Hence

$$t' = 125.3 \times (1.79 - 0.92) = 125.3 \times 0.87 = 109 \text{ seconds}.$$

In finding the final temperature of the rain drop we introduce a new quantity $E'$ instead of $E$ and put $\theta_0$ equal to zero in the equation giving the value of $\theta$. Then we get

$$\theta = \frac{ql}{E'}\left(1 - e^{\frac{3E'}{c\rho r}t''}\right)$$

in which we shall put $145 - 109 = 36$ for $t''$. In actual calculation we put $E$ equals to $E'$ in absolute values, since we have, for the present, no adequate value for $E'$.

Then we have

$$\theta = 2.5 \times \left(1 - e^{\frac{36}{125.3}}\right)$$

$$= 2.5 \times (1 - 1.33) = -2.5 \times 0.33 = -0.8°\text{C}.$$

This is of course the same result which we obtain by putting $t = 145$ in equation (2).

Hence the final temperature of the drop will be

$$-0.8 - 1.5 = -2.3° \text{ C}.$$

From the above calculation we see that in the case under consideration the conduction and evaporation of rain drops falling through ice-cold layers of the atmosphere will be sufficient to cool them many degrees below the freezing point, and to cause them to cover the objects with the coating of ice when they come to touch these objects. In some cases in which the air is too moist the drops of rain cool to the dew point of the air after they fall a few meters from their mother clouds, and condensation begins instead of evaporation on their surfaces. Hence the formation of glazed frost is not probable in such cases.

In conclusion I express my sincere thanks to Drs. K. Nakamura and S. Fujiwhara of the Central Meteorological Observatory for their kind suggestions in the preparation of this note, and also to Mr. J. Yamada of the meterological observatory, Asahigawa for his kindness in sending me the report of the remarkable glazed frost given in the text.

REFERENCES.

(1) **Meinardus, W.** Der Eisregen vom 20. Oktober 1898 über Mittel- und Ost-Deutschland. Wetter, Berlin, 1898, p. 253.

(2) **Angot, A.** Traité élémentaire de météorologie. Paris, 1899. p. 257.

(3) **Hellmann, G.** Ueber die Entstehung von Eisregen. Bericht. d. K. preuss. Akad. Wiss., Berlin, 1912, p. 1048.

(4) **Gold, E.** Glazed frost. Symons's met. mag., London, 1914, **48**, p. 233.

(5) **Trabert, W.** Verdampfung von Regentropfen. Meteorol. Ztschr., Wien, 1896, **13.** Jhrg., p. 323.

## HAZE OF MAY 13 TO MAY 17, 1914.

From the 13th to the 17th of May, in that portion of the United States extending from Virginia north to Maine and west to South Dakota, numerous observers reported the presence of haze which, on investigation, proves to have been principally of a reddish brown tint, apparently due to the dissemination of dust from forest fires. It does not seem to have been due to any special distant volcanic eruption as imagined by some. At Mount Weather, Va., the haze was very dense on and after May 19, but Prof. H. H. Kimball at that place reports that he finds nothing of special meteorological character that can be spoken of as important.—[C. A.]

## THE THERMAL REGIONS OF THE GLOBE.[1]

By A. J. HERBERTSON, M. A., Ph. D., Professor of Geography, Oxford University.

In the paper on the thermal regions of the world, of which I propose to present an abstract, there are a number of sections about which I shall say nothing or next to nothing—e. g., the history of isothermal maps and the description of the different thermal regions. The reason for bringing the subject before this [Research] Department is to discuss the different methods in which the thermal conditions of the earth's surface can best be represented for the use of geographers, and the different attempts I have made to do this, which I wish criticized. In what follows I assume the temperature data are the most reliable available, and that the ordinary precautions have been taken in dealing with them.

If we start with the ordinary isothermal maps of the world, we have in Dr. Buchan's maps in the "*Challenger* Report" the one consistent set of maps which shows the distribution of temperature at sea level for every month of the year. There have been newer maps showing the mean annual temperature for July and January, but at the present time it would take many months to make maps more satisfactory than the *Challenger* ones for the different months of the year.[2]

The ordinary isothermal map contains many lines which, from the point of view of the study of the physics of the atmosphere, are desirable and essential; but for most geographical purposes it is necessary to choose from them those which have the greatest geographical significance. For simplicity's sake I have chosen to deal at present with the lines of 0°, 10°, and 20° C. (32°, 50°, and 68° F.). I have chosen 10° (50° F.) because that line roughly represents the average temperature for the month during which growth becomes active for most plants of economic importance in temperate regions. I have chosen the 20° (68° F.) [line] because it marks roughly on the world the boundary between regions where subtropical products can mature and those where they can not.

Taking those three isothermal lines it is possible from the ordinary isothermal map showing the mean annual temperature to make a map which shows temperature belts, but no map which merely shows the annual temperature is satisfactory. You are all familiar with the objections which are obvious on examining figure 1.[3] On the west coast in our latitudes the mean annual temperature is the mean of temperatures which differ very little from it, whereas on the east coast the same mean annual temperature is found in a region with very much colder winters and hotter summers; consequently, some seasonal isothermal line must be introduced in any maps which show the thermal zones.

In figure 2 is a reproduction[3] of Dr. Supan's map in which he combines mean annual isotherms and mean monthly isotherms taking the mean annual temperature of 20° C for the coldest month. I also have published maps showing the thermal zones, using the lines of 0°, 10°, 20° C., for the warmest and for the coldest month (fig. 3). This map is made by superposing the January and July isothermal maps showing the isotherms of 0°, 10°, 20° C. reduced to sea level.

[1] Abstract of a paper presented at a meeting of the Research Department, Dec. 14, 1911.

*Reprinted from* The Geographical Journal, London, November, 1912, **40**, p. 518–532.

[2] See Bartholomew's Atlas: Meteorology, Plate 3.—[C. A., Jr.]

[3] This and other figures of the original published paper are not reproduced here. The maps referred to as "figure 1" and "figure 2" are to be found in Bartholomew's Physical Atlas: Meteorology, Plate 1, Inserts "Mean annual temperature" and "Temperature zones," respectively.—[C. A., Jr.]

This is a very simple exercise, and anyone who has to teach geography knows how valuable it is to make pupils take a tracing of those three lines from a January isothermal map and a tracing of them from a July map, and then to make a thermal zone map by superimposing the two.

Some important facts illustrated by this map may be noted. There is a wide belt of ocean extending beyond the Tropics with an air temperature which never falls below 20° (68° F.). The belt narrows off the west coast of America, and widens off the east coast; it narrows off the west coast of Africa and widens again off the east coast of Africa. South and north of it are other belts which have summers with a temperature of over 20° C., but the winter's month is cooler than 20° C.

Two years ago I exhibited at the Research Department this and a number of other maps which had been constructed by similar graphic methods, to show mean seasonal temperatures, and from these seasonal maps a new one of the thermal zones. To obtain the seasonal isotherms, the three *Challenger* maps for December, January, and February were taken—the isothermal lines of 0°, 10°, and 20° C. were drawn, and the three maps superposed. The mean position of each isothermal line was determined, and a seasonal map for the northern winter and the southern summer produced. Similarly, the other three seasonal maps were obtained. From the four seasonal isothermal maps a new map was drawn, showing thermal zones which had certain merits which I do not propose to consider further in the present communication.

All these maps were based on isotherms reduced to sea level; but in all geographical work we find that the isotherms reduced to sea level are insufficient. We want a map of the actual air-temperature conditions, and not what they would be if the surface were at sea level. There are, however, many difficulties in the way of the construction of such maps. It is necessary to generalize the lines in order to obtain results which can be shown clearly on a small scale map. It must be remembered that in drawing all small scale maps it is necessary to make such generalizations, and that there is no particular reason why we should not attempt, in dealing with isothermal lines, the task which we always attempt in dealing with ordinary contour lines. Accordingly a good many years ago I took the isothermal maps for January and July, drew them on contoured maps, calculated the actual temperatures from them, and then drew the lines of 0°, 10°, and 20° C. as they run across the actual surface of the continents. The maps of figures 4 and 5 are reproductions of the maps after they have been revised by two pupils, Miss Rogers and Miss Taylor. Miss Taylor not merely revised the lines as they were shown on the earlier map, but first redrew the reduced isothermal lines for January and July, taking recent data into account.

In the ordinary map of isothermal lines reduced to sea level the line of 0° C. in January runs across the North American continent from the south of Vancouver Island to the south of the Great Lakes, but the parts of North America with a mean temperature in January under the freezing point extend much farther south—as far south in fact as the isothermal line of 10° C. in the map of isotherms reduced to sea level. In Asia the 0° C. isothermal line comes much farther south in Tibet than the line of 10° C. at sea level. This is a very important matter, especially in dealing with the distribution of temperature in Asia. It is of value not merely to the geographer, but also to the meteorologist, for it has an important effect on the distribution of pressure and winds. This difference between the two kinds of maps is perhaps even more noticeable in July. In Central Asia the region which has a mean temperature in July of over 20° C. is broken by the great mass of Tibet, and there is complete isolation between the high-temperature region of northern India and the high-temperature region of the Tarim Basin. The examination of no isothermal maps except those reduced to sea level and the forgetting of the height of Tibet, have given rise to some errors about monsoon winds current in ordinary textbooks. When the isothermal lines are not reduced to sea level, the low temperature of Tibet is very clearly shown and prevents any misconception about the action of Tibet on the Indian monsoon.

In the map of the thermal regions of the world (fig. 6) the lines of actual temperature drawn across the continents in the January map and those drawn across the continents in the July map have been superposed.

[In the map which was shown at the meeting the thermal regions of figure 6 were distinguished by means of colors, and it was pointed out that the colors of the map had been purposely chosen so that it was difficult to distinguish between the reds, and that for ordinary school use it was not important that the details indicated by tones of red should be noticed. For the higher classes of schools and for universities the careful examination of the differences of tones of various colors might profitably be undertaken.][4]

This is a map of thermal regions; and not merely of thermal zones. The land surface on the whole is cooler than the maps of thermal zones suggest. For instance, in the ever-hot belt in Africa of figure 3, we find not merely a contraction of the belt, especially south of the Equator, but an almost continuous north and south belt which runs along the East African plateau with a still cooler area over the Equator. The belt of hot summers and cold winters in figure 6 is very much smaller than in figure 3 in the Old World and is divided into a western region and an eastern region by a tongue of land with even colder winters and cooler summers which joins this belt of the North Temperate Zone to Tibet. This actual distribution of hot summers is of great economic importance, as for a number of plants the winter cold does not matter, especially if the plants are annual plants, and summer heat, not winter cold, determines their distribution.

It is not necessary to examine the details of this map more closely for the moment. While it has many advantages over the commoner thermal zone maps, it does not give all the information about temperature which it seemed to me might be expressed on a map of the world without undue complexity. Accordingly I set about making thermal maps which would show the number of months with temperature above 20°, above 10° C., and below the freezing point at each station.

The graphic method used for sea-level isotherms for the seasons was first employed, and these maps were shown here two years ago. This method could have been used for actual temperatures, if monthly maps of real temperatures had been available. It was, however, much simpler to adopt another method.

Standard temperature tables were taken—those in the "*Challenger* Report," in Dr. Hann's Klimatologie, in the official publications of the United Kingdom, United States, etc. From these tables other tables were com-

[4] This map, along with those of true January and July temperatures, is published on a sheet 60×40 inches by the Oxford University Press, price 8s. 6d. mounted on cloth.—[A. J. H.]

piled, giving the number of months that the temperature was over 20° C., over 10° C., and under 0° C., and the numbers were inserted on large-scale maps. The height of each station was noted on another set of maps. Such maps should be made on tracing paper to permit superposition. The line was now drawn separating regions where one month of the year at least had a mean temperature of 10° C. from those where no month had such a temperature and so on. In mountainous countries the valley or plateau conditions were considered, not those of the highest parts of the ranges. These lines are shown in the map of figure 7. The line between three and four months over 10° C. is rather important, as it indicates roughly the northern limit of profitable wheat growing, at any rate in the eastern half of North America.

Practically the whole of the intertropical land, with the exception of some of the higher parts of the Andes, have at least 10 months of the year over 10° C.—that is to say, as far as temperature is concerned, growth would be continuous in these regions, and the periods of growing and resting depend not on temperature but on rainfall.

A map showing the number of months over 20° C. and another showing the number of months under 0° C. have been prepared. From these three maps the map of figure 8 has been constructed. In this map, in the north, the dots indicate the region where no month in the year has a temperature of over 10° C., and that, you will notice, roughly coincides with the region of tundra. The areas with vertical broken lines are those in which at least one month in the year is over 10° C. In the southern part of this area at least three months in the year are over 10° C., but in winter at least six months in the year are under freezing point. Consequently the soil is frozen for over six months throughout this region, yet for at least three months in the south and one month in the north a temperature sufficient for active growth is found. The region with continuous vertical lines has at least four months over 10° C., and it has also four or five months of frost. As we pass from the heart of the continents toward the west the number of months over 10° C. does not alter, but the number of months with frost diminishes. In central Europe there are less than four months of frost, and in western Europe there is no month with a mean temperature under the freezing point. In the Far East, in the east of Korea and the extreme north of Japan, is a region which corresponds in this respect with central Europe, but there is nothing in the east of Asia which corresponds with the British Isles, France, and the Low Countries in Europe. In western North America, however, we find that milder region, as well as in the south of South America, in Tasmania, and in New Zealand.

In the next zone there is an area which still has from one to three frosty months, but here there are at least three months which have a temperature over 20°. That in North America is roughly the northern limit of maize cultivation. South of it comes a belt in which, though frost may occur, the mean temperature of the air is never under freezing point for one month. In this belt there are at least five and in the southern part of it there are six months of the year with a mean temperature of 20° C. In the next belt there are from seven to eight months of the year with a temperature of over 20° C., and in the last there are at least nine months of the year with the mean temperature over 20° C.

This map, perhaps better than any other, shows the very great area of the land surface which has a mean temperature of over 20° C., the most favorable area for plant growth, provided that the water supply is adequate.

In the Southern Hemisphere, of course, those belts are represented in the reverse order, and are most clearly shown in Australia and in South America. In Africa the height modifies the simplicity of the arrangement and we get exceptional areas which are distinctly more temperate than any other part of this belt in similar latitudes in the Southern Hemisphere, except in the Andes.

In the case of the west coasts of the continent we find the cool temperate conditions extending nearer the Equator than they do in the Northern Hemisphere, and going farther north on the western than on the eastern side. It is not, however, necessary for me to analyze the relationship between coastal temperatures, and prevailing winds and ocean currents. This is done in every textbook, and I am now more concerned with the discussion of methods than with the discussion in detail of the results.

There are difficulties in making a map of this kind for a region such as central Asia, where the variations of height are very great. In a mountain region we can not expect to show the actual surface temperature everywhere, as it varies from range to range in very short distances. It is convenient to block out the region over 4,000 meters, which is roughly everywhere a region of constant snow and ice, and then in the marginal region around to select the temperatures of the opener valleys rather than those of the summits as a guide to the shading or coloring which should be employed. The disadvantages of using the temperatures of the lower parts would be neutralized if some special shading were used to indicate a mountainous region. For we must have some convention to represent the condition of a complicated mountain region, and this, perhaps, is the best; but I should like to have the opinion of others on this point.

In addition to the maps, I have drawn a number of curves which show the seasonal distribution of temperature in these different thermal regions, and the gradual change in the range of temperature passing from west to east, the maximum range occurring within a comparatively short distance of the eastern margin of Asia, and occurring on the whole nearer the center of North America. The different types of configuration, the north-to-south mountain barrier in America, the west-to-east barrier in Asia, and the gradual rise of the greater part of northern Asia toward the east, have their effect in throwing the line of greatest range of temperature more toward the center in the case of North America, and more toward the east in Asia.

There is much work to be done in the more careful analysis of regions like British Columbia and the mountain belts of the United States, or of the Andes, or of central Asia, for which the temperature figures at present are insufficient. But that can only be undertaken later, and on much larger scales than this map of the world. For the purposes of the world map the detail I have shown is probably as much as can be used with clearness.

Those are the main points of the paper, which deals with two kinds of thermal region maps. One is made from the lines of warmest temperature and lowest temperature for the year; the other by counting the number of months above or under certain temperatures, plotting them, and drawing lines. The two maps show great resemblances, though they were made quite independently. One map brings out much more clearly the differences between the thermal value of the lands in the plains of North America and Asia than the other; this latter shows certain other points better. In making this new map Miss Evelyn Sandberg has aided me in supervising the whole of the tabulation done by Mr. H. N. Grant, and she plotted the figures on the maps, helped by Miss D. Forsaith in the case of North America.

DISCUSSION.

Capt. LYONS. * * * It is perfectly reasonable that the original data at the various points on the earth's surface should be treated from the special point of view of the geographer, and that from that point of view certainly the actual temperature on the earth's surface is of particular interest to him. * * * I can not say that I am attracted by some of those small and sharp *indentations in the curves*, especially in regions like central Africa and South America and elsewhere, seeing that we are dealing with such very generalized phenomena, and that the maps themselves are on a small scale. I question whether it would not be better to round off these lines somewhat more generally. As regards the question of *introducing the orographical detail* to some extent, I think technically it would be rather difficult to do so satisfactorily where there is already so much color detail on the maps, and in the end it might be preferable to work with a relief map alongside rather than try and include orographical data on the same one. In many cases the mountain range or the plateau is restricted in size, and to add such data from the cartographer's point of view may very easily produce some confusion. For the same reason I can not say that I am very much enamored of the proposal to use black for the high plateau and the highest mountain ranges.

Dr. D. T. MACDOUGAL. * * * I would join with the chairman in suggesting that these sharp deflections of the boundaries of the thermal zones should be avoided as much as possible. * * * We botanists are getting so that we are very much afraid to use average temperatures as a prime factor in determining the distribution of vegetation. To do so is impracticable, because the activity and distribution of vegetation does not depend on average daily, monthly, or annual temperatures. I can only say that our own work, so far as we have gone with it in dealing with the temperature factor and the activity of vegetation, is to use expressions indicating the hour-degrees of exposure above any chosen zero of activity. This radical departure from the temperature summation of averages, proposed a century ago, has been found applicable in determining the beginning of seasonal activity, and the limits of distribution of plants. The two ideas are as the average steam pressure in a boiler and the curve made by a recording gage. From another point of view, it is the maximum and minimum records that count rather than the averages, and vegetation is stopped or started by these extremes of temperature. Furthermore, the rate at which the temperature changes is also, I should say, a prime factor. To give a very common example, I presume everyone in the room is familiar with the starting of bulbs; that to get your bulbs started in the spring the temperature curve must rise rather suddenly. * * *

W. MARRIOTT. * * * Isothermal maps are certainly of extreme value to meteorologists, and I do not know how we would get on very well without having the readings reduced to sea level. Of course, that is the fundamental point in isothermal maps for meteorological purposes. The maps brought before us this evening are of great interest; they show rather the variability of the temperature in the various months, and that is of considerable importance. Of course we know that over the land surface the range of temperature is much greater than it is over the sea, but that is not the principle on which these maps have been compiled. The features, however, that have been brought out are likely to be very useful. Dr. Herbertson has done a great deal of work in the preparation of rainfall maps, and these temperature maps taken in conjunction with rainfall maps will be of great service in determining the climate suitable for the growth of crops in various parts of the world.

Capt. WILSON BARKER. My impression is that Dr. Herbertson's intention is to express meteorological conditions in a geographical manner. Meteorologists reduce all readings to sea level, but I am of opinion that it might be better to reduce them to the mean level of the earth's surface. * * *

Mr. J. FAIRGRIEVE. [Criticized the scale of the published wall chart.—EDITOR.]

Dr. HERBERTSON. * * * The difficulty in distinguishing between certain tints is intentional. * * * The colors were deliberately chosen so that the regions where differentiation was desirable stood out clearly in different colors and the tints of each color were used where differentiation was not so essential. I have used the maps constantly in teaching and have found that they have great advantages over the ordinary isothermal maps reduced to sea level. * * *

I do not mean to imply that these maps supersede the ordinary isothermal maps, even for geographers. Any one teaching geography scientifically must also use ordinary isothermal maps reduced to sea level. [My] real thermal maps are a necessary preliminary study in the investigation I am carrying on of the qualities of the different natural regions of the world. * * *

While bearing in mind the desirablity of selecting for this purpose temperatures which have some meaning for botanists, I do not pretend that those thermal maps, more particularly the early ones, are maps which can be used as a key to the distribution of vegetation. Maps of cumulative temperatures would have better results, but until the data exist the nearest approach to them that we can obtain for a map of the world on this scale is this map based on the duration of selected mean monthly temperatures. For certain parts of the world more may be possible, and I wish to make a thermal map of the British Isles to indicate not merely the number of months, but the number of days of certain average temperatures if the data are sufficient. Undoubtedly, as Dr. MacDougal said, it is necessary to take into account maximum and minimum temperatures and rates of change of temperature, as well as the mean temperature, in discussing the relations between temperature and vegetation.

I wish we could map wet-bulb temperatures, but wet-bulb temperatures are very difficult things to deal with. As far as I know there are very few long-period observations of wet-bulb temperatures which are worth anything. The wet-bulb temperatures made in the ordinary Stevenson screen are practically worthless. You must use some form of ventilated instrument whenever the air is almost still, and as yet the data for a reliable map are lacking. The question of the maximum and minimum temperature is a little less difficult, and Dr. van Bebber's maps[5] may profitably be used to supplement mine. Capt. Lyons says truly that on a map of this scale too much nicety in the curve is not desirable; but the irregularities in southeast Asia, for instance, are diagrammatic and indicate that there are alternations of warmer valley and colder mountain, and so far I think they are justifiable. * * *

[5] See Bartholomew's Atlas: Meteorology, Plate 2.—[C. A., jr.]