The course of this conflagration was with the wind from a southwest to a northeasterly direction, in spite of various timber and fuel types, sharp ridges, valleys, cultivated fields, roads, and rivers. By the morning of August 4 an area 5 miles wide by 11½ miles long had been burned over, with several spot fires still farther ahead and as much as 15 miles from the point of origin. Over 20 of these spots were finally controlled before they burned together or backed to the main fire. The largest reached a size of 350 acres and was 3 miles ahead of the main fire.

This unusual rate of spread obviously points to the great importance of two factors; viz, extreme dryness of the fuel types, and wind as a propelling agent and carrier of blazing embers to start spot fires. These conditions as well as air temperature and relative humidity, are shown in Table I as they were measured at the Priest River station about 2 miles north of the fire. In considering these temperatures and humidities, they should be compared to the 20-year normal maximum temperature of 84.2° F. and the 5:00 p. m. relative humidity of 38 per cent for August 3 at this station.

These data show that when duff and wood moisture contents are as low as 4 or 5 per cent in the open and 9 or 10 per cent under dense timber, wind velocities of 12 to 18 miles per hour, together with maximum temperatures of 90° or 92° F., and humidities of 9 or 10 per cent result in possible spread of fire at about 1,600 acres per hour in northern Idaho.

When these conditions are compared with the measurements made by Gisborne in 1926, it is apparent that the difference between 1,500 acres per day and 1,600 acres per hour is due to what might have been considered as relatively small differences in fuel moisture, wind, temperature, and humidity. This comparison shows very closely, however, that these small differences combine to produce a most exceptional rate of spread of fire. This also demonstrates the importance of recognizing and forecasting temperatures of over 90° F., humidities around 10 per cent, coupled with winds of only moderate velocity, when the duff and slash moisture contents are under 5 per cent. At such times, every effort in control must be made if fires are to be reached and restricted before they grow to such great size as to require tremendous expense for their suppression.

EVAPORATION FROM LAKES AND RESERVOIRS

By C. E. Grunsky

What has heretofore been published on the experimental data relating to evaporation must be used with caution. The United States Weather Bureau standard evaporation pan A, a land pan, does not furnish a satisfactory basis for comparing the evaporation from a large body of water in one place with that from another body of water in some other place. The same is true of most floating pans, nearly all of which have been insufficiently immersed. The Chestnut Hill Reservoir records by Desmond Fitzgerald[1] were obtained in part from a floating pan, the water in which sometimes differed as much as 10° F. from the outside water. The F. H. Bigelow experiments under direction of the United States Weather Bureau at Salton Sea with a battery of pans called floating pans were made with pans whose water surface was 3 or 4 inches above the surrounding water. These Bigelow records should not be credited to floating pans which should always have their water surface lower than that of the outside water. A new type of land pan with shaded rim is below suggested.

Wind effect on evaporation being taken into account the ordinary relation of evaporation to mean monthly air temperature is indicated in this contribution both in a table and by diagram. An altitude factor is suggested to be used until something better is found.

The writer desires to suggest the use of a type of land pan which will give results for some periods of time, such as the month, which will better indicate the relative amount of evaporation loss from widely separated large open-water surfaces. Furthermore, he presents some conclusions bearing on the relation of the mean monthly evaporation rate to mean monthly temperature, with inclusion of the effect on this rate of air movement and altitude.

The standard evaporation pan A of the United States Weather Bureau conforms substantially to the following description:

The pan is circular, 48 inches in diameter, 10 inches deep, and is filled with water to a depth of about 8 inches. It is built of galvanized iron and rests on wooden supports placed on the surface of the ground.

Pans of this character are widely distributed throughout the country and are intended to afford a basis for comparison of evaporation rates in different localities. The measurements of water loss from such pans with suitable correction factors are also supposed to serve as a dependable guide when evaporation from open water surfaces is to be approximated.

The standard pan seems to have been constructed with a view to giving maximum effect to the various factors which contribute to the rate of evaporation. Thus, for example, the sides and bottom of the pan are exposed to air, free circulation even under the pan being prescribed. The sides of the pan outside and inside have maximum exposure to sunshine. The result of this arrangement is that the water in the pan in sunshiny warm weather is materially warmer than the surface of a broad sheet of water would be, and in cold weather it cools off more rapidly. Moreover, the sunshine, which is practically continuous from sunrise to sunset at some places and very spasmodic at other places, falling upon the sides of the pan not only imparts heat to the water in the pan by transmission through the metal of which the pan is made and thereby accelerates evaporation, but the sides of the pan above the water frequently become quite hot and the wind ripples splashing up against and wetting these sides and evaporating therefrom unduly increase the water loss from the pan. When it is considered that an open body of water has only its surface exposed to the sunshine and air and that there are no vertical metal confining sides around small areas, then the inadequacy of this arrangement becomes apparent.

The heat of the sun imparted to the sides of the pan is not a factor that can be evaluated. Sunshine is not continuous; it is not the same from day to day. In the

[1] Transactions, Am. Soc. C. E., Vol. XV.

ideal pan its effect should, therefore, be reduced to a minimum.

The present type of standard land pan should be replaced by another conforming substantially to the following requirements. (See Fig. 1).

The pan should be circular, 4 feet in diameter. It should be placed in the ground with earth banked around it well above the surface of the water in the pan. The rim of the pan should carry an inverted V-shaped rider, the inner limb of which should come to within about 1 inch of the water surface. The purpose of this rider is to shield the side of the pan from the direct rays of the sun on the inside of the pan down to the water surface and on the outside down to the earth fill.

The water in the pan should be at least 15 inches and not more than 18 inches deep.

There should be a peg in the center of the pan with pointed top.

Observations should be taken daily, preferably at about 7 a. m. and at 2 to 3 p. m., of temperature of the air, of temperature of the water in the pan, of rainfall, and of wind velocity.

From time to time the pan should be refilled to the top of the peg. The refilling need not be daily. It should preferably be whenever the water has fallen one-eighth inch or more below the top of the peg.

Special observations should always be made when rain threatens and immediately after rain ceases to fall.

The observer should be provided with a standard cup preferably of such size that one cup full will represent, say, 0.02 or 0.05 inch of depth in the pan. He should be instructed to use full cups only in filling the pan and full cups only in bailing out the pan to the top of its peg.

Greater refinement will only then be required when observations are being made to establish the influence of some particular factor on the rate of evaporation.

The writer has had frequent opportunity of visiting so-called floating pans, the measured evaporation from which is intended to give a close approximation to the evaporation from an open water surface. These pans appear in almost every case to be improperly immersed in the surrounding water or to be otherwise of a type which defeats their purpose. Thus, for example, in the case of the evaporation studies made by Desmond Fitzgerald at Boston, he reports that sometimes the difference in temperature of the water in his floating pans and of the water surrounding these pans was as much as 10° F., and yet his record of evaporation has been generally accepted as classic, although what was wanted was the evaporation from water at the temperature of the surrounding water and not that from water at a different temperature.

The following information is taken from Mr. Fitzgerald's paper (Trans. A. S. C. E. Vol. XV, p. 596).

Referring to two small floating pans, the evaporation from which was measured during periods from 1876 to 1882 when the reservoir was not covered with ice, he says of certain observations taken every hour of the day and night, that these observations led him—

* * * to infer that, owing to the varying temperatures of the water from hour to hour in the tanks as compared with the reservoir and the varying march of these changes according to the month of the year, little dependence could be placed on the value of the results for application under other conditions, unless some relation could be traced by more perfect conditions.

The large tank of the apparatus installed in 1884 for the more refined observations is thus described by him:

In the center of the raft the tank "A", 10 feet in diameter and 10 feet deep, was immersed. This tank was made of staves of wood spaced 1 inch apart except where the hoops were located, so as to give free access for the outer water to the thin copper linine inside. Many holes were bored in the wooden bottom for the same purpose. It was expected that this would keep the water insidg the same, or nearly the same, temperature as that outside, but this was sometimes far from being the case. On one occasion the writer observed a difference of 10° F.

The flotation effect of the wood probably kept the water in the tank higher than the outside water.[2]

Again, Prof. F. H. Bigelow reported on the evaporation from a battery of pans of various sizes "floating" in water at the margin of Salton Sea, Calif. On investigation, however, it is found that his were not floating pans in the true sense. They were immersed pans with water intentionally held 3 or 4 inches higher than the surrounding water. The only influence of the surrounding water was to give some measure of temperature control. All of the heat in the hot rims of the pans above water went into evaporation from the pans and destroyed the value of the observations—a fact which should be made generally known.

As a rule, the so-called floating pans are, as in the case of the Bigelow pans, insufficiently immersed. The explanation given is that thereby more of the side of the pan is above the surrounding water and there is less likelihood of water being splashed into the pan. But all such insufficiently immersed pans show more water loss than a properly arranged floating pan would show. How much
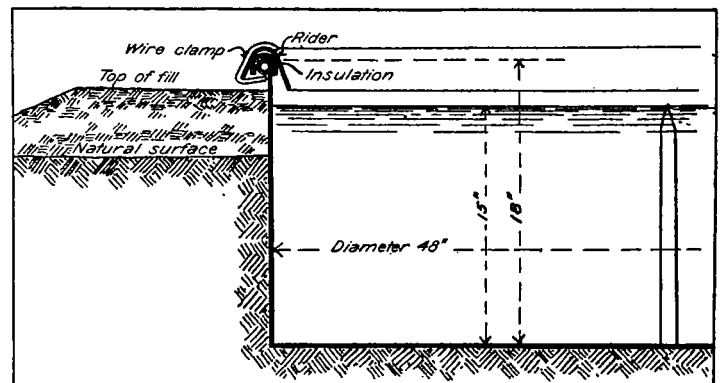

FIGURE 1.—Suggested type of standard evaporation pan

more? What correction factor to use? No one can tell, because sunshine is not dependable either as to duration or intensity. The correction factor would vary from day to day and from month to month.

Reference may be had in this connection to a comparison of evaporation records from two pans recently made, at the writer's suggestion, by the United States Army Engineers at Suisun Bay, Calif. Assistant Engineer C. A. Mees was in charge of these experiments. The evaporation from a pan insufficiently immersed which had been in use throughout the summer season was compared with the evaporation from a properly arranged floating pan during the two months October and November, 1930. It appears from the record that in these two relatively cool months, the pan which was insufficiently immersed showed 10 per cent more evaporation loss than the other.

The properly arranged floating pan will have its water surface at all times lower than the surrounding water. The heat which sunshine or warm air then puts into the sides of the pan above water will go into the outside water and will not contribute to a distortion of the evaporation rates. The floating pan might also to advantage be provided with an inverted V-shaped rim rider.

[2] See illustration, Transactions, Am. Soc. C. E., Vol. XV, p. 597.

The evaporation measured from such a floating pan, not less than 3 by 3 feet square or 4 feet in diameter, with not less than 15 inches of water, if placed well off shore in fairly deep water should be in reasonably close agreement with the actual evaporation from the surrounding water.

Enough has been said to show that very little dependence can be placed on most of the records which are ordinarily marshalled to evaluate coefficients for some evaporation formula or to show the influence of altitude, temperature, wind, and vapor pressure. It need only be added that the attempts to use ordinary meteoro-

it may be a pan floating in shallow, marginal, inordinately warm water.

Because of uncertainty of hours and intensity of sunshine and because of wide variation in wind effect, which is sometimes excessively accelerated by the splashing of water ripples against heated sides of the pans, the Weather Bureau's standard pans do not fairly indicate relative evaporation rates throughout the country. This statement is repeated because this fact can not be too strongly emphasized. It has, heretofore, been generally ignored. These pans, for the same reason, do not correctly indicate for their own stations the relative
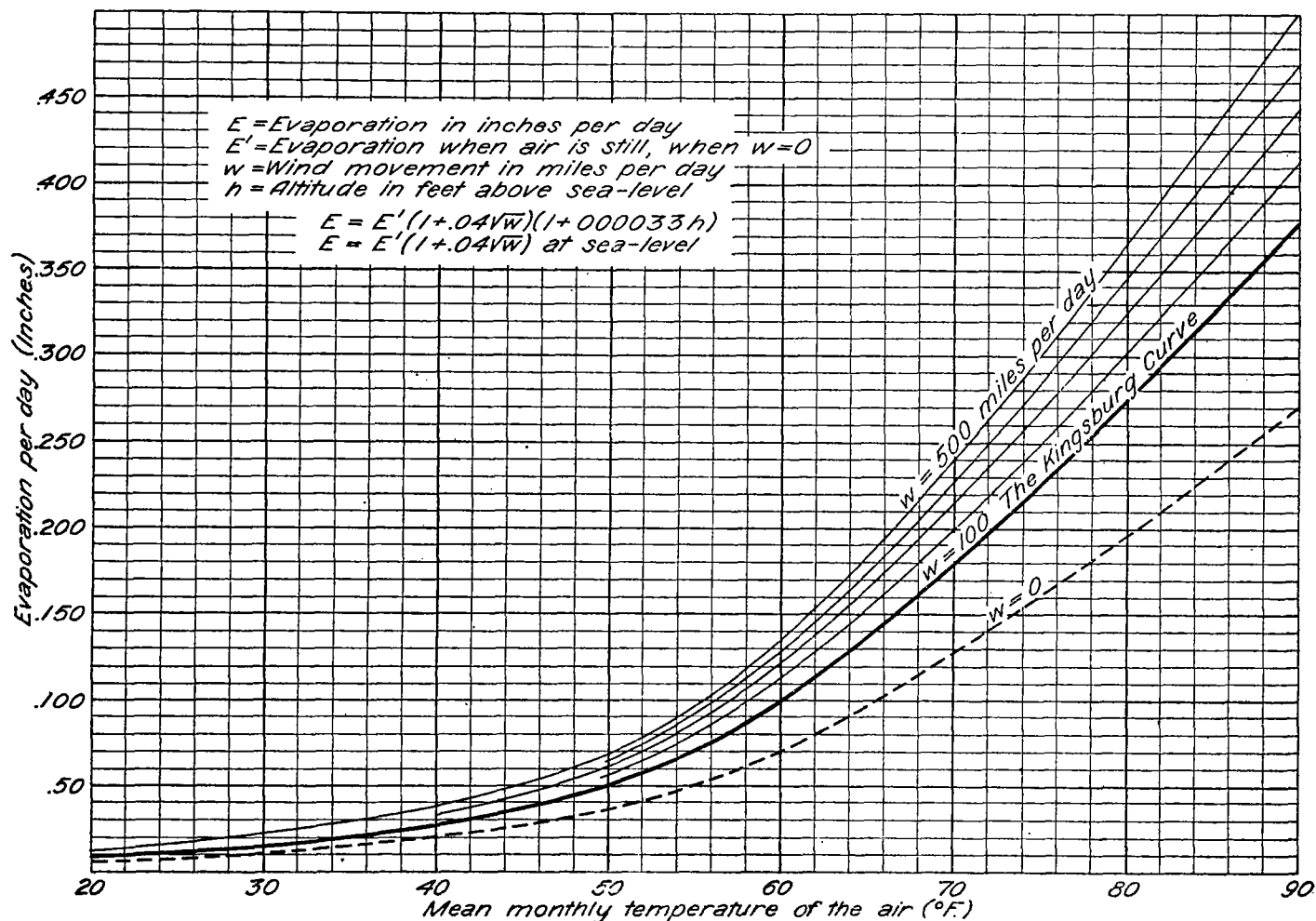

FIGURE 2.—The observations at Kingsburg, Calif., on which these curves are based, covered a 4-year period 1881–1885

Two pans, each 3 feet square were used, one a land pan, embedded; the other a pan floating in Kings River

The mean annual evaporation from the land pan was 4.86 feet, from the floating pan 3.85 feet

Conditions were such that the floating pan must have indicated somewhat less evaporation and the land pan materially more than that from a large open water surface. Consequently, the probable monthly evaporation rates from open water for Kingsburg climatic conditions were approximated by giving the floating pan record three times the weight of the land pan record.

logical data as elements in formulas when these formulas are based on some law of evaporation, have generally been failures. This results from the fact that it is impracticable to use long-time average values of the controlling factors in place of these factors as variables in formulas which should be integrated from minute to minute, or possibly at most from hour to hour. It follows that practically all that has been written on the subject of the loss of water from lakes and reservoirs by evaporation must be read with caution and recourse must be had to original data to determine how it may be used, if at all. Not even the records of floating pans, as above stated, can be accepted without question, because the "floating pan" may be and probably is merely a pan suspended in water or

amount of evaporation month by month. Consequently, no correction factor applicable to the records established by such pans which would fairly approximate actual water surface evaporation can be found. It does not exist.

There are in California alone some 20 or more points at which evaporation from pans is being measured. Of the resulting records comparatively few will be helpful in a study of the relation of the rate of evaporation from a large open water surface to the known meteorological conditions.

The evaporation from pans buried in the ground as above described would serve the purpose of comparison much better and would also be helpful in throwing some needed light on wind effect.

When Professor Bigelow was making his experiments at Salton Sea, the writer tried to have him devote some attention to the determination of the relation of evaporation to ordinary meteorological conditions, such as mean monthly temperature, daily temperature range, relative humidity, and wind movement, but without success. And yet all experiments thus far made show conclusively that mean air temperature, for some period of considerable duration, such as a month, is frequently a fair index of the rate of evaporation from a water surface. This is due largely to the fact that changes in water-surface temperature will follow air-temperature changes, and water-surface temperature is a major factor of influence on the rate of evaporation. Next in influence is the wind movement. Wind movement is generally 100 to 200 miles per day. No great error would be made if its departure in a single month from ordinary wind movement were ignored. This fact has led many engineers in estimating evaporation to the use of curves which show the probable unmodified relation of evaporation to the mean monthly temperature. This is equivalent to assuming, when better information is lacking, uniformity of aggregate wind movement throughout each month of the year. It is astonishing how well such a curve will meet ordinary requirements, when annual evaporation alone is in question.

However, it is frequently desirable to approximate more closely the evaporation during the individual months. Suppose, now, that observations have supplied sufficient basic data to establish the relation between evaporation and temperature for an observed wind movement in some time period, such as a month, then the basic rate of evaporation for no wind can be fairly well approximated by use of a formula of the type

$$E = E'(1 + .04\sqrt{w})$$

Here E is the evaporation rate in feet per day when the wind movement is w miles per day and E' is the evaporation in feet per day for no wind movement. Wind should be introduced in this equation as measured above ground, without reduction to air movement at the water surface. It follows that

$$E' = \frac{E}{1 + .04\sqrt{w}}$$

Table 1.—*The relation between evaporation from an open water surface and mean monthly temperature*

[Based in the main on the State engineer's observations at Kingsburg, Calif., 1881–1885]

[The average monthly wind movement at Kingsburg is about 3,000 miles or 100 miles per day. w=miles of wind movement in 24 hours. The figures in the table indicate the probale average daily evaporation during months with mean temperatures as noted in the first column]

Mean monthly air temperature, degrees, Fahrenheit	At Kingsburg, evaporation in inches per day		Computed evaporation $E=E'$ (1+.04 $\sqrt{w}$), inches per day			
	Measured $w=100$	Estimated $w=0$	$w=200$	$w=300$	$w=400$	$w=500$
20	(0.0091)	0.0065	0.0102	0.0110	0.0117	0.0125
25	(.0126)	.0090	.0141	.0152	.0162	.0170
30	(.0161)	.0115	.0179	.0194	.0207	.0217
35	(.021)	.0150	.0235	.0254	.0207	.0284
40	.028	.0200	.0313	.0338	.0360	.0378
45	.037	.0265	.0415	.0448	.0477	.0501
50	.050	.0360	.0565	.0608	.0648	.0680
55	.070	.0500	.0783	.0845	.0900	.0945
60	.099	.0705	.110	.119	.127	.133
65	.136	.097	.152	.164	.175	.184
70	.178	.127	.199	.215	.229	.240
75	.224	.160	.250	.271	.288	.302
80	.274	.196	.307	.332	.353	.371
85	.325	.232	.364	.392	.418	.438
90	.378	.270	.423	.457	.486	.510

Based on the Kingsburg, Calif., evaporation records (see Transactions, Am. Soc. C. E., Vol. LXXX, pp. 1968 to 1983) the writer has used with much satisfaction the relation expressed in Table 1 and shown in Figure 2, between mean monthly temperature and the mean rate of evaporation, modified by the influence of wind. In individual months, due to unusual conditions of humidity and other factors, some wide departures are still to be expected. The indicated annual in any computation based on the table is believed to be fairly dependable, particularly if an altitude factor be introduced.

The rate of evaporation is unquestionably affected by air pressure. Evaporation increases as air pressure decreases. For the same temperature and wind conditions it will be greater at high altitudes than at sea level. Russell[3] has suggested that this increase is inversely proportional to atmospheric pressure on the surface of the water. According to this conception the altitude factor might be written

$$\frac{30}{30 - \frac{h}{1000}} \quad or \quad \frac{30000}{30000 - h}$$

or near enough $1 + 0.000033\ h$ where h is the altitude above sea level in feet. This expression is based on the well-known fact that atmospheric pressure at sea level is equivalent to about 30 inches of mercury and that this pressure decreases by about one inch of mercury for each 1,000 feet altitude.

The values in the table may, then, until better information is available, be multiplied by this factor and the evaporation rate will be approximated from the values given in the column headed E' in the table by

$$E = E'(1 + 0.000033h)(1 + 0.04\sqrt{w})$$

Where E is the evaporation per day at h feet altitude above sea and at a wind velocity of w miles per day, and E' is the evaporation at sea level in perfectly still air. The value of E' varies with mean monthly air temperature about as shown in the table.

Because the changes of the water surface temperature lag behind the changes of air temperature, the relation shown in the table between mean air temperature and evaporation has no application to short time periods such as an hour, a day, or a week. Even in the case of a 30-day period probability rather than close approximation is indicated. It follows that the principal use of the table should be to determine annual evaporation from mean monthly air temperature, wind movement during the month, and altitude.

The values presented in this table and as shown by the curves may be used with confidence to establish with sufficient approximation for ordinary purposes the annual evaporation from open water surfaces wherever located. In the case of shallow ponds where water temperature is relatively high the evaporation may be considerably larger than the figures in the table would indicate. Where humidity is unusually high the evaporation will probably be less than that given in the table.

It is interesting to note that the use of the table or the curves with introduction of the altitude factor will indicate a probable annual evaporation: For climatic conditions similar to those on the Isthmus of Panama a little more than 7 feet, which is probably in excess of the actual fact; for the Salton Sea in southeastern California, about 6.2 feet; for Lake Superior, about 17.1 inches;

[3] T. Russell, Asst. Prof. U. S. Signal Corps. See Monthly Weather Review, September, 1888,

for Lake Michigan-Huron, about 24.7 inches; for Lake Erie, about 30 inches; for the vicinity of Boston, about 28.5 inches; for Lake Tahoe, Calif., (altitude 6,230 feet) about 22 inches; for Great Salt Lake, Utah (altitude 4,200 feet) about 26 inches.

DISCUSSION

By C. F. MARVIN

Perhaps there is no measurement of a meteorological phenomenon concerning which there is greater diversity of view than prevails with reference to evaporation from free water surfaces. The Weather Bureau, in choosing the present so-called standard type of evaporation pan, fully considered practically all the faulty characteristics pointed out by Mr. Grunsky.

In reaching our decision we are compelled to recognize that the observations must be continued, not for a few weeks or months, but over periods of several years of time, and under the care of observers who are often conscientious enough but, nevertheless, lack the highly trained character of engineers or laboratory physicists whose minds are always alert, as to sources of error and fallacious records. In the case of pans floating in water or pans buried deeply in the ground, it is almost surely a question only of time before an insidious leak develops in the seams, or even in the body of the pan itself, out of which water passes in unknown quantities, always measured as so much evaporation. Maintenance of a proper condition of cleanliness is difficult, unless the pan can be thoroughly washed and rinsed, a process much simplified when the water can be poured out.

Mr. Grunsky's criticism that the Weather Bureau type of pan is so freely exposed to the air, even underneath, that its temperature fluctuates widely, is true, but this construction is one that permits of the discovery of leaks and faults of the apparatus that perhaps might otherwise escape the notice of a careful observer.

Moreover, the conditions that surround the standard Weather Bureau pan undoubtedly lead to a larger quantity of evaporation than that representing conditions over large, free surfaces of reservoirs, lakes, etc. However, this larger evaporation admits of a more accurate measurement, and its subsequent correction is a subtractive reduction of the actual observation, involving in principle a greater accuracy than would otherwise be the case; that is, the engineer in using these data is on the safe side, inasmuch as the evaporation may be really less than that estimated from the observations.

While these remarks are applicable to the Weather Bureau practice, there is a full realization of the decided advantage of making evaporation measurements that require no consequential correction of any kind. However, this concept presupposes that the evaporation characteristic of a given climate is a definite and constant thing for all possible utilization, such, for example, as the water losses from open reservoirs, water losses from vegetation by transpiration, forest cover, etc. Each of these uses of the evaporation characteristic of a given locality is contemplated in the data being collected by the Weather Bureau, and while our results may have a limited value for determining the exact evaporation from a free reservoir surface, they may have greater value for other uses.

RELATIVE FREQUENCY OF CENTERS OF CYCLONES AND ANTICYCLONES IN THE UNITED STATES

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Cyclones and anticyclones are difficult to deal with statistically, hence have not received attention in proportion to their importance as climatic elements. This paper attempts what may be called a "census" of the number of centers that appear in each 5° square of latitude and longitude, at the 8 a. m. and 8 p. m. (eastern standard time) observations, per month and per annum.

In order to eliminate the varying lengths of the months, the monthly data have been reduced to the number of occurrences per 1,000 observations. For the year, the number of centers per annum per 5° square are given here.

The monthly and annual statistics have been entered at the center of each square, and lines of equal frequency drawn. Graphs showing the march of frequency through the year have also been drawn for each square, and these have been transferred to maps of the United States on the Mercator projection, so that each square is of the same width in longitude.

Before enumerating the results of this study, it must be pointed out that these statistics differ from those of Garriott (1) and Kullmer (2), which show the number of centers that passed across the individual squares. The present paper counts only those centers that were in the square at the two daily observations.

The charts and graphs accompanying this paper show that—

(1) The number of centers, of both cyclones and anticyclones, is greater in the interior of the continent than

around the margins. Mark Twain, in a famous after-dinner speech (3) has called attention to the variability of New England weather. These charts show more than twice as many centers over the Great Lakes and the Plains as in New England. Success in weather forecasting (4) is negatively correlated with the number of centers, and is at a minimum in the Lake region.

(2) A center of maximum frequency of cyclones exists in Saskatchewan at all seasons.

(3) There is a maximum of frequency of cyclones in the Lake region in July and August, in the West Gulf States in January. The intervening States show two maxima, one in spring, another in autumn, corresponding to the popular tradition of the "equinoctial storm," and also to two maxima of rainfall; e. g. in eastern and southern Wisconsin. Whether there is continuous travel of a "polar front," or tendency to steep temperature gradients, back and forth from the 30° parallel to the 50° parallel of latitude, may be worth investigating.

(4) In winter, a loop of maximum frequency of anticyclones extends from Saskatchewan to the southern Appalachians.

(5) Centers of anticyclones have a maximum of frequency in Oregon and Washington in summer, when the semipermanent anticyclone in the Pacific is at its greatest intensity.

(6) Maxima of frequency of anticyclones appear successively in contiguous regions as follows: July to