²		
	ALT	CLOUD- INESS	ECLIPSE EFFECT		ALT	CLOUD- INESS	ECLIPSE EFFECT
	Ft		F°		Ft		F°
Mt. Washington	6270	Cloudy	0 ¹	Mt. Washington	6270	Cloudy	0
Lakes of the Clouds	5000	Cloudy	1	Pinkham Notch	2018	Cloudy	2.5
Madison Springs	4900	Cloudy	1	Mt. Lafayette			
Carter Dome	4900	Cloudy	2	(Greenleaf Hut)	4100	Pt. cl.	9.2
Galehead Hut	3900	Cloudy	3.5	Lonesome Lake	2700	Pt. cl.	11.0
Mt. Chocorua	3175	Cloudy	4	Galehead, N. H.	3900	Cloudy	3.5
Zealand Falls	2700	Cloudy	1.9	Gale River			
Pinkham Notch	2018	Cloudy	2.5	(near Twin Mt.)	1400	Cloudy	4.2
Gale River				Mt. Major, N. H.	1800	Pt. cl.	2.7
(near Twin Mt.)	1400	Cloudy	4.2	Alton Bay (near)	700	Pt. cl.	4.5

¹ A 3 F° fall and 1° rise was observed by S. P. Fergusson on the summit of Mt. Washington during and immediately after the 80-90% early morning eclipse of Aug. 30, 1905, but the strong NW wind (20 m/s) and cloudiness, as well as the fact that the fall in temperature had not been preceded by a rise in the hour and a quarter since sunrise, make it highly improbable that this change could have been owing to the direct effect of insolation on the summit, whether or not it was related to the eclipse through convection from the undoubtedly more affected air below. (From Ms record.)

² From Pikes Peak to Colorado Springs during a total eclipse in clear weather on July 20, 1878, at almost exactly the same time of day as the 1932 eclipse, namely 2 17-3 32-3 45-4 32 p m., the temperature changes, adjusted for diurnal course, and therefore strictly comparable with the "eclipse effect" of 1932, were 7.5, 12, 6, and 5.7 F° at Pikes Peak (14,108 ft.), Lake House (10,230 ft.), Manitou (6,300 ft.), and Colorado Springs (6,038 ft.), resp. Another pair, Old Baldy (9,572 ft.) and Virginia City, Mont., (5,810 ft.) had eclipse effects of 11.5 and 9.5 F° in clear weather, during the same eclipse (there 40 min. earlier) (Abbe, 1881).

Ground temperatures or air temperatures close to the ground were not generally recorded during the eclipse of 1932; only the few given in Table 9 and Fig. 14 were received.

It is evident that the change in ground-surface temperature is large but superficial, since the ground is a good absorber but poor conductor. The large difference between air temperature and that of the ground when there is bright sunshine leads to micro-fluctuations of temperature of appreciable size, while the smaller difference during the eclipse reduces these greatly.

Micro-fluctuations of temperature at 50 cm above the ground were recorded with a resistance thermometer by Orlov, Tretiakov and Garkin, 1936, at Tomsk U. S. S. R., before, during, and after the total of eclipse of June 19, 1936. During the 40 min. period centered on totality, the fluctuations were only 0.3 C° to 0.4 C°

TABLE 9. GROUND TEMPERATURES DURING AN ECLIPSE (1st five, Aug. 31, 1932).

LOCATION	SKY	ACTUAL FALL IN TEMPERATURE							
		Not Shaded						In Shade	
		Grass	Bare grd. surf.	Ground at depth of				Grd. surf.	Air
F°	F°	½ in.	2 in.	4 in.	6 in.	F°	F°		
Biddeford, Me . . .	Clear . . .	34	.	..	.	.	.	..	10
Wolfboro, N. H.	Clear-p c	30 ¹	.	.	.	.	.	7	..
Nantucket, Mass.	Clear . . .	32	.	.	.	.	.	.	6 ²
Blue Hill, Milton, Mass.	Cloudy (0.8).	5	7	1.7 ³	.	.	0.5	.	6.1
Montreal (McGill U.)	Cloudy	3	.	.	.	.	.	.	2.5
Santander, Spain ⁴	Clear?	.	.	7	.	1.5	0	.	.
Chlamosfino, Russia ⁵	Cloudy	.	3	1 ³	.	.	.	.	3.4 ¹¹
Tomsok, U.S.S.R. ⁶		.	23 ⁷	.	4.5	.	.	.	4-5
Svobodny, U.S.S.R. ⁸	Clear	.	38 ⁹	.	.	...	.	.	11.5 ¹⁰

¹ Not sure this was on grass² Two ft above grass³ Under thin film of soil⁴ Obs. by E J Lowe, at Santander, Spain, July 18, 1860, quoted by Barlow, 1927a, p 7.⁵ Upton and Rotch, 1888⁶ Orlov, Tretnikov, and Garkin, 1936.⁷ Depth 5 mm⁸ Lukachenko, 1940⁹ Sandy soil¹⁰ At 2 m above ground.¹¹ At 1 m above ground.

but before and after they reached 4.5 C°. The sky was cloudy, with breaks.

Water-surface temperatures, which change slowly, are less affected than land-surface temperatures by the decrease in solar radiation during an eclipse. Clayton, 1905, reports an air temperature fall of 1.5 F° measured over the open ocean on the *Otaria* in the totality zone, while a kite meteorograph record from the *Otaria* gave a fall of 1.1 F° 300 meters above the Atlantic. A report by G. Emmons from the *Atlantis* (35° 0' N, 71° 15' W), though, where the eclipse was nearly 90 per cent total, showed both air and water temperature steady within 0.06 C° throughout the eclipse. The weather was mostly calm. An Assmann aspiration psychrometer was used. Similarly, observations on a small shoal, 1 to 2 ft. deep in Silver Lake, N. H., failed to detect any change in water temperature 1 ft. below the surface due to the eclipse. The air temperature over this shoal, however, in variable breezes from the land, ¼ mi. distant, showed an eclipse effect of 4.4 F°. The weather was partly cloudy, the eclipse total at this point.

Like the altitude control, the purely marine control was often obscured by other factors; but it appears in four of the five groups in Table 10. To eliminate the considerable effects of cloudiness and diverse obscuration only those coastal stations having clear weather were chosen and these were grouped into zones according to 10% differences in obscuration. To make sure of a direct water influence on the temperatures of the coastal stations only those with onshore winds were used.

TABLE 10 ECLIPSE TEMPERATURE CHANGES IN CLEAR WEATHER AS AFFECTED BY WATER vs LAND

OBSCURATION	COASTAL		INTERIOR	
	%	F°	cases	F°	cases
"Blue Hill" stations (11 with sling or aspiration psychrometer)				
100	4.6	8	5.1*	6
Blue Hill and Misc non-Weather Bureau stations.				
90-100	5.1	11	6.4†	16
Weather Bureau stations mostly on high buildings (psy. whirled in shelter)				
90-100	4.1	6	4.5	5
80-90	4.1	6	3.5	13
60-80	2.3	2	2.6	14

* All stations pt. cldy.

† 5 stations pt. cldy.

One might reasonably expect a larger difference. The considerable height of the observation points, the location of the instrument inside the shelter, and the city location undoubtedly have much to do with the small contrast between the coast and interior Weather Bureau stations on a clear afternoon without much wind. Such points do not apply to the Blue Hill stations and other miscellaneous non-Weather Bureau stations, however. Nevertheless, not all the "coastal" stations were right on the shore, and even those which were may have been influenced by radiation, or air rising directly from the hot sand. Thus some eclipse effects of 6° or 7°, even 9° or 10 F°, were obtained at coastal stations. Inland, the falls were somewhat less, owing to cloudiness, than would have occurred had the weather been clear: so the real difference was greater than that shown in the first two lines of Table 10.

Variations in the eclipse temperature effect due to latitude, local initial temperature, or time of day were not satisfactorily shown by the records obtained.

Conclusion. The temperature effect of the 1932 eclipse diminished outward from the path of totality yet could be recognized with assurance as far as the zone of 40% obscuration. For clear stations in the zone of totality it averaged about 6 F° (max. over 9); in the 40% zone it did not exceed 2 or 3 F°.

This temperature effect was markedly decreased by cloudiness. Thus the area of greatest eclipse cooling did not coincide with the path of totality but occurred in the east, in Maine, where skies were clear, in contrast with the cloudiness elsewhere in New England.

From the surface to heights of a few hundred feet, observations on towers, masts, and buildings show a rapid decrease in eclipse effect. At higher altitudes the fall was generally less apparent, though greater on mountains than in the free air, where it could not be traced with certainty above 500 m.

Ground-surface temperatures in the sun fell at least 30 F°, and in the shade or at cloudy stations, 3 to 7°.

On the ocean, no eclipse decrease (in excess of 0.1 F°) could be detected in either air or water temperature. A fairly consistent though slight contrast between inland and coastal stations was evident, coastal stations showing the smaller temperature change.

IV. CHANGES OF PRESSURE AND WIND AT THE SURFACE

A. *Surface Pressure Changes.* (B.H., C.F.B.). According to Clayton, 1908, there are three chief maxima and two minima (see lower portion of Fig. 15). The maxima occur at totality and 75–90 min. before and after totality. The first minimum is 30–50 minutes before, the second, 20–40 minutes after, totality. These changes are very small, however, only some tenths of a millibar at most, and in any single record are difficult to find among other irregular oscillations.

1. *Pressure changes in different eclipses.* On particular occasions the behavior of the pressure has been quite diverse. At Chlamostino, Russia, 1887, there was a 0.1 to 0.2 mb fall, rise, fall, and rise superimposed on the general diurnal rise. According to Bigelow, 1902, no changes in pressure were observed at Weather Bureau stations during the total eclipse of May 28, 1900 which could be attributed to the eclipse with certainty. He thought that Clayton's results (Fig. 15), though more detailed than the Weather Bureau's, lacked the quantitative proof necessary to make them convincing. The stations in the East Indies eclipse of 1901 showed a wide variety of pressure curves. Kimball and Fergusson, 1919, found during the total eclipse of June 8, 1918, a decrease in pressure until the time of totality, then a rise (Fig. 15), conforming roughly with the normal diurnal course of pressure.

On the other hand, Lindholm and Bergsten, 1923, corroborate Clayton, recording the same type of pressure course in the eclipse of Apr. 8, 1921, (their Fig. 7, reprod. in Barlow, 1927a, Fig. 4). They calculate the theoretical change on the assumption that the temperature changed an average of 1 C° to an altitude of 400 m, and derive a value of 0.2 mb, which is of the same order of magnitude as that observed on the Shaw-Dines (20:1) microbarograph at Stockholm during the nearly total eclipse of April 8, 1921. During the eclipse of Jan. 24, 1925, Fergusson, 1925, with an open-scale barograph at Middletown, Conn., found a minimum of

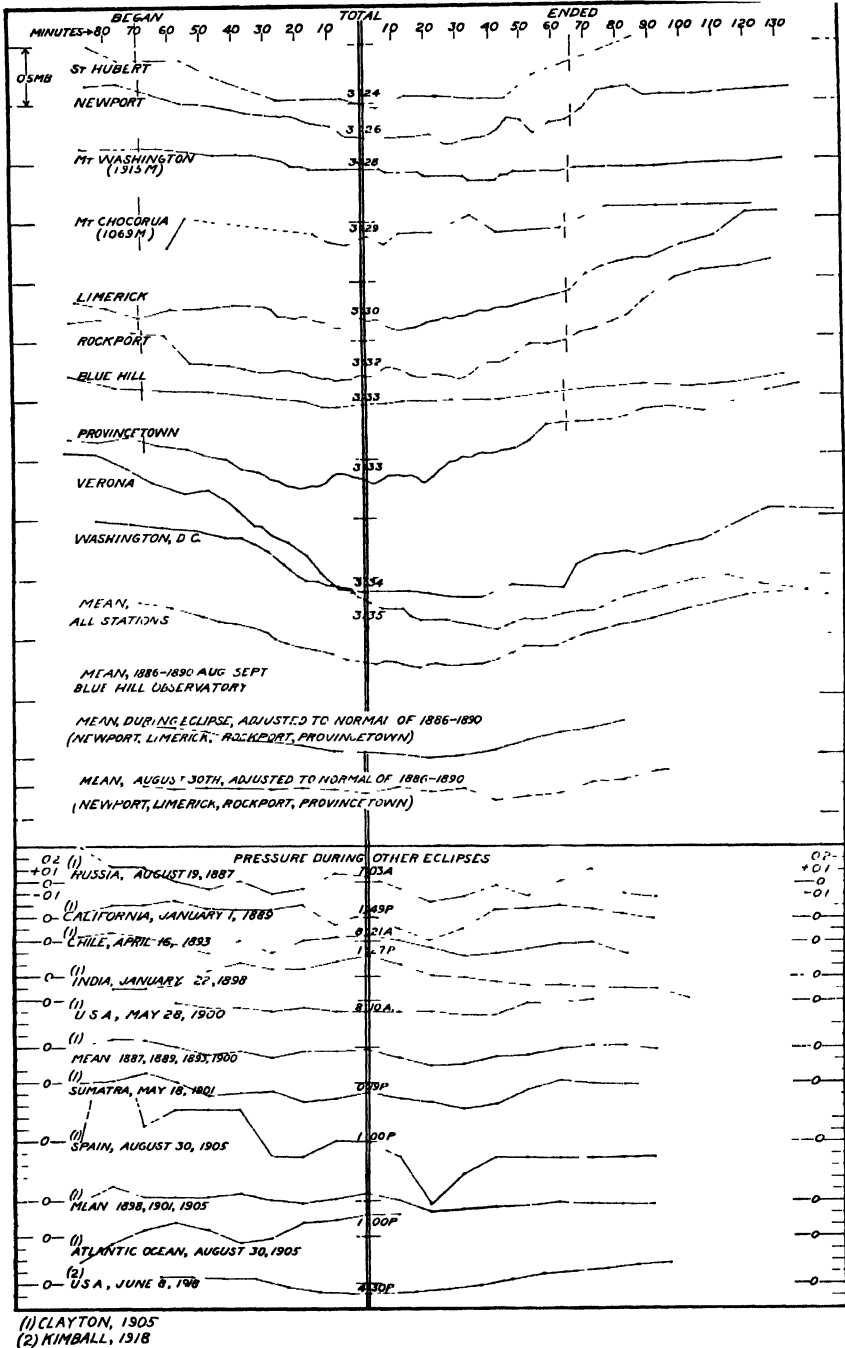


FIG. 15. Course of pressure during total eclipses: upper portion, Aug 31, 1932, including the very open scale records at Newport, Vt., Limerick, Me., Rockport and Provincetown, Mass., and Washington, D. C. (mean of two records on 5:1 syphon barographs); lower portion, pressure changes in various parts of the world. Plotted by S. P. Fergusson.

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−0.2 mb 40 min. before totality, and a maximum of +0.5 mb 10 min. before totality, and a minimum of −0.4 mb 50 to 60 min. after totality.

For the 1932 eclipse, graphs of pressure were drawn for 50 Weather Bureau stations where the eclipse ranged from totality to 80% obscuration. No consistent eclipse effect was apparent; but this is not conclusive, for the barometers were of rather small bore. Curves obtained from the open scale barographs were plotted in detail (Figs. 15, 16.) The fluctuations on the day of the eclipse were of no greater size than those of the previous day (Fig. 16); unfortunately, no open scale barograph happened to be located where a large fall of temperature occurred. The average of four open-scale stations still showed a low pressure, −0.3 mb, lowest at 20 min. after totality, after the normal diurnal course had been subtracted (middle of Fig. 15). When the average of the day before (Aug. 30) was similarly treated the pressure remained constant except for a slight sag after the hour when totality occurred the following day.

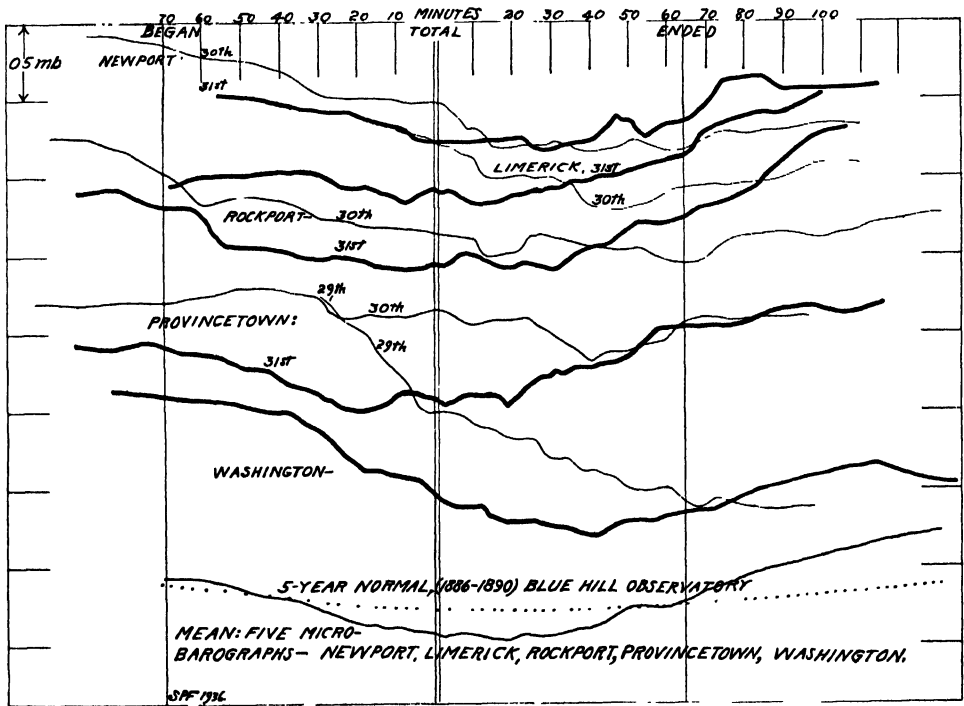


FIG. 16. Course of pressure from open scale barograph records at Newport, Vt.; Limerick, Me.; Rockport, Mass.; and Provincetown, Mass.—eclipse of Aug. 31, 1932 (heavy line) and on the day or two previous (light lines) — also pressure during the eclipse at Washington, D. C. (mean of two 5:1 syphon barographs), the average of all five stations during the eclipse, and Blue Hill normal course of pressure in the afternoon hours. Plotted by S. P. Fergusson.

2. *Theoretical discussion of eclipse effect on pressure.* There are two adequate causes of measurable pressure change due to an eclipse: the reduction of convective interchange between the winds of the free air and the friction-hindered air at the surface; and the fall in air temperature. The first results in a freer flow of the wind above the disengaged surface-friction layer cooled by the eclipse. This freer flow was observed in 1932, the 5 pilot-balloon stations averaging 0.3 m/s more at 200 to 2200 m from 3:40 to 3:50 p.m. (10 to 20 min. after totality) than before and after. This increase in velocity over the shadow causes an attenuation of the air, with consequent fall in pressure. The lowest pressure should come with the minimum of convection, which may be taken as the time when the wind velocity begins to pick up appreciably and the vapor pressure to fall. These in the 1932 eclipse came 25 min. after totality (cf. Figs. 17, 18, 20). So from this cause the pressure should have been lowest about 25 min. after totality. The observed minimum came at 20 min. in 1932, and 20–40 min. in other eclipses. It would occur a little earlier than this average of around 30 min, were not the small rise in pressure superimposed as a result of inflow aloft.

With regard to the second cause, we have already mentioned that the cooling is very much less a few hundred meters aloft than at the surface. According to the findings of the Concord airplane ascent during the 1932 eclipse (see Fig. 24, p. 100, below), the temperature drop could not be traced with assurance any higher than 600–700 m. Since a solar eclipse has such a short duration compared with the daily period, its effect must correspondingly decrease more rapidly with elevation, there being so little time for the cooling of the lowest layers to affect the temperature of the higher layers.

Clayton suggests that the 'eclipse cyclone' "can result to only a slight extent from the cooling within a few metres of the earth's surface, but is chiefly brought about by the small cooling of the body of the atmosphere," which he judges to be about 0.6 C° . This figure, based on a kite observation 300 m. above the ocean, seems too large, however, to apply to the upper atmosphere. The diurnal change due solely to radiation at levels of 1,000 m and above has been computed as only 0.6 C° . (cf. p. 101, esp. footnote 1). If this change takes place in 12 hours, cooling by radiation proceeding at a nearly constant rate at this elevation owing to practically unchanging temperature, the expected cooling during the one hour from the beginning of the eclipse to totality would be only about $0.6\text{ C}^\circ/12 = 0.05\text{ C}^\circ$.

We may make a rough estimate of the possible pressure and wind changes due to the cooling. Let the drop of the air temperature at the ground equal $-\Delta T_0$ and let the temperature remain unchanged at the height h . If we assume a linear

lapse-rate of temperature before and after the cooling we find that the mean temperature (T'_m) of the whole air column of the height h after the cooling is

$$T'_m = T_m - \Delta T_0/2$$

Let us further assume first that the pressure p at the level h remains unchanged, or, in other words, that an air column of the height h is replaced by a column of the same height but lower temperature.

The hypsometric formula is

$$P = pe^{\frac{g}{R} \frac{h}{T_m}}$$

where P is the surface pressure, T_m the mean temperature of the air column up to the height h . If we recall that under our assumption T_m and P are the only variables, we find by logarithmic differentiation

$$dP = - \frac{g}{R} \frac{h}{T_m^2} P dT_m$$

If we assume a temperature drop at the ground of $\Delta T_0 = 6^\circ\text{C}$, $T_m = 280^\circ$, $P = 1000$ mb, and the height of the air column affected by the temperature drop to be 800 m, we find a change in pressure of $+1.05$ mb (0.031 in.) at the ground. We should expect a smaller value if we consider our assumptions as probably more favorable for the occurrence of a pressure rise than is justified.

An average, based on tower and airplane observations (see Tables 7, 34), of 3.2°C for 0 to 10 m, 1.8° for 10–20 m, 1.1° for 20–30 m, 0.9° for 30–250 m, 0.7° for 250–500 m and 0.5° for 500–800 m, is but 0.7°C for the 800 m, or one-fourth of the $-\Delta T_0/2$ ($= 3^\circ$) assumed.

But if we assume an eclipse effect of 0.05°C , due to radiation (see p. 55, above), or, to be liberal, 0.1°C , to great heights above 800 m, even involving the entire 90% of the atmosphere above this level, the total effect of the eclipse on the atmosphere would be roughly equivalent to a change of 0.6 or 1.2°C in the lowest 10%, or 800 m, which is less than half the $-\Delta T_0/2$ assumed in the computation.

We should have found a smaller increase in pressure if instead of assuming that the pressure remains constant at the elevation h we assumed that the whole air column shrinks and sinks during the cooling process and that only a small amount of air flows in above the area of shrinking. Naturally, as soon as the air column is shrinking the air will flow in above, and consequently the pressure will rise at the ground. However, this rise will not continue after hydrostatic equilibrium is reached again. Since the moon's shadow travels at a high speed (across New England on Aug. 31, 1932 it was approximately 0.8 km/sec, or 1800 mi/hr), the wind will not be able to keep up with the cooling effect. Therefore, the rise in pressure

will be definitely less than the small amount computed above. The maximum pressure from accumulated inflow aloft is, naturally, to be expected at, or a few minutes after, the time of lowest temperature. But, since the heating and expansion make themselves felt before new convection resulting therefrom has a chance to make a good start, the fall in pressure due to decreased friction will continue after the rise in pressure due to inflow aloft has come to a stop. Therefore, the actual pressure peak of the rise superimposed on the longer-continuing fall is advanced to approximately the time of totality, as found in most previous eclipses (Fig. 15, and top of p. 54). In agreement with these considerations, a small fall in pressure averaging 0.3 mb, and a faint suggestion of a superimposed rise (of less than 0.1 mb) near totality is found in the mean of four open-scale lowland records in the totality zone Aug. 31, 1932 (Fig. 15).

B. Surface Wind. 1. *How strong a wind could the eclipse pressure gradient produce?* (B.H., C.F.B.) From our preceding discussion of the possible pressure rise it can be seen that any outward flow near the center of the shadow must be very small. With the velocity of the moon's shadow about 0.8 km/sec., if we take 70 min. as the time from first contact to totality, we find the distance between a point unaffected by the eclipse and a point in the center to be 3300 km, approximately. Of course, the rapid fall of temperature and therefore the appreciable change does not begin at the time of the first contact, but much later. Even if we assume that all the changes take place inside an area of not more than 1000 km radius, we should find a pressure gradient of only 0.105 mb/100 km. If ρ is the density of the air, $\omega = 7.29 \times 10^{-5}$ sec⁻¹, the angular velocity of the earth's rotation,

φ the latitude, $\frac{\delta p}{\delta n}$ the pressure gradient, the gradient wind for straight isobars is

$$v = \frac{1}{(2\omega \sin \varphi) \rho} \frac{\delta p}{\delta n}, \text{ which would be less than 1 m/s.}$$

It might be objected that the surface pressure distribution caused by a solar eclipse would consist of anticyclonic isobars rather than of straight ones. In this case, we have for the velocity, $v = r\omega \sin \varphi - \sqrt{(r\omega \sin \varphi)^2 - \frac{\tau}{\rho} \frac{\delta p}{\delta n}}$, where τ is the radius

of curvature. We find for the velocity in this case for a radius of curvature

r	500 km	200 km	100 km	50 km
v	1.0	1.0	1.1	1.3

The greatest velocity possible is $v_{\max} = r\omega \sin \varphi$.

If the pressure gradient is given, the radius of curvature for this maximum velocity

is $r = \frac{1}{(\omega \sin \varphi)^2 \rho} \frac{\delta p}{\delta n}$.

If we introduce the expression for the velocity for straight isobars, we find

$$r_{\max} = \frac{1}{(\omega \sin \varphi) \rho} \frac{\delta p}{\delta n} = 2 v_{\text{straight}}$$

Thus in the anticyclonic case the velocity can become no more than twice as great as in the case of straight isobars.

We have to take into account that all our considerations hold only in the case of gradient winds when steady conditions prevail, for in the latitudes of New England, where $\omega \sin \varphi \cong 10^\circ$ per hour, it would require 9 hours for a gradient direction 90° to the right to be attained in the absence of some local cause of deflection. But during a solar eclipse, the moon's shadow and therefore the cooling effect move rapidly and are continually affecting new masses of air. The masses cool, the pressure changes, and a small wind arises. Thus we can by no means expect a gradient wind. On the front side of the moon's shadow we shall have increasing winds, in other words, acceleration, and therefore the pressure gradient is balanced by the Coriolis term and the inertia term in the equations of motion, while in the gradient wind relation only pressure gradient and Coriolis term remain. Thus the eclipse winds, due to eclipse pressure gradients will be even smaller than the values estimated here. Finally, the influence of the surface friction and turbulence will further diminish their intensity, till an outward flowing eclipse wind of no more than a very small fraction of 1 m/s could be expected.

To check further these theoretical conclusions, wind velocities and directions were studied, not only in the 1932 eclipse, but also in the Indian eclipse of 1898, the United States eclipse of 1900, and the Borneo eclipse of 1901. Previous investigators, after factoring out the general wind, have reported a slight flow inward near the periphery, and outward near the center, of the shadow. Sometimes (as in Bigelow) a calm has been interpreted as a negative wind component opposite to the previous general wind, but this can be more simply explained as the usual decrease in velocity through the increasing effectiveness of friction as convectational interchange diminishes.

2. *Convectational changes in wind.* (C.F.B.) Since a solar eclipse makes a miniature night we naturally expect whatever winds may be blowing when an eclipse comes on, to change toward the nocturnal type for the place and prevailing weather, and after the eclipse minimum of temperature to return toward the daytime pattern if the eclipse ends before late afternoon. In other words, a general reduction in wind velocity and gustiness is to be expected, with a slight tendency for the direction to shift to the left (in the northern hemisphere) as the more deflected upper winds cease diving to the ground. On slopes the daytime wind upslope may be expected to weaken or cease, and perhaps to give way to the nighttime wind downslope. On coasts the sea-breeze should weaken, though, in the time involved, hardly

stop or give way to the land breeze. Such phenomena were noted in the eclipse of July 18, 1860, when at Aulezavik Is., northern Labrador, the squally W or NW wind of 5 to 10 mi/hr stopped showering, became less cloudy and died down nearly to a calm at totality, 9:15 a.m., with increase in velocity and cloudiness after totality. There was no systematic change in direction. In Washington Terr. in the same eclipse, there total at 4:48, only 18 min. after sunrise, a calm gave way to a very light air (prob. non-eclipse) (Supt. . . . , 1861).

An eclipse wind, if present, could be detected only after allowing for (1) any progressive change in wind direction, (2) any reduction in velocity and change in direction due to decreased convection, and (3) any local winds due to the cooling, such as air-drainage or a land-breeze. The chances of success seem remote, especially since according to a liberal estimate the eclipse wind is so light.

Wind changes, India, 1898. (E. S. B., C. F. B.) The Indian eclipse of January, 1898, occurred under such nearly perfect meteorological circumstances—cloudless skies, light winds, and high sun—and with so many stations (155) observing, that it should indicate an eclipse-wind if any could. Therefore the wind changes at the 98 cloudless stations were analyzed for convectional change in direction as well as for the well-known decrease in velocity, and also for a change in direction which might be expected from a tendency of air to flow outward from the central line of totality. Though 72 per cent of the stations showed the characteristic convectional decrease and then increase in wind velocity, and 40 per cent had a central period of calm, there was no systematic change in direction to the left with decreasing wind and later to the right with increasing wind (see Table 11 a). However, in such a low latitude the rotational deflection of the wind aloft could be but small. Also the majority of surface winds were so light that their directions were variable, having little relation to the gradient wind directions aloft. With the possible convectional change in direction not consistently toward the left, any change due to an eclipse pressure gradient should have been relatively conspicuous (see Table 11 b). Although there are a greater number of eclipse turns than anti-eclipse turns, especially in the inner zone, less than 1/3 of all the stations showed the eclipse turn.

Gusts, (E. S. B.) were reported in Labrador during the eclipse of 1860 (Supt. . . . , 1861), and during the Indian eclipse of 1898 (Eliot, 1899) and have been cited by Clayton, 1908, as evidence of an eclipse cyclone. The gusts were usually from the same direction as the general wind. The most extreme instance, that of 36 mi/hr at Buxar was marked questionable in the tabulated data for that station. It is difficult to see how gusts of over 10 or 20 mi/hr can possibly be attributed to eclipse changes in pressure—always extremely small. Such gusts occurred on that day not only during the eclipse period but also before and after. The gusts occurring between 12 and 1 o'clock (mostly in the first quarter) could hardly be attributed to the eclipse.

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TABLE 11. CHANGES IN WIND DIRECTION DURING THE SOLAR ECLIPSE OF 1898

a. Convictional influences

Eclipse zone	Period	No. of stas.	Convictional	No change	Anti-convictional
			To L. bef.; to R. aft		To R. bef.; to L. aft.
0-500 km from central line (cloudless stations)	1st hf.	61	% 38	26	% 34
	2nd hf.	61	20	56	25
	Average		29	41	29.5
500-1500 km from central line (cloudless stations)	1st hf.	33	18	45	36
	2nd hf.	33	30	61	9
	Average		24	53	22.5

b. Changes accordant with expectations of eclipse gradient

Eclipse zone	Period	Stas.	Eclipse turn	No change	Anti-eclipse turn
0-500 km from central line (cloudless stations)	1st hf.	61	% 43	% 29	% 28
	2nd hf.	61	28	62 ¹	10
	Average		35	46	19
500-1500 km from central line (cloudless stations)	1st hf.	33	24	52	24
	2nd hf.	33	21	61	18
	Average		22.5	56	21

¹ Many calms.

To examine further the character of the Indian gusts, we tabulated their occurrence during the four quarters of the eclipse. The data were not adequate to permit statistical comparison of the eclipse period with earlier and later hours of the day. A gust, a strong gust, and a very strong gust were arbitrarily defined as an increase in wind amounting to at least 5 mi/hr, 10 mi/hr and 15 mi/hr, respectively, and at least 50% of the previous velocity—comparing successive 5 min. averages. To be counted as a gust this increase must also be followed by a decrease amounting to half as much in the next 10 min.

Gusts were counted and classified at the 41 stations within 300 miles of the center line which furnished sufficiently detailed data: 25 (5/8) had no gusts accordant to the above definitions; the 16 remaining had 22 gusts distributed as shown in Table 12.

TABLE 12. DISTRIBUTION OF GUSTS BY QUARTERS OF THE ECLIPSE OF 1898

	1st	2nd	3rd	4th
Gusts	10	4	2	1
Strong gusts	2	1	0	0
Very strong gusts	2	1	0	0

This would seem to indicate merely an initial gustiness subsequently reduced by the decreased convection caused by the eclipse. Gustiness was not characteristic of the eclipse of 1932. However, Barlow, 1927b, describes a striking gust of 7–10 mi/hr (est.) breaking the calm about $\frac{1}{2}$ hr. after the beginning of the eclipse of June 29, 1927, in England. It appears that with the beginning of a virtual calm as the eclipse cooling stabilizes the lower air the occasional gusts that break through seem pronounced even though their velocity is appreciably less than pre-eclipse gusts.

Wind changes in the 1900, 1901, and other eclipses. (C.F.B., E.S.B.) For the early morning eclipse of May 28, 1900, in the eastern United States, wind data from 71 stations are available (Bigelow, 62, Clayton, 9). The clear, quiet weather was favorable. A well marked, though moderate, fall in wind velocity was observed at 47% of the stations, with, perhaps, a slight convectonal change in wind direction (toward the left); and a rise in the second half of the eclipse was noted at 60%. Both fall and rise occurred at only 38% of the stations; whereas, there was a central calm at 6%. It was too early for convection to be fully established.

A possible eclipse wind was factored out of automatic open scale records by Clayton. This "eclipse wind", however, includes the much more pronounced changes due to the slowing down of the general wind, resulting from reduced convection, and is centered upon the shadow rather than on the region of lowest temperature.

In the long, high-sun, midday eclipse over Sumatra and Borneo, May 18, 1901, the fall and recovery in wind velocity at 36 stations was pronounced. Van Bemmel, 1903, having just read Clayton's 1901 paper, looked especially for an eclipse wind, but failed to find it. The unexpected directions were not ascribable to a dying sea-breeze or to a light land-breeze replacing it, for the wind changes were quite diverse, even at stations close together, and appeared to hold no relation to the spot of greatest cooling.

The eclipses of 1905, 1918, 1921, 1925 and 1927 added little. The large, cross-country network in 1918 proved indeterminate on account of much local cloudiness. Kimball and Fergusson, 1919, did not find a definite circulation around the area of

minimum temperature, but only a general tendency for the wind to blow *towards* the shadow. The eclipse of 1932 presented another such opportunity, but, again, clouds interfered to a considerable extent. In the total eclipse of June 19, 1936 decreases to calm or nearly calm were widely noted.

Correctional changes in wind velocity during the eclipses of 1932, 1900, and 1898. (E.S.B., C.F.B.) were determined in the following manner: For each half of the eclipse the wind velocity was tabulated as decreasing (-), no change (no ch.), increasing (+), or calm (0); and the results summarized by sequences considering the two halves together. - 0 + means the wind died down to a calm as the eclipse passed and then sprang up again. - + is a similar decrease but not to a calm. These sequences are typical of an eclipse. For the 1932 eclipse, we have also added - no change, because in the latter part of the afternoon the wind is naturally decreasing and the expected rise after the eclipse may not be sufficient to offset this, especially when the wind is very light. These three sequences have been added together to give the percentage of stations showing a probable eclipse effect on wind velocity. The mean fall in wind velocity was about the same whether the direction turned left or right.

For the morning eclipse of 1900, no ch. + has been used instead of - no ch. because at this time of day the wind is naturally rising and the eclipse decrease in the first half would result in approximately no change. This tendency is apparent in Bigelow's curve of mean wind velocity. Compare Fig. 17 (C), for the 1932 eclipse.

The Indian eclipse occurred so close to midday (about 1:30 p.m.) that only - + or - 0 + stations were considered as showing an eclipse effect.

The data tabulated in this manner are presented in Table 13.

Fig. 17 (A) shows a composite course of wind velocity based on the automatic open-scale records from Newport, Vt., Brunswick, Me., Concord, N. H., Rockport and Provincetown, Mass., shown individually, in Figs. 2 and 18. The readings gave actual velocities at the time; hence the curve is not smooth. Since convection and its related wind velocity usually stay strong till after 4 p.m., we may take the pre-eclipse average, 2 to 2:30 p.m. to subtract mid-eclipse values from to get the eclipse effect, which here is about $2\frac{1}{2}$ mi/hr from slightly over 7.

Fig. 17 (B) indicates the azimuth for the same stations obtained from automatic records. A fair degree of parallelism between the two curves is apparent. A decrease in azimuth means a swing of the wind towards the left, the change to be expected with reduced convectational interchange.

In the composite course of average wind velocity at 18 ground stations, Fig. 17 (C), owing to the diurnal trend the rise in velocity after the eclipse is less pronounced than the fall preceding, the average reduction amounting to between $2\frac{1}{2}$ and 3 mi/hr from an initial velocity slightly over 5 mi/hr.

TABLE 13. CHANGES IN WIND VELOCITY DURING THE TOTAL SOLAR ECLIPSES OF 1932, 1900, AND 1898.

ECLIPSE ZONE		No OF STA.	APPARENT ECLIPSE REDUC. OF CONVECTIONAL MIXING				NO APPARENT ECLIPSE EFFECT	
Dist. from totality	By 10% of max. obsc.		-0+	-+	-no ch. no ch +	Total	00	All others

a. Eclipse of Aug. 31, 1932, U.S.A.

	A'	18	33	50	5	88	0	12
	X	59	17	42	12	71	2	27
	A	33	9	43	6	58	12	30
< 500	A'XA	110	17	44	9	70	5	25
> 500	B	15	0	47	0	47	0	53
	C	14	0	29	0	29	0	71
	D	15	0	40	0	40	0	60
> 1000	E	8	0	37	0	37	0	63
	F	4	0	0	0	0	75	25
0 to > 1000	All	166	11	41	6	58	5	37

b. Eclipse of May 28, 1900, U.S.A.

< 600		71	8	28	14	50	1	49
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c. Eclipse of Jan 22, 1898, India (cloudless stations)

< 50	X	9	56	33	11	100	0	0
50-400	A	44	50	34	9	93	0	7
400-1300		98	40	32	9	82	0	18
0-1300		151	44	33	9	86	0	14

For a group of 11 Weather Bureau stations, Fig. 17 (D), the average initial velocity is slightly higher, over 8 mi/hr, and the reduction less than in 17 A and C, between 1½ and 2 mi/hr. This may be due partly to increased distance from the eclipse and partly to the location of the observers in towns, frequently on tall buildings where the eclipse effect may be less than at the ground.

Bigelow's curve of the mean reduction of wind velocity at 61 Weather Bureau stations within 600 miles of the center of the shadow (Bigelow, 1902, chart 10) shows an eclipse effect, i.e., a reduction of 1.5 mi/hr below the rising morning value expected; but on account of the time of day the rise, 2.0 mi/hr, following totality is more pronounced than the fall, 0.4 mi/hr, preceding totality which is nearly balanced by the positive morning trend.

In studying the *changes in wind direction during the 1932 eclipse*, the data (see Fig. 18) were examined for any progressive change in the course of the eclipse. The

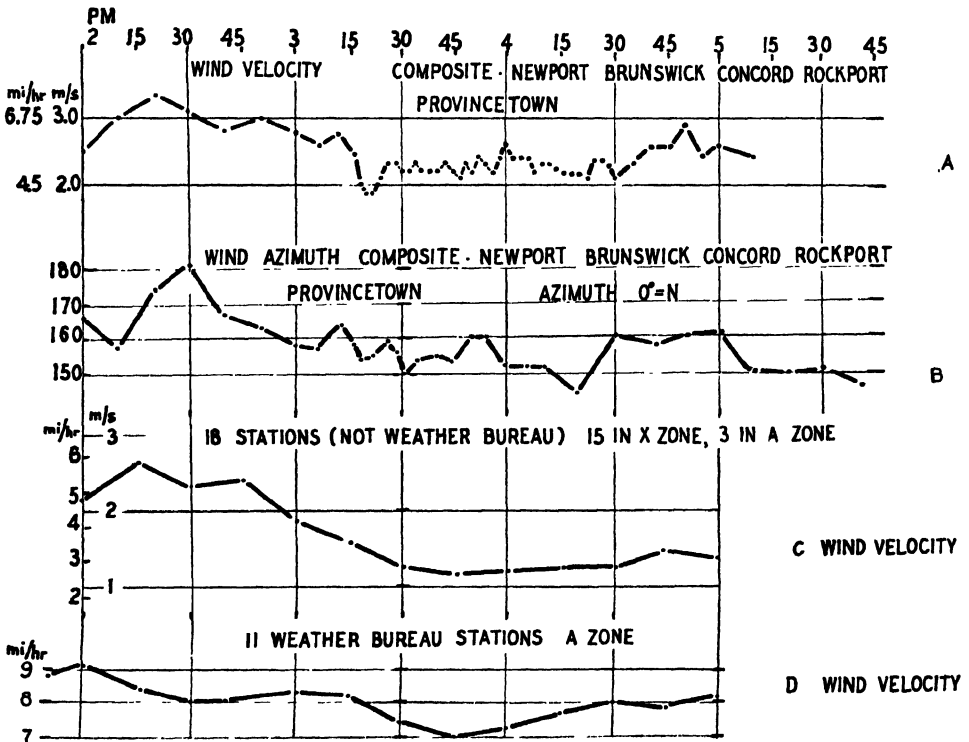


FIG. 17 (A) Composite course of wind velocity based on the automatic open scale records from Newport, Vt., Brunswick, Me., Concord, N. H., Rockport and Provincetown, Mass., during the eclipse of Aug. 31, 1932. (B) Composite course of wind direction (azimuth from north) for the same stations as (A) (C) Composite course of wind velocity at 18 ground stations, none of them Weather Bureau stations: 15 in the totality zone, 3 nearby in New York, in the 90-99% zone. (D) Composite course of wind velocity at 11 Weather Bureau stations in the 90-99% zone.

curve given in Fig. 17 (B) derived from the automatic records, indicates a decrease in azimuth or turn to the left. The course of the wind at other stations was tabulated as L (left), R (right), or NC (no change) by comparing the prevailing direction in the second half with that in the first half of the eclipse. Table 14 gives the results for the special stations alone and then for all stations by groups of zones. Turning to the left is fairly frequent in the case of the special stations, but is not well shown in general. Bigelow's curve of wind azimuth variations from means of 61 stations, reporting directions to nearest of 8 points, (Bigelow, 1902, chart 11), shows a left turn averaging about 6° and back in the half hour following the eclipse maximum.

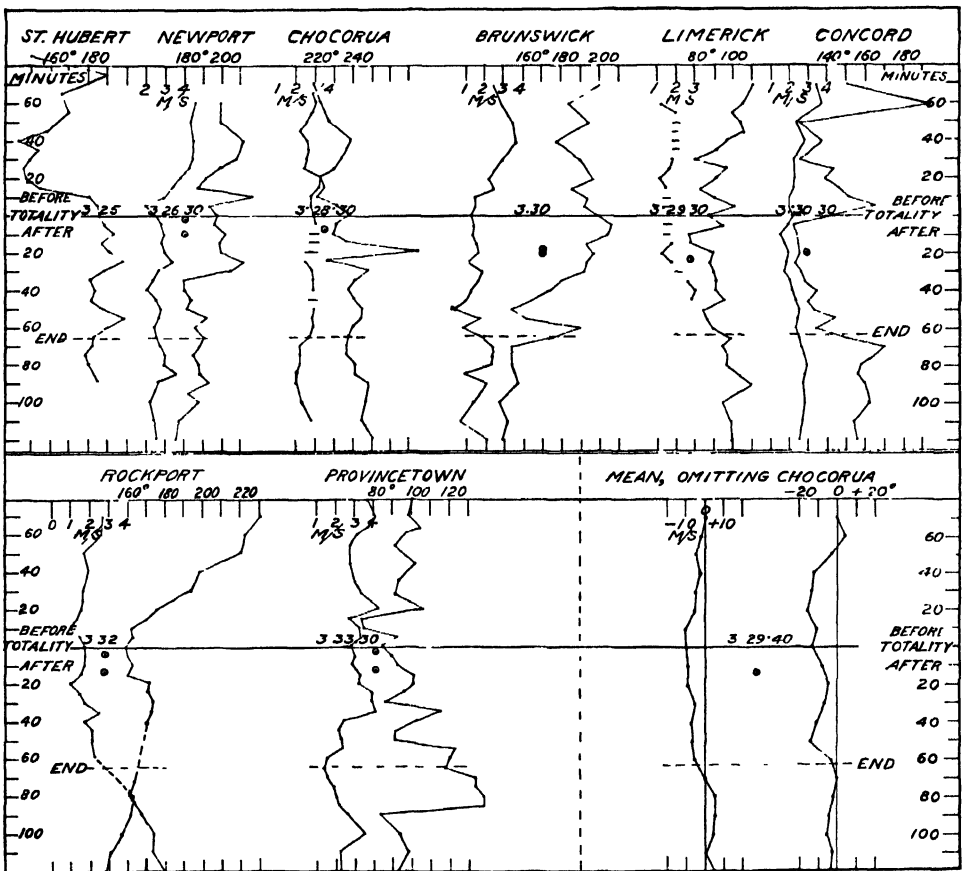


FIG. 18. Wind velocities (left in each pair) and directions (right) Aug. 31, 1932, from about the beginning of the total solar eclipse to two hours after the end of the eclipse. Directions in deg from N (=0). The circles with a dot in each mark the time or times of lowest temperature. Composites of 5 of these stations are shown in Fig 17 A & B. Copies of the original records at Rockport are presented in Fig 2, p 14. Computed and plotted by S. P. Fergusson.

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TABLE 14. CHANGES IN WIND DIRECTION DURING THE TOTAL SOLAR ECLIPSE OF AUG. 31, 1932: SECOND HALF VS. FIRST HALF.

STATION GROUP	No. of stations	To left	No change	To right
		%	%	%
All "special" lowland stations in zones X, A', and A	24	33	63	4
All stations with more than 4.0 F° eclipse change	78	31	43	26
All stations in zones A', X, A, B (incl. sev. mtn. stas.)	147	24	50	26
All stations in zones C to F	63	19	71	10

Fig. 19 shows the wind directions at frequent intervals during the eclipse at the 8 stations where very open scale records of wind direction were obtained. No consistent pattern of change with the approach and recession of the maximum phase of the eclipse is evident, except for the slight tendency to the left near totality.

Table 15 gives the results from 9 mountain stations in the totality zone and indicates that the characteristic decrease in velocity was experienced at 2/3rds of the stations, even at these upper levels, but there was little effect on wind direction. Mountain stations, notwithstanding their altitude, may still experience the effects of surface friction to some extent, and thus act somewhat like a lowland station. Consistent wind direction changes are not well shown except at ground stations with good equipment. Miscellaneous stations lacked facilities for accurate observations, while Weather Bureau stations were probably handicapped by urban location.

TABLE 15. WIND DIRECTION AND VELOCITY CHANGES AT MOUNTAIN STATIONS IN NEW ENGLAND DURING THE ECLIPSE OF AUG. 31, 1932, AT ALTITUDES OF 2700 TO 6200 FT.

DIRECTIONS			VELOCITIES						
L	NC	R	Apparent eclipse reduction				No apparent reduction		
			-NC	-0+	-+	Total	NC	NC	++	Total
2	6	1	2	1	3	6	1	2	3

The question arises, is this slight turning to the left at ground stations mainly a convectonal effect, or should it be regarded as an eclipse wind? There appear to be no consistent differences between stations on the opposite sides of the eclipse path.

Eclipse components derived by Clayton from our 1932 data in the usual way suggest, as for the eclipse of 1900, a cyclonic inflow in the outer portion of the shadow and an anticyclonic outflow near the center. Since, however, these include the large fictitious components equal and opposite to the decrease in velocity and change in direction due to reduced convection, we cannot accept them as significant.

3. *Possible eclipse winds according to pattern of temperature falls.* (E.S.B., C.F.B.)
 While our argument pp. 57-58, above, seems effectively to dispose of any general eclipse wind of more than an exceedingly light movement, it does not entirely do away with an eclipse wind of irregular pattern such as could arise from local differences in pressure owing to markedly differing eclipse effect on the temperature of a clear vs. a cloudy area nearby; a clear coastal plain vs. the sea; or a mountain region vs. the lowlands. In the 1932 eclipse the principal cooled area was in Maine, mostly east of the totality zone. The eclipse temperature map, Fig. 11, shows gradients of

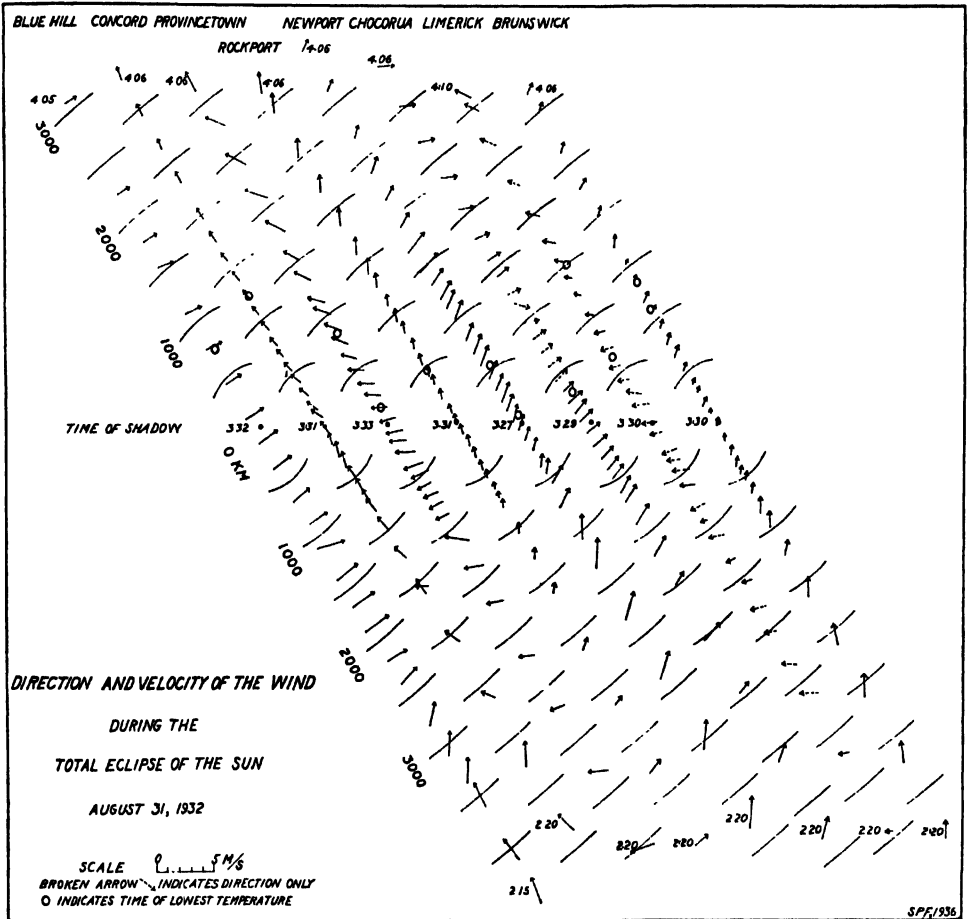


FIG. 19. Wind directions and velocities during the eclipse of 1932 with respect to distance and direction from the point of maximum eclipse. The times of the first and last observations plotted at each station are shown at the bottom and top of the diagram, respectively. North is toward the top; arrows fly with the wind. Thus an arrow pointing straight up represents a south wind. Plotted from automatic records by S. P. Fergusson.

temperature change between clear or partly cloudy and cloudy areas of 2 to 3.5 F° in 20 mi., while between land and sea the rate is much steeper, even 5 F° in 3 or 4 mi.¹

These, under Dr. Haurwitz's assumptions, would result in pressure gradients which are much greater than the general eclipse gradients entering into his calculations. But the depth within which these differences in short distances would obtain would be less than those included in the calculations. The high pressure which should result over the most greatly cooled area could then not produce more than a small fraction of the gradient velocity, which, in the absence of other turning, would take nine hours to develop in this latitude; and, owing to friction, such wind as would be produced could be but half the free-moving value. So, even with our steepest local gradients, the eclipse wind should be very small, though perhaps observable.

Following these principles we have computed the direction and rate of temperature change gradients for the 9 Blue Hill stations in Zones X and A which showed most definite changes in wind direction (8 left and 1 rt.). In every case the recorded change indicated an outflow from an eclipse cooled area. The winds were generally light and the eclipse component where it could be computed did not exceed 2 m/s (our computed maximum). Classifying the same winds in accordance with the position of the eclipse path, however, gave indifferent results. Three were outflows, 3 inflows, and 2, in the middle of the path where there was no eclipse component, turned but slightly.

It is unfortunate that circumstances were such that in every instance but one the eclipse components, based on cooled areas, like the convective factor, favored a left turn.

Table 16 shows the convective and eclipse factors for 19 stations² in the totality zone, and a group of 25 miscellaneous stations. In Maine we have less complete records, but clearer skies and a better chance to see convective decrease and theoretical eclipse flow pulling in opposite directions. Either decrease in wind velocity or decrease in low clouds is taken as evidence of decreased convective mixing; usually they occur together. The convective control might be expected to be strongest where the weather is fair, i.e., clear or partly cloudy, which is the case to a certain extent. Where there is a definitely established sea breeze, a change in wind direction is less likely.

The 8 left turns at the totality zone's 19 special stations accord with both convective (except in one instance) and eclipse factors. Which is the real control, or

¹ See Table 28 and large local differences in the White Mountains, Fig. 11.

² The stations selected are the Blue Hill stations (omitting mountains) and three others with detailed instrumental observations.

TABLE 16. OBSERVED TURNS IN WIND DIRECTION COMPARED WITH TURNS EXPECTED FROM REDUCED CONVECTIONAL EXCHANGE AND FROM PROBABLE DIRECTION OF A PRESSURE GRADIENT THAT SHOULD ATTEND THE OBSERVED GRADIENT OF TEMPERATURE-FALL DURING THE ECLIPSE OF 1932

NO. OF STATIONS WITH SKY			OBSERVED TURN		CONVECTIONAL DECREASE			ECLIPSE GRADIENT FAVORING TURN		
Clear	Pt. cldy.	Cldy.	Dir	No. of stas.	Occurred, so L. turn expected	None, so no turn expected	Left	No	Right	
Zone X: 19 special stations (incl. Alton, Bartlett and Twin Mtn)										
4	2	2	Left	8	7	1	8	0	0	
3	1	4	None	8 ¹	6	2	5	2	1	
0	1	2	Right	3	3	0	2	0	1	
Zones A' and X: 25 miscellaneous stations in Maine										
8	1	0	Left	9	8(+1?)	1(?)	2	2	5	
10	4	0	None	14 ²	9	5	7	2	5	
2	0	0	Right	2	2	0	0	0	2	

¹ Includes 3 cases with sea-breeze

² Includes 2 cases with sea-breeze.

do both operate? In Maine, the eclipse gradient indicated 12 right turns among the 25 stations, but only 2 right turns were reported. The eclipse gradient called for 9 left turns; in only two of these cases were left turns observed. Convectional decrease favored 19 left turns; 9 occurred. Probably the number of stations listed as without a turn is too large, particularly in this Maine miscellaneous group, for without instrumental observations, small changes in wind direction are less likely to be noted. The decrease in cloudiness or a drop in wind velocity, which are taken as indications of convectional decrease, are more easily observed. Thus we may have too many instances of convectional decrease without a corresponding left turn. Also an eclipse gradient may be operating without a turn being recorded.

Of the 44 stations, taking only those 8 cases in which the convectional effect was apparently lacking, the eclipse gradient was satisfied in the single case in which a turn occurred. In the other 7 cases, whatever eclipse tendency to turn to the right or left there may have been, no turn was observed.

It may be recalled that Bigelow's average curve of wind azimuth showed a left turn shortly after totality. Left turns were apparently more frequent than right in both the eclipses of 1901 and 1932. It seems, therefore, that change in convectional mixing is probably the major factor in any changes of wind direction during an eclipse.

Summary of Pressure and Wind

There are pressure changes during eclipses which should be due in part to the eclipses. These often take the form of a general fall and recovery, interrupted by a rise and fall centered on or near maximum eclipse, as pointed out by Clayton. In the eclipse of 1932, the course of pressure (av. of 4 open-scale barograms in totality zone corrected for progressive and diurnal changes) was a fall and rise of 0.3 mb, with minimum 20 min. after totality, a feature explainable by the attenuation of the air as the wind moves more rapidly over the eclipse shadow, where it is released from convectational retardation. A very slight rise, centered on totality, also appears, due to inflow aloft owing to the sinking of the surfaces of equal pressure over the cooling and shrinking air, which, in combination with the pressure fall in progress, advances the time of maximum to totality, or several minutes before the time of minimum temperature. Systematic wind changes observed at the surface can mostly be accounted for by the reduced exchange between the surface and the free air owing to the decrease in daytime convection resulting from eclipse cooling (see Table 17). The expected pattern of outflow from the most cooled areas, not necessarily in the zone of totality, may be present, though unfortunately, so obscured by the convectational effect, as to be very difficult to find.

TABLE 17. SUMMARY OF ECLIPSE EFFECTS ON WIND.

ECLIPSE	WIND VELOCITY AFFECTED?	CHANGE IN DIRECTION	
		Convectational	Eclipse
India, 1898	yes	no	yes
U. S. A., 1900			
Bigelow	yes	yes?	no
Clayton	yes	...	inconclusive
Borneo, 1901	yes	..	no
U. S. A., 1918	?	...	inconclusive
U. S. A., 1932	yes	yes	inconclusive
U. S. S. R., 1936	yes	...	...

V. HUMIDITY, CLOUDINESS, SHADOW-BANDS

A. Changes of Relative Humidity at the Earth's Surface. (E.S.B., C.F.B.) The rise in relative humidity occasioned by a solar eclipse, since changes in absolute humidity are small, is largely a function of the temperature, as has long been recognized. In the total eclipse of 18 min. after sunrise July 18, 1860 in Washington Terr., a light fog formed at sunrise and heavy dew continued to accumulate (Supt. . . . 1861). In general, the greater the temperature fall the greater the rise in relative humidity.

In the eclipse of August 31, 1932 there was found, as usual, a fairly regular gradation of increasingly large changes in relative humidity with increasingly large falls in temperature (Table 18).

TABLE 18. RISE OF RELATIVE HUMIDITY WITH FALL IN TEMPERATURE
DUE TO THE SOLAR ECLIPSE OF AUGUST 31, 1932

ECLIPSE EFFECT ON		CASES
Temperature	Relative Humidity	
F°	%	
<i>From sling or whirled psychrometer observations</i>		
0-1	1.8	3
1-2	2.6	15
2-3	4.4	25
3-4	5.9	23
4-5	9.7	19
5-6	9.9	8
6-7	10.0	4
7-8	12.0	1
<i>From thermohygrograph records</i>		
7-8	9.0	3

The relative humidities for all but the last line of Table 18 were computed from observations of whirled or sling psychrometers, and curves for each of the 98 stations were plotted. The departure from a hypothetical curve for the day was estimated, as in the case of temperature. The automatic records were replotted, then treated in the same manner.

A rise of 12-13% in relative humidity (by Assmann asp. psy.) was noted during the total eclipse of June 19, 1936, at Tomsk, U. S. S. R., by Orlov, Tretiakov, and Garkin, 1936, even though the air temperature fell only 2 to 3 C° (3.6-5.4 F°).

Since the fall in temperature was related to the degree of obscuration of the sun, we find that the rise in relative humidity also exhibits an eclipse-zone pattern (Table 19).

TABLE 19 RISE IN RELATIVE HUMIDITY DUE TO THE ECLIPSE OF AUG. 31, 1932, BY ECLIPSE ZONES,
FROM OBSERVATIONS WITH SLING OR WHIRLED PSYCHROMETER

Maximum Degree of Eclipse	Mean rise of Relative Humidity	Cases
%	%	
100	7.3	29
90-99	6.2	27
80-89	5.5	18
70-79	3.9	24

The relative humidity was usually highest shortly after the maximum eclipse, when the temperature was lowest. In some instances, as has previously been noted (cf. Upton and Rotch, 1888), dew formed on grass or other exposed surfaces, the

temperature of which fell 30 F° or more in the X zone (cf. Table 9, p. 50). Shadow-band sheets were very moist, even "wringing wet with dew."* The probable slight increase in vapor pressure (see below) after totality would also be a factor in the rise in relative humidity.

B. Absolute Humidity (Vapor Pressure) Changes at the Surface. 1. Earlier results; theory (B. H.). While the temperature minimum lags somewhat behind the time of totality, the absolute humidity usually has a minimum coinciding with the time of totality, though, probably, we should consider the subsequent maximum as representing the culmination of the eclipse effect. In a compilation from numerous eclipses, Clayton, 1908, found a maximum vapor pressure (representative of absolute humidity) 30 to 50 minutes preceding totality, a minimum at the observation nearest totality and a second maximum after totality. Since this course was observed not only on the ground but also in the free air at 300 m., Clayton ascribed it to the descent of drier air at the time of totality. The coincidence of the minimum of vapor pressure with the time of totality can, according to Albrecht (Süring . . . , 1934), be explained in the following way, however. The absolute humidity, and therefore the vapor pressure, depend essentially on the evaporation from the surface of the earth or whatever surfaces give moisture to the air (e. g., plants). The temperature of these surfaces follows directly the heat balance so that the evaporation and therefore the vapor pressure must follow closely the radiation intensity. Thus, with diminishing radiation intensity, the amount of water evaporated decreases and may not be sufficient to replace the moisture still transported even by the reduced convection to higher regions by mass exchange. Furthermore, a settling and mixing of drier air from aloft may help reduce the moisture. Only with increasing evaporation after totality does the vapor pressure rise again. Neither explanation accounts for the maxima before and after totality. This point will be considered later.

2. The changes in absolute humidity due to the eclipse of 1932, 1898, and 1900 (E.S.B.) were more irregular and difficult to evaluate than the obvious rise in relative humidity. The results of the Indian eclipse of 1898 showed a rapid increase of vapor pressure during the second half of the eclipse followed by a marked decrease, the total variation equalling 20 to 50% of the mean vapor pressure for the day. Unfortunately, the observations on which these conclusions were based are open to objection, as Clayton has pointed out, the readings having been made from stationary wet and dry thermometers. The marked decrease in wind velocity during the eclipse would reduce the rate of evaporation from the wet bulb, and hence the difference in reading between the two, producing an artificially large apparent increase in vapor pressure.

* Reported to A. C. Maury by Mrs. Hobbs, Kennebunk, Me.

For the eclipse of May, 1900, Bigelow, 1902, computed vapor pressure from observations of whirled psychrometer for 61 stations divided into groups according to their distance north or south of the path. He stated that the groups show very great irregularity. The mean curve (61 stations) indicated a "decrease of the vapor tension of about 0.01 inch at the time of the maximum cooling . . ." (p. 40). His curve showed a fall of about 0.005 in. from 15 min. before totality to a few min. after, then a gradual rise of about 0.010 in. the following hour.

The results of the eclipse of 1932, based on psychrometer observations with readings to 0.1 F.°, also gave widely varying curves. Maximum departures in mid- or late eclipse were measured from a line joining the prevailing before and after eclipse values. Table 20 presents these changes tabulated with respect to the temperature effect. Table 21 is the same, tabulated according to zones of maximum obscuration.

TABLE 20. CHANGE IN VAPOR PRESSURE GROUPED ACCORDING TO THE CHANGE IN AIR TEMPERATURE DUE TO THE TOTAL SOLAR ECLIPSE OF AUG 31, 1932

TEMPERATURE CHANGE	PERCENT OF STATIONS WHERE VAPOR PRESSURE			ALGEBRAIC MEAN CHANGE IN VAPOR PRESSURE	CASES
	Increased	Did not Change	Decreased	In. Hg.	
F deg	%	%	%	In. Hg.	
0-1	67	33	0	+0.022	3
1-2	47	33	20	+0.007	15
2-3	56	20	24	+0.007	25
3-4	61	0	39	+0.006	23
4-5	52	5	43	+0.021	19
5-6	50	12	38	+0.005	8
6-7	33	0	67	-0.011	3
7-8	0	0	100	-0.042	2

TABLE 21. CHANGE IN VAPOR PRESSURE BY ECLIPSE ZONES, 1932.

MAXIMUM OBSCURATION	PERCENT OF STATIONS WHERE VAPOR PRESSURE			ALGEBRAIC CHANGE IN VAPOR PRESSURE	CASES
	Increased	Did not Change	Decreased	In. Hg.	
%	%	%	%	In. Hg.	
100	50	10	40	+0.005	29
90-99	55	4	41	+0.001	27
80-89	55	11	34	+0.011	18
70-79	54	30	16	+0.019	24

It will be noted that there is no orderly sequence in the amount of the vapor-pressure change, and that, although the resulting average is usually plus, hardly more than half the stations show a plus departure.

3. *Vapor-pressure changes from quarter to quarter during the eclipses of 1932 and 1900.* (E.S.B.) In an attempt to gain more consistent results another method of analyzing the data was tried. The two-hour eclipse period was divided into four quarters of $\frac{1}{2}$ hour each. For each period the trend of vapor pressure was tabulated as plus, no change, or minus.

Table 22 shows for each quarter the percentages of stations with plus and minus vapor-pressure trends. (The number of cases is three less than in the preceding tables because not all stations had data for all quarters.)

TABLE 22. PER CENT OF STATIONS WITH PLUS OR WITH MINUS TREND OF VAPOR PRESSURE DURING EACH QUARTER OF THE SOLAR ECLIPSE OF AUG. 31, 1932.

MAXIMUM OBSCURATION	QUARTER OF THE ECLIPSE				CASES
	First	Second	Third	Fourth	
%	%	%	%	%	
		<i>With plus trend</i>			
100	43	46	71	46	28
90-99	44	48	56	52	25
80-89	55	55	72	33	18
70-79	29	67	63	40	24
70-100	43	54	65	43	95
		<i>With minus trend</i>			
100	57	50	22	39	28
90-99	48	32	28	28	25
80-89	33	29	11	44	18
70-79	60	25	25	50	24
70-100	45	38	22	40	95

A tendency for the vapor pressure to rise in the third quarter, that is, just after totality, is apparent, especially in the zones of 80-89% and totality.

To test further the matter of a rise of vapor pressure just after totality a composite curve (Fig. 20) was made from records at the 15 ground stations (13 in the zone of totality and two in the 90% zone) which we believe furnished the most complete and careful records. There are 19 points during the time from 2 to 5 p.m., $1\frac{1}{2}$ hours before to $1\frac{1}{2}$ hours after the maximum of obscuration. This curve shows a fall of about 0.008 in. (0.3 mb) to the time of totality followed by a rise of perhaps 0.018 in. (0.6 mb) within a half hour. To what extent the fall is related to the eclipse is uncertain. Table 22, above, shows plus trends to be generally more frequent than minus in the second quarter. The daytime minimum of vapor pressure

at inland stations occurs in mid-afternoon, the maximum in mid-morning. Thus, the eclipse of 1932 came shortly before the time of diurnal minimum, the eclipse of 1900, at diurnal maximum. The usual diurnal range is small — 0.010 to 0.015 in. (0.3–0.5 mb).

Bigelow's, 1902, data of the eclipse of 1900 (in and near the zone of totality) show a fall of 0.015 in. (0.5 mb) vapor pressure in the 15 min. preceding the maximum eclipse, with a gradual rise of the same amount in the following hour. This effect appears superimposed upon the usual morning trend. Frequent psychrometric observations by A. E. Benfield¹ at Ak-Bulak, U. S. S. R., in the total eclipse of June 19, 1936 (9.15–11 a.m.) showed a first-half fall of 1 mb (.030 in.) and a second-half rise of 1.5 mb (.044 in.) (smoothed values). The actual range was from 11.5 mb (.34 in.) to 8.5 mb (.25 in.) to 11.1 mb (.33 in.) Pre- and post-eclipse values were 10 and 11 mb, respectively (.30 and .32 in.).

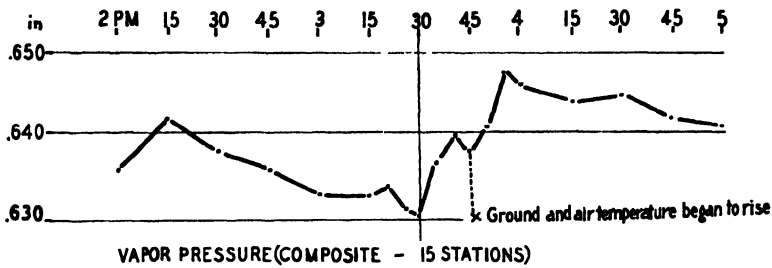


FIG 20. Composite course of vapor pressure at 15 stations, solar eclipse of Aug 31, 1932.

4. *Post-totality maximum due to increasing evaporation with a decreasing convection.* (C.F.B.) It is difficult to obtain a clear picture of any typical effect, but perhaps some explanations of apparent inconsistencies may be offered.

As already stated, there are two chief factors involved in any change of vapor pressure in the lower portion of an air mass in fair weather: the rate of evaporation from the earth's surface, and the rate of turbulent mixing of the humidified surface air with the general mass.

As an eclipse progresses, evaporation from the ground is considerably reduced. A fall of 34 F° in surface temperature (cf. Table 9, p. 50) will reduce the rate of gross evaporation to about $\frac{1}{4}$, but, as the time involved is short, the deficit is not large. The usual reduction in wind velocity occasioned by the eclipse would also favor a decrease in net evaporation (though this is not its chief effect) and an accentuation of local differences. These considerations might lead one to expect a slight decrease in vapor pressure during the first half of the eclipse, accentuated by

¹ Personal communication.

condensation in cases where ground surfaces cool to the dewpoint. It should be emphasized, however, that observations made at Weather Bureau stations on tall buildings in cities could hardly be expected to show a decrease in vapor pressure due to reduced evaporation, as there is little or no evaporation taking place from dry streets or buildings and any change in evaporation from the surrounding countryside could hardly be felt in measurable degree, particularly at the height of the tops of the buildings. Moreover, at stations near water a slight shift in the wind direction might cause a larger change in vapor pressure than that attributable to the eclipse, which over water would be very small owing to the small change in surface temperature.

Turning to the second factor controlling vapor pressure, the rate of turbulent mixing, we find here again some chance for an eclipse effect, possibly the most important. The source of water vapor is the earth's surface. If it is not carried aloft vapor pressure increases. This is typical of late afternoon and early evening. The change of vapor pressure most definitely associated with the eclipse of 1932 is the rise in absolute humidity during the half hour after totality, which appears in both the curve from selected stations and to a lesser degree in the table including also Weather Bureau stations in cities. This is readily explained by the marked decrease in convection, which reached a minimum after totality; though increasing evaporation from the immediately warming surface with returning sunshine may also be a factor in the open country. It is interesting to compare the vapor pressure curve (Fig. 20) with composite curves for wind velocity (Fig. 17A, Fig. 18, pp. 64-65), although they could not be based on exactly the same set of stations. Both show evidence of decreased convection, with recovery after 3:55 p.m. or a little later. (Cf. also data on Cu. clouds, Table 23, p. 77.)

It seems likely that the convective factor in the increase of vapor pressure was more prominent in the eclipse of 1932 than in that of 1900. In the latter case totality occurred at 10 a.m., about the hour of the morning maximum of vapor pressure, before day-time convection is well established. Perhaps this accounts for the pre-totally maximum mentioned by Clayton. Less marked changes in wind velocity were noted in connection with this eclipse and the wind velocities were generally higher.

5. *Summary.* The net change in vapor pressure due to an eclipse is relatively small (0.5 to 1.0 mb) and quite diverse, being the resultant of opposing factors, evaporation and convection, possibly with settling from aloft, though aerological data (cf. pp. 96-98, 101-102) seem to minimize this. In the first half of an eclipse in clear weather, the vapor pressure is likely to fall, apparently because the rate at which the air is charged by evaporation decreases more rapidly than the rate of reduction of vapor concentration owing to decreasing convective exchange. Immedi-

ately after totality, however, the vapor pressure usually rises, probably because evaporation is then increasing while exchange is still decreasing.

C. *Cloudiness Changes During an Eclipse.* (E.S.B., C.F.B.) 1. *Low clouds.* Many eclipse-expeditions have almost "miraculously" obtained photographs of the totally eclipsed sun when low clouds broke away just in time, and closed in again shortly after. When we remember, however, that these low clouds are usually the result of daytime convection, it is not surprising that they cease forming when the sunlight is shut off. When the sky is not overcast it is a matter of common observation (cf. Brooks, 1919) that cumulus clouds decrease as an eclipse comes on, and increase again as it passes off. During the eclipse of 1932, the changes in the amount of low clouds were tabulated for 164 stations where the eclipse was 70 per cent or more (Table 23).

TABLE 23. EFFECT OF SOLAR ECLIPSE OF AUGUST 31, 1932 ON LOW, OR MIDDLE AND HIGH-LEVEL, CLOUDINESS IN 70-100% ZONE¹

SKY COVER OF LOW OR MIDDLE AND HIGH LEVEL CLOUDINESS, RESP.	BEFORE MAXIMUM ECLIPSE				AFTER MAXIMUM ECLIPSE			
	No. of Stations	Decreased No Change		In- creased	No. of Stations	Decreased No Change		Increased
		% of stas.	%			%	%	
1/10								
		Low Clouds						
No low clouds	3	0	100	0	21 ²	0	100	0
Few to 3	71	81	12	7	50	30	42	28
4 to 7	44	66	5	29	42	31	19	50
8 to 10	46	28	62	10	44	20	60	20
		Middle and High Clouds						
No m. or h. clds.	1 ³	0	100	0	2 ⁴	0	100	0
Few to 3	33	52	12	36	30	40	28	37
4 to 7	21	29	14	57	22	41	9	50
8 to 10	13	23	46	31	13	31	46	23

¹ It should be noted that the stations are here classified according to the *initial* cloudiness—at the beginning of the eclipse for the left half of the table and at the maximum of the eclipse for the right half—not *average* cloudiness for the whole eclipse period and all levels, as was the case with the temperature tables

² Of these 21 stations with no low clouds at maximum obscuration, only 3 were cloudless, while 16 were "clear" with respect to total cloudiness (0 to 3 tenths) and 2 were "partly cloudy" (4/7).

³ Enough low clouds present to make sky partly cloudy.

⁴ One station clear, one partly cloudy, owing to presence of low clouds.

At 77% of the stations with under 0.4 of initial low-level cloudiness, there was a decrease as the eclipse came on and at only 7% an increase. If we disregard the 3 stations with no low clouds where, naturally, no decrease could occur, the percentage

of stations with decrease becomes 81%. While there were only 3 stations without low clouds at first contact, after the eclipse there were 21 such. Where the low-level cloudiness was 4 to 7 tenths at the start of the eclipse, the decrease was less marked, being noted at 66% of the stations, while with 8 to 10 low cloudiness there was no change in the majority of instances.

After totality, an increase in low cloudiness could take place in mid- and late afternoon only under the most favorable circumstances, namely, where the humidity was high enough to maintain low clouds throughout the eclipse, yet not so high as to keep an extensive cover which would prevent the returning sunshine from warming the ground. Consequently 50% of the partly cloudy stations showed an increase after totality, while cloudiness increased at only 28% of the clear and 20% of the cloudy stations.

The decrease in low cloudiness as the shadow advances appears, then, to be the most marked effect of the eclipse on cloudiness. We should normally expect little change in the amount of cumulus before late afternoon. In Table 24 we have subtracted the percentage of cases of decrease in the second half from that of cases of decrease during the first half of the eclipse. The remainder may be considered as the *minimum* effect of the eclipse. Owing to normal decrease in low cumuliform cloudiness in the late afternoon the remainder should be a negative quantity on a non-eclipse afternoon.

TABLE 24 PERCENTAGE OF CLOUDINESS STATIONS SHOWING DECREASE IN LOW CLOUDINESS DURING THE ECLIPSE OF AUG. 31, 1932

PERIOD OF ECLIPSE	LOW CLOUDINESS AT BEGINNING OF ECLIPSE		
	Few to 3	4 to 7	8 to 10
	%	%	%
First half	81	66	28
Second half	30†	31†	20
Difference, or minimum apparent effect of eclipse	51	35	8

† Excluding stations with no low clouds.

2. *Middle and high level cloudiness* could be considered only where there were so few low clouds that a reliable estimate could be made of the extent of the upper clouds. At 68 stations where obscuration was 70% or more, there seemed to be no consistent effect of the eclipse on the extent of middle and high cloudiness. This appears reasonable in view of the absence of appreciable changes of air temperature

or of convection at these heights (cf. pp. 94 fig.). The preponderance of decreases with Few to 3 tenths of middle and high cloudiness and some of the decreases in the other groups may have been due in part to the fact that at some stations the "middle" clouds were rather low and of the cumulogenitus type or convectively uparched lenticular clouds. Making allowance for these, the group as a whole seems to indicate a slight tendency towards an increase, due, perhaps, to a general increase in cloudiness in the 70-100% obscuration zones with the approach of the strong northwestern cold front and the southern tropical cyclone. Nevertheless, such a progressive change may be more or less factored out of our compilation by subtracting from the percentage of stations with dominant trends in the first half of the eclipse the percentage having the same trends in the second half, as was done for low-level cloudiness in Table 24. In Table 25 the remainders, ascribable to the eclipse, are small, conflicting, and, therefore, inconclusive. A *formation* of cirrus 1½ hours after the beginning of an eclipse, growing to cirrostratus and altostratus then evaporating just before the end was observed by Wyatt, 1915. An increase followed by a slight decrease in middle and high cloudiness was noted in Texas during the afternoon eclipse of June 8, 1918 (Brooks, 1919).

TABLE 25. PERCENTAGE OF STATIONS SHOWING PREDOMINANT DECREASE OR INCREASE IN MIDDLE AND HIGH CLOUDINESS DURING THE SOLAR ECLIPSE OF AUG. 31, 1932, GROUPED ACCORDING TO INITIAL CLOUDINESS

PERIOD OF ECLIPSE	DECREASE		INCREASE	
	Few to 3	4 to 7	8 to 10	
	%	%	%	
First half	52	57	31	
Second half	40	50	23	
Difference, or possible effect of the eclipse	12	7	8	

3. *Summary.* A solar eclipse tends to reduce low-level cloudiness, owing mainly to the reduction of convection from the surface of the earth. Detached clouds are most affected. Though observations in other eclipses seem to point to an increase in the higher clouds, there are no significant changes apparent in the middle-and high-level cloudiness in 1932 which can be definitely attributed to the eclipse.

C. *Shadow-bands; Sky.* (C.F.B.) The observations of shadow-bands obtained in 1932, though not extensive, tend to confirm previous studies. The most complete

set of observations of shadow-bands was organized and discussed by Bigelow, 1902. The subject has since been well summarized by Rotch, 1908, and Barlow, 1927a.

Shadow-bands are undulated or crescent-shaped dark bands with light spaces between, appearing within about 15 minutes of totality. They tend to be parallel to the solar crescent. As a rule, they do not show any color. Their width is given as 2 or 3 inches for the dark and 7 inches to a foot for the light bands. They follow one another usually in a direction perpendicular to the tangent to the crests, with speed varying from 3 to 25 mi/hr. Shadow-bands differ considerably in intensity, width, and speed. The generally accepted theory today, as, indeed, for half a century, at least (cf. Abbe, 1900), is that these shadow-bands are caused by the diminishing crescent of light penetrating air layers of different refractive index, and are analogous to the twinkling of stars. Much has been learned about shadow-bands by observing them as the sun rises or sets behind a mountain (Rozet, 1906). Typical "shadow-bands" have also been observed at the edge of the shadow of a building. All bands resemble the flickering of heated air over a chimney. The agitated mass moves with the wind.

With a camera designed for the purpose, Douglass, 1926, obtained photographs of shadow-bands in the total eclipse of Jan. 24, 1925 (reproduced by Barlow, 1927a), which, he said, proved beyond any doubt that they were caused by irregularities in the density of the atmosphere. Fergusson's, 1925, measurements of these shadow-bands showed them moving in the direction and with the probable velocity of the wind at the top of the calm body of cold air in the valley at Middletown, Conn., where he made his observations, the wind at more exposed places having been light westerly. They were much slower than the alto-cumulus cloud motion.

Close correspondence between the lie of the shadow-bands and the edge of the moon's shadow is shown by the following observations reported by Father John Theobald to Prof. C. C. Wylie, (eclipse of 1932) and kindly made available to us by the latter:

"We were stationed at Berthierville, about fifty miles northeast of Montreal. The position was approximately: Long. $73^{\circ} 10'$; Lat. $46^{\circ} 6'$. The shadow-bands were seen clearly and distinctly shortly before totality. Their direction was, as near as I could measure, $4^{\circ} 24'$ south of west. These are the magnetic directions. We estimated that the bands persisted for about two seconds, that they were from 1 to $1\frac{1}{2}$ inch apart, and possibly $\frac{3}{8}$ inch wide. I do not know how good these estimates are, but for the direction I placed a yard stick on the sheet and measured afterwards.

"We saw no shadow-bands after totality as the sun was hidden by clouds by the time of third contact."

Prof. Wylie comments (by letter Jan. 13, 1933):

“Correcting for magnetic variation according to the 1925 chart, Father Theobald’s observation indicates that the bands pointed toward 22° south of west. The theoretical direction calculated for the station at the time of second contact is $18\frac{1}{2}^\circ$ south of west. Considering the indefinite nature of the bands, the agreement is sufficiently good.”

In addition, Mr. Clayton has written that

“Shadow-bands were observed at Rockport, Mass. from 3:29 to 3:33 p.m. by Miss Ruth Worcester and H. Berman, on a sheet lying on the ground, and by Dr. Dwight O’Hara from the roof of the building.

“Miss Worcester and Mr. Berman determined the direction of motion of the bands as from 20° west of north by compass, which would place them as coming from 151° azimuth ($S=0^\circ$) on my mirror orientation . . . Dr. Dwight O’Hara placed them as coming from 150° azimuth (determined from my mirror) and moving as rapidly as a fast sprinter, say 20 miles per hour.

“The bands were narrow, perhaps an inch in width, and were seen only about a minute before and a minute after total eclipse. The surface wind was from ESE.

“The estimates by Dr. O’Hara independently and by Miss Worcester and Mr. Berman working together are in surprising agreement, considering the indefiniteness of the bands and agree with my measurements of the azimuths from which the Alto-Cumulus clouds were moving (156° at 3:27 p.m., 157° at 3:35 p.), clearly indicating that they came from the layer of air in which these clouds were floating.”

This? cloud layer was reported by two airplanes to have been encountered at 8000 ft (2430 m) and 2400 m, respectively. The angular velocity by nephoscope was 2.7 m/s per km of height before and 2.6 after; which, multiplied by 2.4 (km), gives 6.6 m/s, or 15 mi/hr. The mean of the six observations between 3 and 4 p.m. was 2.9, equivalent to 7.0 m/s, or 16 mi/hr. If the height of the top of the general cloud sheet (11,000 ft = 3350 m, Stevens, 1932) is taken instead of the base, the speeds become 8.9 m/s and 20 mi/hr. These speeds are reasonably close to the estimated velocity of the shadow-bands; and, taken in conjunction with the accordance of direction, within 6° , leave little doubt that these shadow-bands were caused by irregularities in the altocumulus level.

Other reports of shadow-bands in 1932 include the following:

“Shadow-bands were seen for about two minutes before totality, and for the same time thereafter. On a vertical white sheet, facing the sun, the shadow-bands ran diagonally down from the upper south-east corner to the lower north-west corner, at an angle of about 45° , both before and after totality. They appeared as

ill-defined, brownish broken lines, perhaps 2 inches wide, and spaced some 6 inches apart."—*Greenleaf W. Pickard*, Seabrook Beach, N. H.

At Portland, Me., shadow-bands were described as wavy lines $\frac{1}{4}$ - $\frac{1}{2}$ inch wide (*Boston Evening Transcript*, Sept. 1, 1932). Shadow-bands were seen on the sand at Pocono Head and Wauwinet, Nantucket. They were reported from Limerick, Me., "after totality . . . rather faint;" Concord, N. H., "confused, at maximum eclipse;" and Blue Hill, Milton, Mass., "faint, moving N-S, 3:30-3:31P.," also, but were too indefinite or faint to permit measurement.

Feldman, 1935, noted shadow-bands as far south as Virginia: ". . . the maximum darkening [89%] at Falls Church [Va.] occurred from 3-36 to 3-37 [p.m.] Shadow-bands were observed by me and identified with certainty, during a minute or more, disappearing at 3-33-30. I had about given up the hope of seeing them after the maximum when there was a recurrence, fainter than the first seen, at 3-45, continuing perhaps half a minute . . . the bands preceding maximum advanced about SSE, following maximum WSW . . . they were about one inch wide and perhaps half a foot apart. Their rate of advance across the sheets was . . . about as rapid as that of snowflakes past a window-pane . . ."

Feldman, 1935, presented a detailed discussion of how diffraction could be the cause of shadow-bands, and even forecast the directions in which the shadow-bands should be expected to move before and after eclipse maximum across Eurasia in the eclipse of June 19, 1936. The same directions would also apply for bands caused by atmospheric refraction, however. Shadow-bands in Greece moved from the NNW, while Feldman's prediction called for NW or SE—a close correspondence. Whether or not the diffraction of light passing as if through the thin "slit" (source of light) of the crescent is in any way responsible for shadow-bands, irregular atmospheric refraction could alone be responsible for the wavering character of shadow-bands and for some of the progressive movement as the atmospheric irregularities are carried forward with the winds at different heights (cf. the Rockport observations). Diversity of refractive irregularity and atmospheric transparency in different eclipses and at different places in the same eclipse would also account for the marked differences in intensity, sharpness, and definiteness of motion.

In conclusion, it appears that the shadow-band observations of 1932 confirm previous theory on the following points: (1) that they are caused by irregularities in the atmospheric refraction of the thin sliver of the sun when it is nearly totally eclipsed; (2) that the lie of the bands is essentially parallel to the long axis of the solar sliver; (3) that when their progressive motion can be observed fairly accurately by the motion of spots or other irregularities within the bands, this motion is likely to correspond to that of the layer of the atmosphere having the greatest internal

contrasts in refractive index. They resurrect the old hypothesis that diffraction of the sun's rays rounding the edge of the moon may also be involved; but, since the sliver of the sun, itself, would make the lie of the bands the same as if they were due to diffraction, this hypothesis cannot be proven. Against the diffraction hypothesis is the usual lack of great speed, such as shown by the margin of the shadow; so also is the usual lack of color in shadow-bands.¹

Sky. Many authors have described or measured the color or spectrum (cf. Cohn, 1934b) of the sky and the illumination of the landscape during an eclipse (cf. Abbe, 1881, Barlow, 1927a, b). We shall add impressions of totality from the eclipse of 1932:

"During totality the horizon to the east, southeast, south, southwest, and west became a rich orange, the clouds growing dark gray."—*Mrs. John Downes*, Meredith, N. H.

"Greenish gray twilight was then over grass and people on the plateau."—*A. C. Maury*, Limerick, Me.

"The general color of the sky, air, and land seemed to me to be about the same as I have often seen when the air is thick with smoke from forest fires, or when the sun is shining brightly through from behind a hail storm."—*Laurence LaForge*, Provincetown, Mass.

The parallel of eclipse to hail-storm lighting is good—in both cases practically all light from overhead is cut off and only that scattered by air at a distance, and traversing a long stretch of the lower dusty air, is to be seen.

Another feature is the increase in the sky polarization and rotation of its plane during a solar eclipse, as described, for instance, by Cohn, 1934b, 1934d.

VI. FREE AIR DATA OBTAINED DURING THE ECLIPSE OF AUGUST 31, 1932

A. Cloud Motion by Nephoscope. (E.S.B., C.F.B.) 1. *Sources of data.* The study of changes in cloud motions during the eclipse was based on nephoscope observations from 6 Blue Hill stations, 5 in the zone of totality, and 22 Weather Bureau stations scattered throughout the United States. These were supplemented by non-instrumental estimates of cloud motions from 67 Weather Bureau stations and 9 miscellaneous sources, and observations of winds at 9 mountain stations.

¹ Even the presence of colors, however, would not prove the case in favor of diffraction, for the colors could be owing to irregular refraction in the atmosphere, which so commonly varies the colors of stars or planets near the horizon. Thus, in the early morning eclipse of July 18, 1860 (Supt. . . . , pp 285-286) when totality near Steilacoom, Wash. Terr., occurred only 18 min. after sunrise: "At the moment of totality beads of golden and ruby-colored light flashed almost entirely around the moon. They were not constant in dimension or color at one point, even for a second, but fitfully flickering, as reflections from rippled water, and as unstable in the respective places of color. I do not think the band could have been more than 10" or 12" broad."—*J. M. Gillis*. Colors were still to be seen 4½ hrs later when totality reached northern Labrador: "We observed a few shadows flying over the ground to the

2. *Theoretical considerations.* One should expect subsidence to occur over an area cooled markedly by the eclipse, with a tendency of surrounding air to flow in at upper levels, thereby turning the existing upper wind toward the cooled area. The difficulties of demonstrating any eclipse effect are at once apparent, however. The height of the cloud layer, which in the absence of information is assumed to be constant, may well vary during the eclipse, thereby changing the computed speed, and, indeed, bringing the cloud into winds differing in velocity and direction from those of the original level. Minor fluctuations in the observed directions of cloud motion are common at any time. Inaccuracies of observation, especially where the observer is inexperienced, account for some of these. The remainder may be due to turbulence in the cloud layer (particularly Cu), a vertical component of cloud motion, a progressive evaporation or growth of the edge of the cloud under observation, or minor variations in wind direction. Furthermore, the eclipse effect was most marked, naturally, at stations where clouds were few: in many instances where large temperature falls occurred, the cessation of convection caused disappearance of cumulus clouds about the time of totality, thereby terminating the cloud record too soon.

3. *Reduction of the data.* The data of the 1932 eclipse were first grouped according to type of observation, cloud levels, and eclipse zones, and roughly summarized. For each quarter of the eclipse the progressive change in direction was noted as "no change," "clockwise" (right), or "counter-clockwise" (left). Fluctuations within the limits of 5, 10 and 20 degrees for the upper, middle and lower clouds, respectively, were considered "no change," but a continuing change within these limits was counted as a turn.

4. *Direction of turn and trend in velocity.* Using only the nephoscope data, and comparing the initial cloud motion with that at eclipse maximum (see Table 26), more turns were recorded, with right and left about equally common, taking all levels together, though with a preponderance of left over right at middle and high levels. The number of cases is so small, however, that this may be without significance. If there were a convectational control a preponderance of right turns should have occurred.

A comparison of velocities before and after the eclipse at nephoscope stations in zones A-D likewise brought out no consistent differences (Table 26). Little change could be expected save possibly an increased speed at Cu levels due to less mixture with the frictionally hindered lower air. This effect might have been either reduced or increased by changes of velocity due to the theoretical tendency to eclipse inflow. The cloud velocities, then, like the directions, show no convectational change.

The data on mountain winds, on the other hand, representing somewhat lower levels and not strictly free-air conditions, do indicate the decrease in velocity near eclipse maximum which is so common at lowland stations. (See Table 26.)

TABLE 26. CHANGES IN CLOUD MOTIONS ACCORDING TO OBSERVATIONS WITH NEPHOSCOPES IN ECLIPSE ZONES A-D AND IN WINDS ON MOUNTAINS, FROM BEFORE OR EARLY IN THE ECLIPSE OF AUG. 31, 1932 TO ABOUT 15 MIN. AFTER THE MAXIMUM ECLIPSE; AND SIMILARLY IN THE ECLIPSE OF JUNE 8, 1918, THE NUMBERS IN (), FROM 10 STAS., FERGUSSON, 1919

CLOUD LEVEL	DIRECTION OF TURN			TREND IN VELOCITY		
	Left	No ch.	Right	Decr.	No ch.	Incr.
Upper and middle clouds						
High	2 (1)	1 (1)	1 (0)	2 (0)	0 (1)	1 (1)
Middle	3 (1)	1 (0)	1 (1)	1 (1)	1 (1)	2 (1)
Hi. & mid.	5 (2)	2 (1)	2 (1)	3 (1)	1 (2)	3 (2)
Low clouds and winds on mountains						
Low clds.	6 (3)	1 (1)	6 (1)	3 (1)	1 (1)	4 (1)
Mtns. ¹	2	6	1	6	1	2 ²
Low clds & mts	8 (3)	7 (1)	7 (1)	9 (1)	2 (1)	6 (1)

¹ Altitudes 2700-6200 ft.

² Increase both before and after eclipse maximum.

5. *Analysis for eclipse effect in relation to temperature-change gradient.* A further endeavor was made to isolate the eclipse factor by analyzing the nephoscope data in more detail. The isothermal maps of temperature effects (Figs. 1, 11) were used to estimate for each cloud station the direction and steepness of the gradient of surface-temperature change ascribable to the eclipse (cf. p. 91). The direction was a matter of some uncertainty in cases where stations were far apart, or nearly surrounded by ocean (e. g. Provincetown or Key West) or between two marked areas of cooling. In the latter case, Limerick, a resultant gradient was estimated.

The average direction of motion for each cloud level an hour to half an hour before the eclipse maximum was compared with the direction shortly after the eclipse maximum (perhaps 15-30 min.)¹ and the amount and direction of change noted in degrees right or left. The direction of the first of these with reference to the gradient of temperature change was also recorded in degrees right and left. An eclipse effect required a right turn in a cloud moving to the left of the gradient of temperature change, and vice versa; i.e., the cloud should turn toward the area of

¹ It is not possible to state the time exactly, as the frequency of observations differed at the various stations.

greatest cooling. Such an effect was observed in less than half the cases. (See Table 27.)

TABLE 27. TENDENCY OF CLOUD MOTIONS TO CHANGE IN ACCORDANCE WITH HYPOTHETICAL ECLIPSE SUBSIDENCE (numbers of cases,—sometimes more than one cloud level per station)

(a) <i>Blue Hill and Weather Bureau nephoscope stations treated separately</i>			
STATION GROUP	(TOTAL STAS)	ECLIPSE EFFECT	NO ECLIPSE EFFECT
Blue Hill stas.	(6)	4	5
Weather Bur. stas.	(22)	12	17
Totals	(28)	16	22

(b) <i>Blue Hill and Weather Bureau stations combined</i>			
CLOUD LEVEL	APPARENT ECLIPSE EFFECT	NO APPRECIABLE CHANGE	COUNTER ECLIPSE
High	2	1	4
Middle	3	2	5
Low	11	2	8
Totals	16	5	17

Still looking for an eclipse wind aloft, we analyzed the cloud data graphically to compute a possible eclipse component, using 8 stations having temperature-change gradients in excess of 5 F° and reasonably complete nephoscope observations of both direction and velocity of clouds.

The cloud motions before and after the eclipse were plotted on polar coördinates and joined by a straight line. The deviation of the observed cloud motion from the line was taken as the eclipse (or counter eclipse) wind component. Ideally, an eclipse component should be down the gradient and deflected by the earth's rotation slightly to the right and should vary roughly with the steepness of the temperature-change gradient.

Again, we find eclipse turns (the positive components of velocity down the temperature-change gradient in Table 28) in less than half the cases, only 4 out of 12. It is obvious also that the magnitude of the eclipse component down the temperature-change gradient has no relation to the value of the gradient, shown in the last column of Table 28. But perhaps it can be claimed that the 2 to 1 tendency of middle clouds to respond to the temperature-change gradient indicates a flow at middle cloud levels (about 2 to 7 km) towards the areas of greatest cooling, and possibly that the 4 to 1 tendency of low clouds to move opposite to the temperature-change gradient indicates a flow at low levels outward from the cooled areas, as would be

TABLE 28. MID-ECLIPSE DEVIATION OF WIND DIRECTION AND VELOCITY IN THE FREE AIR FROM WHAT IT WOULD HAVE BEEN ACCORDING TO A LINEAR TREND FROM BEFORE TO AFTER THE ECLIPSE, AS SHOWN BY NEPHOSCOPE OBSERVATIONS AND THEIR RELATION TO THE DIRECTION AND STEEPNESS OF THE TEMPERATURE-CHANGE GRADIENTS AT THE SURFACE CAUSED BY THE ECLIPSE OF AUG. 31, 1932

STATION	ECLIPSE COMPONENT ¹				MAX. GRAD. OF TEMP.	
	Direction		Velocity		Dir. down t.-ch gradient	Gradient per 20 mi.
	From (N=0°)	Relative to dir. of t.-ch. gradient	Obsd.	Component down t.-ch. gradient ²		
	°	°	m/s	m/s	°	F°
<i>High clouds</i>						
Concord	320	Rt 60	0.5	0.3	80	3.5
Binghamton	0	L. 105	3.0	-0.8	285	2.5
Provincetown	180	Rt. 180	0.2	-0.2	180	0.3
Mean, High clouds		L. 106	0.9	-0.2		5.1
<i>Middle clouds</i>						
Concord	318	Rt. 58	1.0	0.5	80	3.5
Key West	188	L. 82	7.5	0.1	90	5.0
Newport	50	Rt. 91	0.4	0.0	139	2.1
Limerick	75	Rt. 155	0.5	-0.5	100	2.0
Mean, Middle clouds		L. 79	1.5	0.0		3.2
<i>Low clouds</i>						
Blue Hill	157	L. 32	0.2	0.1	9	2.8
Limerick	139	L 141	0.7	-0.5	100	2.0
Newport	175	L. 144	3.0	-2.4	139	2.1
Chicago ³	221	Rt. 161	2.2	-2.1	240	4.4
Binghamton	290	L. 175	5.0	-5.0	285	2.5
Mean, Low clouds		L. 169	2.0	-2.0		2.8

¹ Deviation of cloud dir. and vel. at about 15 to 30 min. after eclipse max. from a mid-eclipse value (interpolated for that time from dirs. and velts. at or near beginning and end of eclipse).

² Cloud vel. in dir. of max. rate of temp. fall due to the eclipse. Obtained from cloud vel. multiplied by cos of dir. of eclipse component rel. to temp.-ch. grad.

³ Direction of temp.-ch. grad. difficult to determine at Chicago

expected from the higher pressure that should develop from the inflow of air aloft. But even the low clouds were too high for the maximum depth that the outward flow could be expected to develop.

6. *Summary.* The best that can be affirmed is that, while these nephoscope data are inadequate to prove the existence or absence of an eclipse circulation, they

offer possibly a faint corroboration of the eclipse(?) circulation suggested by the more accurate and detailed results obtained from some of the pilot balloon runs, which are presented in the following division.

B. Pilot-Balloon Data. (C.H.P., H.W., E.S.B., C.F.B., E.M.B.) 1. *Stations, observational conditions, equipment, runs.* In order to study what influence the solar eclipse exerted on atmospheric movement observations of pilot balloons were made at five stations, so distributed that a cross-section of the air above the eclipse path could be made. These stations were: East Boston, Mass. and Concord, N. H., on the southwestern side of the path, Limerick and Cape Elizabeth, Me., near the center of the path, and Brunswick, Me., a few miles inside the northeastern edge. The men participating in the pilot-balloon work of each were: *Brunswick, Me.*, C. H. Pierce and Harry Wexler; *Limerick, Me.*, C. Harmantas, S. P. Fergusson, and Naval officers Graves, Hoyt and Shelton; *Cape Elizabeth, Me.*, Maj. Henry Peabody, assisted by four men of the 240th Coast Artillery, Maine National Guard, at Fort Williams; *Concord, N. H.*, C. F. Brooks, Jerome Namias, Irving I. Schell, and Sidney Serebreny, from Blue Hill, M.I.T., and N. Y. Univ., and C. J. Closby, R. V. Dobbs, P. W. Kenworthy, B. F. Loveless, U. S. Weather Bureau; *East Boston, Mass.*, (U. S. Weather Bureau), A. D. Ross, and J. L. Paulhus. Others whose cooperation helped make this work successful were: Prof. N. C. Little and R. F. Derby of Bowdoin College; Capt. C. H. J. Keppler, in charge of the U. S. Navy Eclipse Expedition; Col. G. E. Fogg, commander of Fort Williams, and C. J. Marston, manager of the Concord Airport.

Observational conditions were excellent at all the stations. The standard 6-inch pilot balloons used by the U. S. Weather Bureau, commercial hydrogen from cylinders, and the usual balloon balances were employed and inflation was made indoors, except at Brunswick and Limerick. At Brunswick the balloons were inflated in the open air to a circumference of 7 ft. (2.1m) and the free lift measured in lulls between the light gusts, with small spring scales graduated in grams. The ascensional rates were computed from the 135-180 gr. lifts measured. At Limerick the balloons were inflated in a tent till they would just lift the standard weight required for an ascensional rate of 180 m/min. Four stations were equipped with single theodolites and the other, Concord, with two.

At Brunswick, Limerick, and Concord ten balloon runs each were made during the day. At all five stations at least four runs were made during the afternoon, two of which were directly before and after totality.

2. *Representativeness of the single-theodolite runs.* The double theodolite station, at Concord, had its base line unfortunately limited to 300 m, the width of the field. This caused occasional small irregular discrepancies in altitude from observation

to observation when horizontal distances exceeded 1500 m. Nevertheless, a comparison of the double runs with the corresponding "single" runs (by taking the ascensional rate computed from the 125 gr. free lift of the balloon and the observations from one of the two stations for the "single" run), gives gratifying results. The two curves procured by plotting wind direction and velocity against height for the "double" and "single" runs on the same graph show close agreement for each of the four runs. This encourages us to believe, then, that the single-theodolite runs at the other stations are sufficiently accurate for the detection and evaluation of changes in wind velocity at different levels during the eclipse.

3. *Evidence of change due to reduced convection.* Before looking for an eclipse wind, we might examine the data for any evidence of convectonal change (see Table 29).

TABLE 29. CHANGES IN WIND DIRECTION AND VELOCITY ASCRIBABLE TO THE ECLIPSE OF AUG. 31, 1932

HEIGHT ABOVE SURFACE	VELOCITY CHANGE ACCORDING TO DIRECTION OF TURN FROM MEAN OF RUNS BEG AT 2.00 AND 2.50 P TO RUN BEG AT 3.40 P.																	
	Concord			Limerick			Cape Eliz.			Boston			Brunswick			Totals		
	L	No ch	Rt.	L	No ch.	Rt.	L.	No ch	Rt.	L.	No ch	Rt.	L.	No ch	Rt	L	No ch	Rt.
m																		
2	-			+?					0	+					-			
2-200	+			+					0	+			-		-	+++		0
200-400	+		+	+				+		+			+	+	+	+++++	+	++?
400-600	+			+				+		+			+			+++++		
600-800	+					+		-				-	+			++?		+ -
800-1000	+	-		+		+			-			-			-	++		---
1000-1400	-		-	+		-		+				-			-+	+		+ + - - -
1400-1800			-	+	+	+		+							+	+	+	+ + + -
1800-2200	0							+					+					+
2200-2600			+					-					+		-	+-		+
2600-3000								-										-
3000-3400							0	-									0	-

Table 29 does not exhibit such an effect, which is not surprising, perhaps, for the following reasons: (1) The combined left turn and decreased velocity at the surface, with increase at moderate heights is not well shown at these balloon stations, except Concord. Since, of the 5 balloon stations, Limerick and Concord were partly cloudy, and the others were on or near the coast, none were well situated for experiencing a marked decrease of convection. (2) The effect has to be averaged through a considerable range of height and so is less readily apparent aloft than when concentrated at the surface.

TABLE 30 CHANGES OF WIND-VELOCITY ASCRIBABLE TO THE ECLIPSE, CLASSIFIED BY THE TURNING OF THE ECLIPSE COMPONENT: WHETHER THE VELOCITY IN THE BALLOON RUN AT ABOUT 3:40 P.M. WAS GREATER OR LESS THAN, AND TO THE LEFT OR RIGHT IN DIRECTION WITH RESPECT TO, THE HYPOTHETICAL WIND AT 3:40 P.M. DERIVED FROM UNIFORM RATE OF CHANGE FROM THE MEAN WINDS OF THE 2 AND 2:50 P.M. BALLOON RUNS TO THE MEANS OF THE 4:30 AND 5:10 P.M. RUNS

HEIGHT ABOVE GROUND	ECLIPSE TURN			
	To Left		To Right	
	Vel. incr.	Vel. decr.	Vel. incr.	Vel. decr.
m	m/s	m/s	m/s	m/s
0-400	+0.8, +2.6?	-0.6	+0.1	-0.1?
400-1000	+1.5	-1.4, (-0.5)?	-	-0.1, (-0.7)
1000-1800	+1.1	(-0.5)	+2.0?	-0.5, -0.3?

"?" indicates record not complete; "(" indicate opposite turn in part.

The usual turning to the left as wind velocity decreases and to the right as it increases in accordance with reduced convective interchange between the freer and faster winds aloft and the friction-hindered surface winds is not apparent in Table 30. In fact, these balloon data tend to indicate the opposite, which is as it should be in this case, the wind velocity having been found to decrease aloft at all the stations: so the release by the eclipse of the lowest layer of air from strong convective interchange with the light winds aloft permitted an increase in velocity with a turning to the left near the ground and a decrease in velocity with a turning to the right at a moderate height, as shown in Table 30. The wind at the ground, however, was cooled so much that, except at the most exposed stations, it became fairly disengaged even from the wind at a height of 50 or 100 meters, and so suffered a decrease in velocity during the eclipse, as has been shown in Figs. 17 and 18.

4. *Graphical determination of eclipse component.* In order to obtain the magnitude and direction of the eclipse component as a function of altitude for each station, the data were analyzed graphically at heights about 200 m apart up to the top of each flight. The wind directions and velocities at each level observed on four or five successive balloon flights at the station were indicated by vectors: OA_1 , OA_2 , OC' , OB_1 , OB_2 in Fig. 21. The eclipse component, CC' , was found by constructing the mean wind velocity, OC , from the winds, OA_1 , OA_2 (before eclipse), OB_1 , OB_2 (after eclipse), and comparing it with the wind velocity, OC' , observed at approximately the time of maximum eclipse effect. The vectors OA and OB , representing the mean winds before and after the eclipse, were found by giving equal weights to OA_1 , OA_2 , and OB_1 , OB_2 , respectively. The times corresponding to A and B were found similarly by averaging. Then C, at its known time, was chosen

between A and B on the assumption that the wind would have changed at a steady rate during the time of the eclipse if there had been no eclipse. In Fig. 21, C was placed so as to divide the line AB into segments proportional to the time intervals. If either A_1 or A_2 or B_1 or B_2 were missing from the observations, A was chosen at A_2 or A_1 ; and B, at B_2 or B_1 .

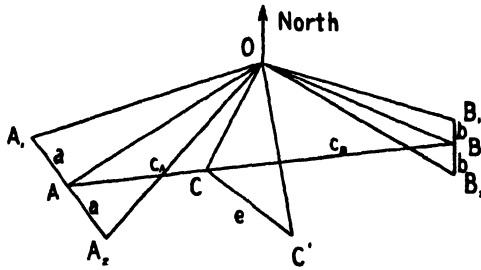


FIG. 21. Graphical determination of possible eclipse wind.

5. *The eclipse components derived.* After deriving the eclipse components by the method just described, we have estimated for each station the direction and steepness of the rate of temperature change. Thus, for Concord, the figure 80° means that the principal nearby cooled area lay a little N of east from Concord. The rate of temperature change in that direction, caused by eclipse cooling, was about 3.5° in 20 mi., i.e. a place 20 miles east of Concord might have a drop of temperature 3.5° greater than that at Concord. The small gradient computed for Limerick is due to components between cooler areas to the southwest and to the northeast which more or less balance. (See temperature-map, Fig. 11). Cape Elizabeth has a large gradient because in that region the temperature-fall was considerable (7°), probably changing rapidly to zero over the ocean a few miles from shore.

Any eclipse pressure-gradients should be controlled more directly by the location of the principal cooled areas (under clear skies) than by the exact astronomical eclipse-path. Consequently, we have determined inflow or outflow with respect to the temperature-drop gradient instead of the eclipse-magnitude gradient. For Concord, therefore, with the gradient direction of 80° , a line at right angles to this would be the limit between "inflow" and "outflow". Hence eclipse components from between 350° to 360° and 0° to 170° mean an "outflow", those between 170° and 350° an "inflow"; the most definite eclipse component would be one parallel to the gradient (i.e. 80° or 260°).

On this basis Fig. 22 shows for each level for the five balloon stations whether an inflow or outflow is indicated. The surface winds in general were southerly, turning

to more westerly directions with increasing elevation. This tendency to increasing azimuth with increasing elevation is observable also in the eclipse components and suggests that the general wind was not sufficiently factored out.

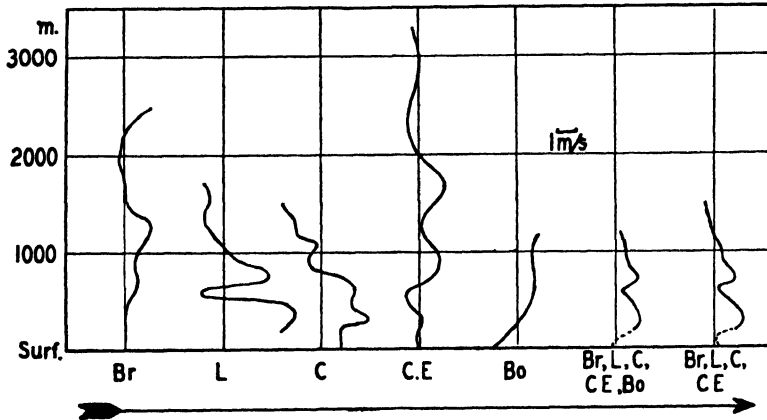


FIG. 22. Eclipse wind components as to whether inward (to rt.) or outward (to left) from the direction of greatest cooling (shown by arrow.) Based on pilot-balloon data of Aug. 31, 1932.

For comparison we made a similar tabulation using the direction of the eclipse path, at an azimuth angle of 325° , as the dividing line between in and outflow, therefore $325^\circ-145^\circ$ for all stations, in and out reversed on opposite sides of path, i.e. N of path, components between 325° and 145° indicate an outflow; S of path, components between 325° and 145° indicate an inflow. (Fig. 23.)

It has been suggested by others that cooling by the shadow should cause subsidence over the cooled area accompanied by inflow aloft and outflow at the surface. Lindholm and Bergsten, 1923, who made nine pilot balloon runs at Stockholm during the nearly total eclipse of 1921, on a clear morning, found such a circulation in their eclipse components, outward 0-400 m. and inward 400-900 m. We failed to find definite evidence of outflow at the surface. However, conditions were complicated by convective decrease which in many instances seemed to act in the same direction.¹

Our balloon observations do not show this tendency at all conclusively. The Boston figures indicate a counter-eclipse flow, i.e. onshore at the surface and out above, probably a mid-afternoon sea-breeze. The sudden reversal of the 3:40 p.m. eclipse component at about 400 m and the constancy from 600 to 1200 m, also the change of velocity (+ with wind more from sea, - with wind more from land), confirm this. At Cape Elizabeth the components are more variable, possibly representing a mix-

¹ Cf. p. 68.

ture of sea-breeze and eclipse effect, for here the temperature-change gradient was larger than at Boston (15 vs. 6). However, this explanation is a mere surmise.

At Brunswick in spite of possible sea-breeze complications, the outflow at the earth's surface and inflow above is in accordance with the eclipse gradient, but the outflow seems too marked and at too high an elevation.

Conditions at Limerick and Concord would seem to come nearest to the hypothetical eclipse flow. At Concord the cloud observations (q.v.) also show an inflow aloft, but data from the airplane flight did not indicate that subsidence occurred. The balloon data at Concord are probably the most accurate, being based on double theodolite runs. The systematic turning of the eclipse components at Concord and

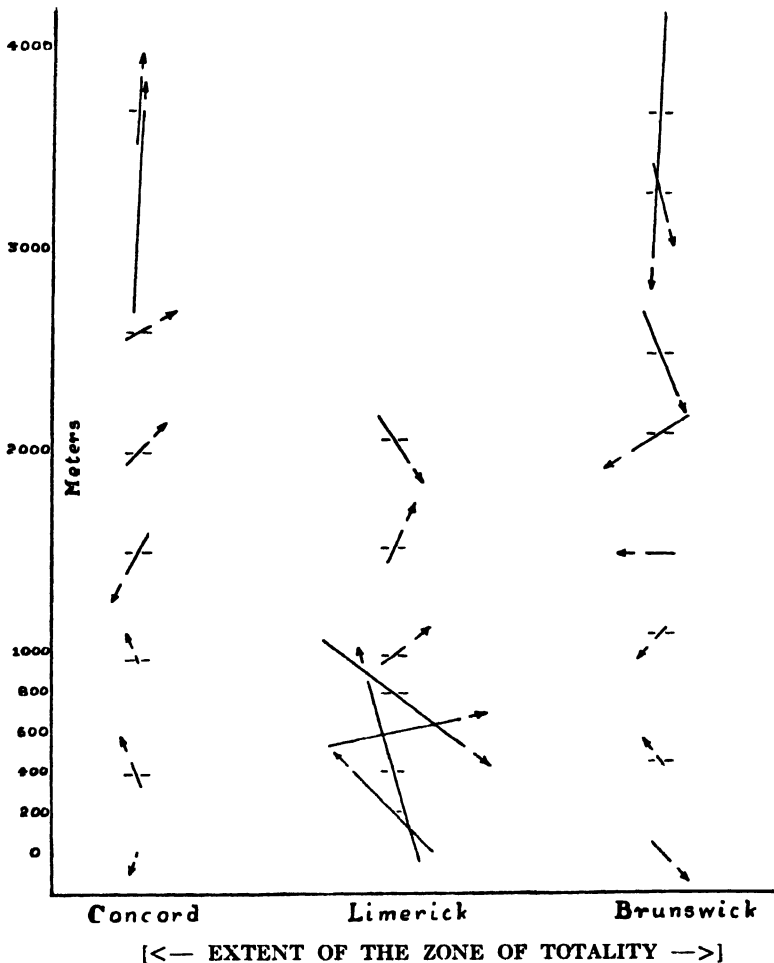


FIG. 23. Eclipse wind components with respect to the path of the center of the eclipse. Computed and plotted by H. Wexler and C. H. Pierce.

Limerick is similar, and the directions of the gradients at the two stations are nearly the same (80° and 100°). If we had centered our eclipse flow on the eclipse path, however, Limerick, unlike Concord, could have shown no eclipse component at all.

6. *Summary.* In the chapter on pressure and wind, Haurwitz emphasized the smallness of any possible eclipse gradients under the most favorable circumstances. With regard to our balloon runs, the evidence is divided, and more cases are needed to establish the point. Concord, the station with the most detailed observations, points to an apparent outflow and inflow possibly due to the eclipse. The outflow is deeper than reasonable for the shallow flow which might possibly be caused by an eclipse. Such flows are duplicated at Limerick, but reversed at Cape Elizabeth and Boston, and doubtful at Brunswick. However, the data for the three stations near the coast, which are subject to sea-breeze influence, need not weigh heavily against the evidence at Concord and Limerick.

C. *Airplane data.* Airplane observations indicate that in the free air the temperature effect may have reached great heights but could not be traced with certainty any higher than 500 m. Dines, 1906, however, found a rise of 1°F at 3500 ft (1060 m) by kite meteorograph after the maximum phase of the eclipse of Aug. 30, 1905.

1. *The Concord flight (J. N.).* In securing upper air observations during the eclipse of Aug. 31, 1932, one airplane sounding to the altitude of about 2700 m was made through the generous cooperation of Dr. Irving Langmuir, who was primarily interested in getting photographs of the spectacle from aloft. Dr. Langmuir permitted a meteorograph to be mounted on his biplane, and took an excellent set of notes of atmospheric conditions while in flight.

A Bosch and Bosch instrument was loaned by the Massachusetts Institute of Technology. The traces recorded were comparatively free from effects of vibration, and could be accurately evaluated. An electro-magnetic pen of the meteorograph enabled the pilot to register marks upon the revolving drum as he entered and left a layer of cloud or haze. The instrument was given a thorough "massage" (conditioning) the day preceding the eclipse, and it was calibrated at the meteorological instrument laboratory, M. I. T., on the day following the eclipse. The pressure steps were made at rates in general agreement with the rates of ascent and descent of the plane.

The flight was made between 2:45 and 4:08 p.m., E.S.T. The pilot flew nearly horizontally during totality, but not sufficiently so for the determination of any temperature change due to the eclipse.

The finally evaluated record of the sounding is shown in Table 31 and Fig. 24.

There was a superadiabatic lapse rate of temperature from the surface to about 370 m (above the surface) (500 dyn.m above m.s.l.)—not uncommon for hot summer afternoons. From this level up to 1240 m (1300 dyn.m) the lapse rate was adiabatic, followed by an almost isothermal layer to 1835 m (1900 dyn.m), and thereafter roughly equal to the saturated adiabat. Although this layer was recorded as not quite saturated (95%), it seems justifiable to assume that the relative humidity was 100%, in view of the lag of the hair hygograph. Cumulus clouds were observed both in ascent and descent, as was also a thin layer of broken lenticular

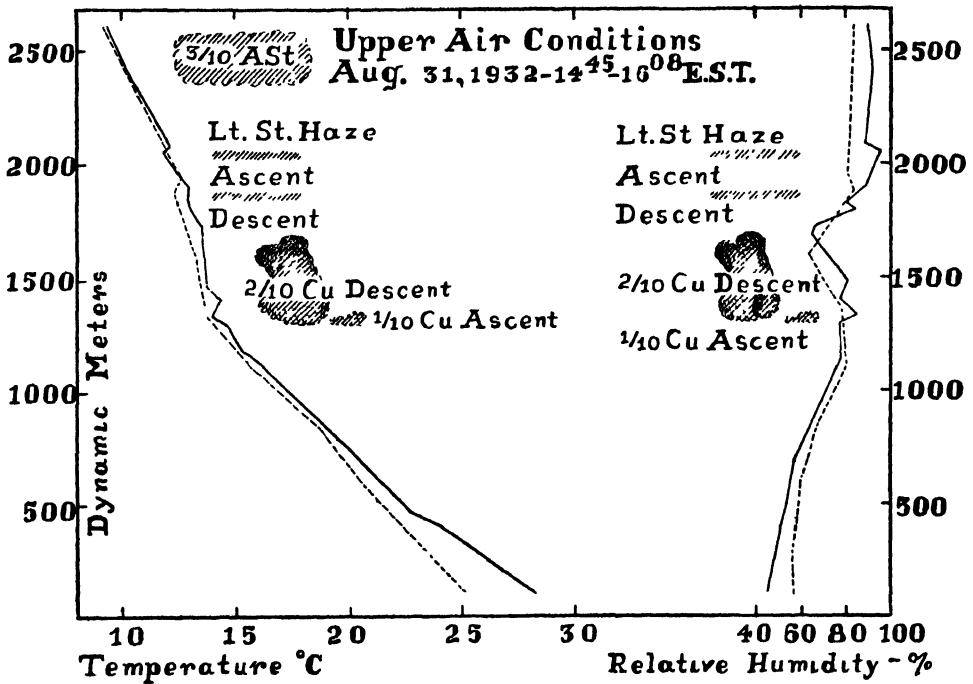


FIG. 24. Free-air temperatures, humidities, clouds and haze layers observed by airplane from Concord, N. H., early and late during the eclipse of Aug 31, 1932. The flight was made from, and return to, the Concord airport by Dr Irving Langmuir carrying a Bosch & Bosch airplane meteorograph loaned by Mass. Inst. of Technology. The heights are in dynamic m above sea-level. The altitude of the ground is 103 dyn m. For comparing with pilot balloon data the heights in the text are given in m above the surface (1 m=0.98 dyn m). The cloud observations do not correspond exactly to those made from the ground at Concord, for the airplane did not keep over Concord; most of its climbing and descent, however, were accomplished fairly near the airport. The middle layer cloud, called A.St., was noted as Ac from the ground. It is to be noted that the heights of the haze layer and of minor irregularities in the temperature and humidity curves are lower on the descent (broken lines) than on the ascent (solid lines), also that temperatures are lower and humidities higher, level for level, a difference that can be accounted for by the lag of the meteorograph. The eclipse effect on temperature and humidity extended surely to 460 dyn.m (365 m above surface) and perhaps to 800 dyn.m (710 m).

ECLIPSE METEOROLOGY

TABLE 31. DATA FROM THE CONCORD, N. H. AIRPLANE SOUNDING, AUG. 31, 1932, IRVING LANGMUIR,
PILOT. EVALUATED BY JEROME NAMIAS. SEE FIG. 24.

TIME E.S.T.	PRESS MB.	TEMP. C°	REL. HUM.	ALTITUDE DYN. M.	HEIGHTS OF CLOUDS DYN. M.
			%		
			<i>Ascent</i>		
2:45p	1000	28.2	45	103	
	966	24.1	51	400	
	960	22.8	53	460	
	933	20.5	58	700	
	884	15.7	78	1160	
	882	15.3	78	1180	
2:59	870	14.7	77	1290	Cu bases at 1290
	865	14.0	86	1330	
	858	14.4	78	1400	
	850	13.8	81	1480	
	850	13.6	65	1690	
	824	13.6	67	1730	
	818	13.1	85	1800	
	816	12.9	80	1820	
	809	13.0	89	1900	
	3:08	793	11.9	96	2060	Lt. St. haze 2020 to 2060
789		12.2	89	2090	
760		10.4	92	2400	A.St. 2350 to 2550
3:35	739	9.4	90	2610	
	739	9.2	90	2610	
3:41½	739	9.2	84	2610	
			<i>Descent</i>		
4:08p.	1000	25.1	57	103	
	979	23.4	57	290	
	945	20.6	60	600	
	919	18.8	67	830	
	886	15.6	80	1120	Bases of Cu. at 1270
5:44	862	13.7	78	1360	
	837	13.3	64	1600	Highest Cu. top at 1590
5:42½	810	12.4	84	1880	Lt. St. haze 1840 to 1880
	803	12.7	81	1950	
5:41½	739	9.2	84	2610	

masses of haze, and, finally, near the top of the climb, a layer of altocumulus (A.St. in notes).

The relative humidity was fairly low at the ground (45%), and rose practically to saturation values above 1430 m (1500 dyn.m). At all levels the moisture content was fairly large, and the existence of several strata of cloud is not surprising.

2. *The question of subsidence.* (E.S.B., J.N.) With the fall of temperature in the surface layers during an eclipse, a reduction in volume of the air takes place which

perhaps leads to a measurable subsidence of air aloft. However, the mean temperature in the lowest 2000 m at the time of the ascent was 295° A, and the mean on the descent 293°A. Assuming unchanged pressure at 2000 m this would cause a shrinkage of $2000 \times 2/295 = 14$ m, a subsidence too small to measure. In Fig. 24 it will be noted that the haze layer which in ascent (before totality) was found at 1955 to 1995 m (2020–2060 dyn.m) was found at 1815 to 1770 m (1840–1880 dyn.m) in descent. An actual sinking of the layer at first appears quite definite, and the temperature and humidity elements of the meteorograph responded as would be expected through this layer. In each case, immediately above the layer we find a small inversion of temperature and a sharp drop in relative humidity. There are also other discontinuities of lapse rate and humidity shown in Fig. 24 which appear at lower elevations in the descent than in the ascent, suggesting subsidence during the time-interval between ascent and descent.

It should be noted, however, that when the airplane first started down, it made a very rapid descent, from 2560 to 1815 m in $\frac{3}{4}$ to $1\frac{1}{4}$ min. (10–17 m/s). (See Table 32.) Under these circumstances a lag of but 15 sec. in instrument and pilot's recordings would account for the total differences in elevation of the haze observed. The time marks could not be read with certainty nearer than to the nearest $\frac{1}{2}$ min. Then, too, the boundaries of a haze layer are often indefinite. Probably a few seconds lag on the ascent placed the haze layer a trifle too high originally, but a greater error would be expected in the much more rapid descent. With such a rapid rate of descent, the record of temperature might be expected to lag 15 sec. behind that of pressure¹, which would place the small inversion lower by about the amount ob-

TABLE 32. RATE OF CHANGE OF HEIGHT

ASCENT				DESCENT			
Time	Height	Time since take-off	Rate of change of height	Rate of change of height	Time bef. landing	Height	Time
E.S.T.	m	min.	m/s	m/s	min.	m	E.S.T.
2:45p	2	0			0	2	4:08p
2:45–2:59			1.4	0.9			3:44–4:08
2:59	1210	14			24	1280	3:44
2:59–3:08			1.5	5.8			3:42 $\frac{1}{2}$ –3:44
3:08	1995	23			25 $\frac{1}{2}$	1815	3:42 $\frac{1}{2}$
3:08–3:55			0.3	12.4			3:41 $\frac{1}{2}$ –3:42 $\frac{1}{2}$
3:55	2555	50			26 $\frac{1}{2}$	2560	3:41 $\frac{1}{2}$

¹ K. O. Lange and C. S. Draper, The meteorological airplane ascents of the Massachusetts Institute of Technology, 1934. M.I.T. and Woods Hole Oc. Inst., v.3, no. 2, 1934, Table XII, p. 25.

served. At a lower elevation (1210 m) where the plane was changing height less rapidly, the Cu bases were found to have remained practically at a constant level.

If the haze layer settled, it must have settled as a whole, for it is not reasonable that the small cloud droplets would fall through the air at the rapid rate of more than 5 m/min.

Obviously, the haze layer alone could not descend independently of other air masses. What evidence is there of subsidence above or below it? The Cu bases did not change in elevation, but, since Cu are formed in rising local columns or bubbles, they cannot be taken as indicators of the position of a *layer* of air.

Above the haze layer before the eclipse the relative humidity was at least 95% (probably 100%), and the lapse rate of temperature about the saturation adiabatic rate. If we consider the mass not saturated, it should in descent warm up at the dry adiabatic rate, of approximately 1 C°/100 m, which would place the descending temperature curve appreciably to the right of the ascending at this elevation of around 1900 m. No such difference is found.

The pilot-balloon measurements at Concord also do not suggest subsidence. Here, two of the double-theodolite balloon runs, starting at 2:51 and 3:41 p.m., show directions fairly consistently between N and NW, and a fairly sharp increase in wind velocity at the level of 1720 m occurring at almost exactly the same level in both flights. See Table 33.

TABLE 33. WINDS AT 1500-2100 M AT CONCORD EARLY AND LATE IN THE ECLIPSE OF AUGUST 31, 1932

EARLY IN ECLIPSE				LATE IN ECLIPSE			
Time	Height	Dir.	Vel.	Time	Height	Dir.	Vel.
E.S.T.	m	0°=S	m/s	E.S.T.	m	0°=S	m/s
2:58p	1600	80°	0.8	3:49.5	1510	136	0.6
2:58.5	1720	133	2.6	3:50	1740	205	1.2
2:59	1740	153	5.8	3:50.5	1720	178	1.6
2:59.5	1900	146	5.0	3:51	1760	161	4.8
3:00	2000	156	7.0	3:51.5	1860	153	5.6
3:00.5	2080	127	6.0	3:52	1890	156	6.6
				3:52.5	2050	145	5.8

It appears, therefore, that the subsidence indicated between the curves of ascent and descent is not real, and that the apparent sinking can be adequately explained as the result of instrumental errors (especially the failure of the temperature and humidity pens to adjust themselves quickly enough to rapidly changing conditions).

3. *The Scarboro-Fryeburg flights.* (C.F.B.) At the request of Prof. Oliver J. Lee, the U. S. Navy flew three aerometeorograph-carrying airplanes from Scarboro, Me. to Fryeburg during the eclipse. The aerometeorographs were supplied and the records evaluated by the Weather Bureau, and were published in detail by Lee and Bryant, 1933. The airplanes took off at 2:19, 2:22, and 2:23 p.m., arrived over Fryeburg and took up their stipulated heights at 2:50, 2:51, and 3:00 p.m., which they maintained until 3:55, 3:58, and 4:01 p.m., then returned to Scarboro, arriving at 4:24, 4:30, and 4:38 p.m. These and the Concord flight provide a fairly adequate basis for determining (a) the changes of temperature due to the eclipse (and, unfortunately, other causes) to a height of 4000 m in the free air, and especially, (b) those at the heights at which the airplanes flew for a considerable time; and (c) whether there was any evidence of a decrease in humidity aloft, such as Clayton found in a kite record obtained on the *Otaria* (Clayton, 1908, p. 200, 201, 216).

TABLE 34 TEMPERATURE CHANGES FROM EARLY TO LATE IN THE ECLIPSE OF AUG 31, 1932, AS REVEALED BY AIRPLANE SOUNDINGS CORRECTED FOR TEMPERATURE LAG SEE FIG 25

HEIGHT ABOVE m s.l.	FLIGHT FROM CONCORD, N H	FLIGHTS FROM SCARBORO AIRPORT, ME			MEANS OF ALL FLIGHTS	AT CONSTANT LEVELS OVER FRYEBURG
		No. 35	No. 25	No. 4		
m	C°	C°	C°	C°	C°	C°
4000	.	+0.4	.	.	+0.4	
3500	.	+0.8	.	.	+0.8	
3000	.	+2.2	.	.	+2.2	-0.3†
2500	+0.8	+2.3	.	.	+1.6	
2000	+1.2	-0.4	.	.	+0.4	
1500	-0.1	+2.8	.	.	+1.4	
1250	-0.1	+2.1	.	.	+1.1	
1000	-0.1	+1.3	.	+1.0	+0.7	-0.4†
750	-0.3	+0.2	.	+0.9	+0.3	
500	-0.5*	+0.2	-0.2	+0.5	0.0	
250	-1.4*	-0.4	-1.3	-0.4	-0.9	-0.7†
0	-3.0*	-3.3	-3.5	-1.4	-2.8	

* At heights above the take-off, 105 m above m. s. l.

† At heights above Fryeburg, 128 m above m. s. l.

(a) In Table 34 and Fig. 25 the original data in Table 31 and as published by Lee and Bryant have been corrected for the lags of the temperature elements in order to give as closely as possible the true temperatures, level for level, notwithstanding the rapid rate at which the airplanes usually crossed them. In accordance

with the experiments of Lange and Draper¹ a lag coefficient of 0.27 was assumed for the Bosch & Bosch meteorograph (Concord) and one of 0.90 (mean of 0.75 and 1.04 found in two instruments) for the Friez meteorographs used on the Scarboro flights. The temperatures during the Scarboro flights were also corrected according to a lag coefficient of 0.75, with results differing little from the values obtained by using one of 0.90: for the 20 values of difference between ascent and descent only 3 were decreased by 0.2 (none more), and 6 by 0.1 C°. A temperature fall (partly diurnal) of 1.4 to 3.5 C° (mean 2.8 C° = 5.0 F°) on the ground gave way to falls of 0.4 to 1.4 C° (mean 0.9 C° = 1.6 F°) at 250 m, and falls of 0.2 to 0.5 C° and rises of the same amount (mean 0) at 500 m. Above this, the Concord flight showed a fall of

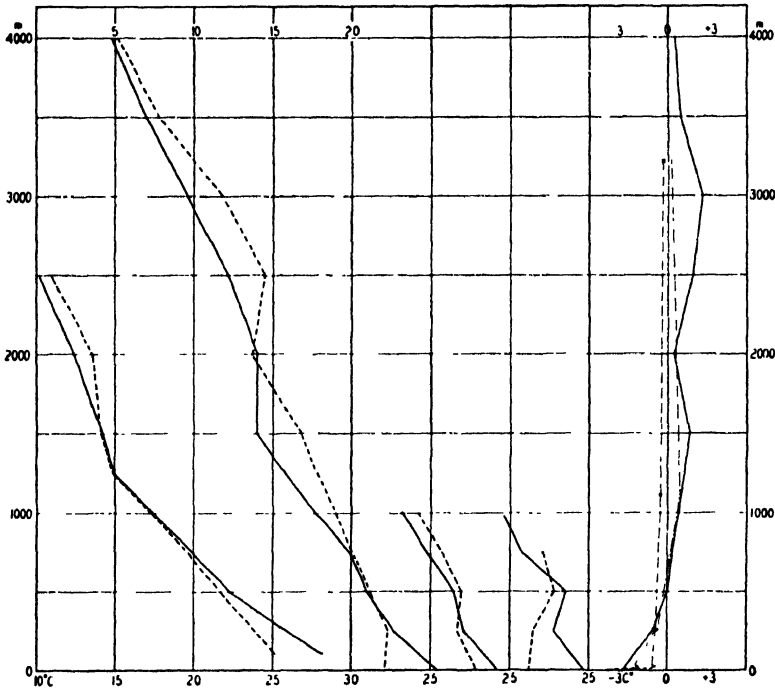


FIG. 25. Airplane temperature data, Aug. 31, 1932, corrected for thermometric lag, by levels of 250 or 500 m: early in the eclipse(——) and late in the eclipse(-----). The graph at the left is the Concord ascent, shown in detail in Fig. 24 and Table 31. The middle three are the Scarboro flights (Lee & Bryant, 1933). The right hand(——) graph is the mean difference between the early and late eclipse values for all four flights. The ----- line at the extreme right shows the eclipse effect (taken as the departure from the estimated diurnal curve) on temperature at the three heights maintained by the airplanes over Fryeburg, and at the heights on the mast there corrected (right line at base) and uncorrected (left line) for radiation effect. The . - - - line shows the net change in temperature while the airplanes remained at their standard heights.

¹ Loc. cit.

0.3 C° (0.5 F°) at 750 m (650 m above the ground) and 0.1 C° (0.2 F°) from 1000 to 1500 m, and above that, rises of 0.8 to 1.2 C° (1.4 to 2.1 F°). All the Scarboro flights showed rises at all levels above 500 m, except for one small fall at 2000 m, the means ranging from 0.4 C° (0.8 F°) at 750 m to 2.8 C° (5.0 F°) at 1500 m, above which the single high flight varies from -0.4 to + 2.3 C° (-0.7 to + 4.1 F°). The average from 1500 to 4000 m is 1.1 C° (2.0 F°).

Our analysis of the Concord flight (pp. 94-98) indicates a subsidence of 14 m as a possible cause of 0.15 C° of this rise, which leaves as the principal causes of the rise in temperature the continuing distribution of heat by long-wave radiation, by convection, and by advection of air from the heated interior. The convective distribution was effective to a height of 1700 m, the height of the tops of the Cu clouds (Fig. 24), while advection from the interior was confined to the layers above 1500 m, where the wind aloft first began to move from a continental direction. While no lowering of temperature due to the eclipse is proven above the 500 m level, it would be a mistake to claim that none was present, for this may well have occurred as an offset to the rise in temperature in progress there by radiation, convection, and advection. Perhaps the continuous gradation of increasing rise in temperature to 1250 m may be taken as an indication of an eclipse effect of at least a few tenths of a deg. C. to at least 1000 m. In fact, there must have been some tendency toward a reduction in temperature owing to the loss of direct solar radiation, which, to a height of several km, is responsible for a few tenths of a deg. of the diurnal range¹ (cf. par. (b), below), though in the short period of an eclipse should not exceed 0.1 C°.

(b) The 3 planes from Scarboro flew over Fryeburg at nearly constant heights of 3090, 988, and 256 m above the ground, which was 128 m above m.s.l. Treated in the manner that other temperature data were handled (see pp. 35-38), after correcting the observed temperatures to the average level according to the lapse-rates of temperature, it appears that the eclipse effect was a cooling of 0.7 C° at 256 m,² 0.4 C° at 988 m,³ and 0.3 C° at 3090 m. For the two upper levels these "coolings" are taken from a general rise of 0.2 C° at 3090 m, and 0.8 C° at 988 m, while there was a general fall of 0.6 C° at 256 m, all from about 3:00 to 4:00 p.m. The time of minimum relative temperature (i.e., when the "eclipse" effect was greatest) at all three levels was 3:33 p.m., 2 min. after the end of totality, suggesting that in the free

¹ Cf. H.-J. Tanck, Die tagliche Erwärmung der Atmosphäre infolge der Absorption der direkten Sonnenstrahlung durch den atmosphärischen Wasserdampf. *Ann. d. Hydr. u. Mar. Met.*, v. 86, p. 47-63, pl., Hamburg, 1940. [In July and Aug., which for the lat. of Hamburg would correspond to the end of Aug. in New England, the daily warming is approx. 0.6 C° to a height of 3-4 km.]

² Cf. 0.6 C° eclipse effect at 300 m observed by kite (Clayton, 1908).

³ Cf. approx. 0.6 C° eclipse(?) effect at 1070 m observed by kite (Dines, 1906)

air the temperature effect of the eclipse was largely due to reduction of direct solar radiation.

(c) The data of vapor pressure showed no consistent change at all levels. At 3090 m it rose 3% between 3:00 and 3:33 p.m., and 3% more by 3:55 p.m. At 988 m, it fell 6% from 3:01 to 3:33 p.m., and 1% more to 4:01 p.m. At 256 m it rose 4% from 3:00 to 3:30, fell 1% to 3:33, and, after a decline to the 3:00 p.m. value at 3:40 and 3:45, returned to the 3:33 p.m. value. The Concord flight, which, however, did not remain over a single spot, showed a fall of 12% in vapor pressure. Since the temperature fell 0.2 C° and, as has been shown in sec. 2, above, since there was no evidence of subsidence, this decline in vapor pressure must be ascribed to horizontal differences. Samuels, 1925, reports kite data showing simultaneous falls of temperature and vapor pressure at Ellendale, N. Dak., and a fall in temperature with rise of vapor pressure at Groesbeck, Texas, in the eclipse of Jan. 24, 1925. Our conclusion is, therefore, that there is no substantiation here of Clayton's hypothesis of subsidence, based on his single kite observation at sea.

4. *Summary.* The data from four airplane flights indicate a temperature effect caused by the eclipse decreasing geometrically by about $2/3$ of its value for each 250 m up to 500, and that above this there is perhaps a 0.4 C° eclipse fall at 1000 m, and 0.3 at 3000 m, owing in part to the loss of the heating effect of direct solar radiation, for the eclipse minimum comes at the first observation after totality, in this case 2 min after. There is pretty definite evidence in unchanged haze-layer heights, cloud heights, wind-boundary heights and a lack of consistent decrease in vapor pressure that no circulatory subsidence of any consequence could have taken place. This confirms the evidence from cloud motions and pilot balloons that, while a weak inflow above and outflow below may have occurred in some instances it was not enough during the eclipse of 1932 to produce what might be called a cyclone.

VII. SUGGESTIONS FOR FURTHER STUDY

By B. HAURWITZ AND C. F. BROOKS

In a total eclipse the direct and sky-reflected solar radiation reaching the earth's surface are reduced to zero in about an hour. The rate of decline is practically identical with what would be expected from the rate at which the area of the sun is obscured and the rate at which the intensity should change with the altitude of the sun, taking into account both the changing amount of total absorption in the atmosphere and the changing spread of the rays over the surface on which the intensity is measured. If these factors could be taken into account with great precision

there should remain a small deviation of the observed from the computed rate of change, namely, that due to the slightly less radiation from the margin than from the center of the sun. Perhaps this difference can be measured in an eclipse, though atmospheric transmission may change owing to eclipse cooling; but it appears that more accurate results are obtainable from direct determinations of radiation nearly simultaneously from different parts of the uneclipsed sun. The same is probably true for the relative spectral composition of sunlight. These are astronomical points, but they are important to meteorology, for, with these facts definitely established, any deviations from the astronomical expectations may then be ascribed to the atmosphere. Thus, the radiation should be measured as accurately as possible with and without color filters, before, during and after the eclipse, in order to discover probable variations of atmospheric turbidity which might be caused by reduced convection and phenomena of slight condensation.

Observations of sky-polarization would also prove interesting, especially if it were possible to determine the sky-polarization at a great number of points during a short interval of time, as with Sekera's¹ or Cohn's² apparatus. Such data might also give hints as to condensation.³

Measurements of atmospheric radiation during eclipses are scarce and much needed for a full understanding of the observed temperature effects. Though the average fall in air temperature as ordinarily measured at a meteorological station is of the order of 0.7 F° per 0.1 g. cal/min, cm² fall in total solar and sky radiation on a horizontal surface, there are appreciable deviations from this, which measurements of atmospheric radiation would surely help to explain. Other factors in the fall in air temperature are, naturally, the ground-surface temperature and the specific heat and conductivity of the ground (or its vegetation-cover), the eddy conductivity of the lowest layer of air and the absorption or emission of heat in evaporation or condensation. Observations should include, therefore, not only ground-temperatures, at the surface and different depths, the conductivity of the soil and the specific heat of the ground surface, but also the air temperatures, humidities and wind at a number of heights (say, 0.5, 2, 5, 10, 20, 35 and 50 meters). There should be more than one station, to represent diverse ground-surface conditions, and others to include measurements over water. Measurements of long-wave atmospheric radiation or at least of humidity would be particularly important for the study of temperature-changes, since the moisture content affects the radiative transfer of heat. Steel structures, like radio masts, seem very suitable for such observations.

¹ Z. Sekera, *Lichtelektrische Registrierung der Himmelpolarisation*, *Gerl. Beitr. z. Geophys.*, v 44, p 157-175, 1935.

² W. M. Cohn, *Polarization of skylight close to the sun*. *Ibid.*, v. 53, p 159, 1938.

³ I. F. Hand, *An aid in locating and studying clouds*. *Mon. Weather Rev.*, v 61, p. 302-303, 1933.

While additional open-scale measurements of pressure might in the course of time provide a sufficient body of data for the statistical elimination of irregular variations of weather and the diurnal course of pressure, it seems that variations of pressure, which are merely an index of circulation caused by an eclipse, might be established more readily by observations of temperature, humidity, and winds to heights of 2 or 3 km. The data of temperature and humidity would be obtainable by captive balloon, airplane, or radiosonde; the wind data by frequent (every 15 min.?) pilot balloons with rapid rate of ascent. There should be two theodolites per station or the "tail" method should be used, or else a balloon with radiobarograph attached and viewed through a single theodolite. If a number of stations can be manned, at least four should be installed 200 and 500 km from, and preferably in a line perpendicular to, the path of the shadow. The use of cloud motions to determine upper air circulation is disappointing, perhaps because of the small number of observations, but nephoscopic observations, or, better still, photographs of the sky every 5 min., should serve as a valuable adjunct to observations of pilot balloons.

Further observations of shadow-bands would be of value if related to full aerological observations (including cloud motions) and especially if they can be observed simultaneously on surfaces at different heights in the same locality. A horizontal white surface, and separate observers for lie of bands and for direction and velocity of progressive movement are desirable. Precise measurements of shadow-bands (usually very difficult), and attempts minute by minute to factor confused motions into groups differing in size, direction and velocity, are desirable. One group may dominate first, and then another, as the crescent of the sun changes in thinness. The relative prominence of different groups may vary as the crescent of the sun changes in width.

While eclipse meteorology may contribute little to the elucidation of general meteorological problems, the phenomena during an eclipse of the sun add interest to the occasion and their interpretation challenges ingenuity.

END

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This bibliography does not repeat the comprehensive list of titles given by Barlow, 1927a, (except where they are referred to in our study), but merely adds to his list; nor does it include publications mainly astronomical, unless there is meteorological material of present significance

SPECIAL ABBREVIATIONS

- BAMS Bulletin of the American Meteorological Society, Milton, Mass
MWR Monthly Weather Review, U. S. Weather Bureau, Washington
QJRMS Quarterly Journal of the Royal Meteorological Society, London.

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