*FINN MALMGREN*

# STUDIES OF HUMIDITY AND HOAR-FROST OVER THE ARCTIC OCEAN

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## RESULTS FROM THE "MAUD" EXPEDITION

BY *FINN MALMGREN*

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We know very little about the meteorological elements that are connected with the presence of aqueous vapour in the air in the polar regions. This especially concerns the conditions during winter. It must be admitted that there have been published long series of hourly observations of cloudiness and hydrometeors, as well as hygrographic records and regular hygrometer observations. So great difficulties, however, are connected with all these observations, as well as with the recording of the humidity during the polar winter, that the results must be dubious.

The reason for these difficulties arises partly on account of the low temperature and partly on account of the winter darkness.

The low temperature has the result that the absolute humidity of the air becomes extremely small. At —40° C the weight of water vapour in 1 $m^3$ saturated air is only 0.12 g. To determine directly with a balance such a small water content with a precision of, for instance 2 %, is a tedious task especially under the difficult conditions of work on a polar expedition. Equally difficult is the determination of the relative humidity at these low temperatures. Several expeditions have tried to use the hair hygrometer or the hair hygrograph, but — as will be shown later on — the results of such observations and records can only be accepted with great reservation.

The small humidity content of the air during the polar winter in its turn causes the amount of precipitation to become small, even if the precipitation may have a rather long duration. It can for instance snow for a whole day without the water equivalent of the precipitation exceeding 1 mm. A snow-fall of such a small intensity may easily be overlooked at the times of observation. As we are more apt to make this mistake in the dark hours, the effect is that we risk obtaining an erroneous daily period of this snow frequency. The case of fog is similar. A thin fog observed during the relatively light hours may easily be overlooked during the night. The determination of the cloudiness is also influenced by the light conditions, as already pointed out by several authors. The marked nightly minimum of cloudiness which characterizes Arctic regions during the spring may chiefly be accounted for in the following manner: A sky, the cloudiness of which during the day was denoted by 10° might during the ensuing night — the stars shining through the thin cloud vail — often be given the figure 0 for cloudiness.

In the above mentioned brief examples are slightly indicated the difficulties, which are connected with an investigation of humidity and hydrometeors in the Arctic regions.

In order to facilitate the solution of these problems, a good deal of work was devoted to the study of humidity and hydrometeors during the "Maud" expedition 1922—1925. It is of this work that I here shall make a brief abstract. The results hold for the Polar Ocean, and can therefore not without further study be generalized to cover the whole of the Arctic region. The instruments and methods which were used can however, be applied other places.

Before I proceed to discuss the investigations, I may perhaps in a few words give an outline of the expedition.

The Norwegian Polar expedition left Seattle during the summer of 1922 and steered through Berings Strait out into the Polar Ocean. It tried with its ship the "Maud" to make its way as far north as possible. However, when in the autumn of 1922 the cold set in, the ship had not reached further than to a point 72° 20′ N. L. and 175° 25′ W. Gr. There the "Maud" froze in among the drifting floes, and was kept by the ice for nearly two years, following the ice in all its movements. Under this she drifted chiefly towards WNW to about 76° 30′ N. L. and 143° 15′ W. Gr.

During the summer of 1924 an attempt was made to return through Berings Strait, and although the ship succeeded in getting out of the drifting ice and in covering some of her home passage, she was forced on account of new ice difficulties to winter at the "Bear Islands" near the north coast of Siberia. The next summer the ice difficulties were smaller and "Maud" was able to return to civilization.

Regular observations were made every fourth hour from and including September 1922 and up to and including July 1925. Besides this there are for the whole period, or at least a great part of the period, barographical, hygrographical, sunshine-, hoarfrost- and a large quantity of other records.

The leader of the expedition's scientific work was Dr. H. U. Sverdrup. I here take the opportunity of expressing my most sincere gratitude for the great interest he took in my work, and for the valuable help with which he facilitated my investigations.

# I. Conditions of Humidity in the Polar Sea.

### The Thermopsychrometer.

In order to make humidity observations possible at low temperatures, I experimented with a new instrument, the thermopsychrometer. The instrument consists of an Assmann Aspiration psychrometer from which the thermometers are removed and replaced by thermo elements.

A view of each element is shown on Fig. 1, *a*. *A* and *B* are both pieces of uninsulated copper thread, 1.5 mm thick, and 3 cm long. They are connected with each other by means of a thin insulated constantan file which is soldered to *A* and *B* at $l_1$ and $l_2$. Besides this there are soldered to the ends of *A* and *B* thin insulated copper threads, which couple the element into series with the other elements. The number of thermo elements is 7. The elements are arranged with all the thermic active soldering places in two groups, in the same manner as the three elements are arranged in Fig. 1 *b*. The thick copper threads in one group are then fastened, each one insulated from the others, to a thin ivory rod, so that together they form a cylinder almost 5 mm thick with the ivory rod in the middle. All the soldering places were twisted outwards. In this manner we obtain a thermo battery as that shown on Fig. 2. The battery is placed in the Assmann psychrometer, so that the thermical cylinders come where the thermometerbulbs are otherwise found. This is accomplished by putting the ivory rods through the holes which in the Assmann instruments are open for the projection of the thermometers. The arrangement is shown on Fig. 3. The current from the thermo battery is taken out at $P_1$ and $P_2$.

The thermopsychrometer is used in the same manner as an ordinary aspiration-psychrometer. When used one thermic cylinder, which was wrapped in tulle to absorb and hold water, was wetted. The aspiration was started and the air was forced to pass both cylinders. In this way a difference of temperature occured, which in its turn caused an electric current. From the instrument which hung in the open air, the current was lead into "Maud's" laboratory along a well insulated cable. There, the force of the current was decided by the aid of an Deprez-d'Arsonval's Galvanometer with telescope reading. The galvanometer was from the Swedish firm Rose, of the type which is used for radiation measurements. Besides this there was a reverser and a breaker in the circuit.

As a rule the aspirator work was screwed up and allowed to run twice. The first time no readings were made, because the cylinders

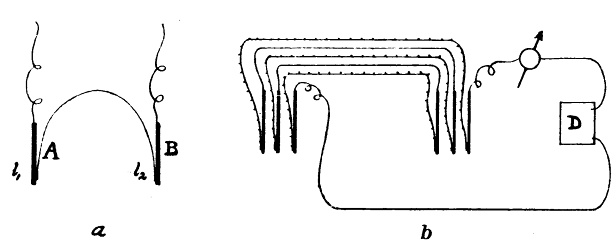

Fig. 1.

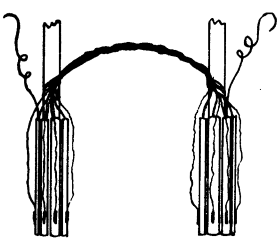
Fig. 2.

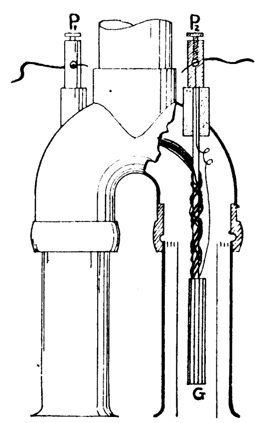

Fig. 3.

had not yet had time to assume the equalibrium temperature. The second time the galvanometer was read off 10 to 20 times with intervals of 20 seconds. The direction of the current was reversed after each reading.

The difference between the readings on the telescope scale before and after the reversal of the current ($D$) are proportional to the current intensity ($B$), as long as the tortion angle of the galvanometer spool is small. The current intensity in its turn is proportional to the temperature difference ($\triangle t_1$) between the soldering places of the dry and wet cylinders. We thus have:

$$D = k_1 B; \quad B = k_2 \triangle t_1; \quad D = k_3 \triangle t_1, \quad \text{where } k_1, k_2 \text{ and } k_3 \text{ are constants.}$$

It is, however, of small interest to determine the difference in temperature $\triangle t_1$ between the dry and the wet cylinders, as this is not only dependent on the temperature and humidity but also on the construction of the instrument, its dimensions etc. I have, however, through numerous comparisons between the thermopsychrometer and Assmann's psychrometer found that the difference in both the instruments between "wet" and "dry" temperatures are always proportional. If the difference in temperature in Assmann's instrument is called $\triangle t$, we thus have:

$$D = k_4 \triangle t$$

or

$$\triangle t = CD,$$

where $k_4$ and $C$ are constants and $\triangle t$ expresses the difference in temperatur which the wet and dry thermometers should show in the Assmann aspiration psychrometer if we were able to determine the difference with such great accuracy. With the observations taken I have thus always first determined $\triangle t$. I have done this order in to use the formula and tables which belong to Assmann's aspiration psychrometer.

The constant $C$ is determined through direct comparison of both the instruments, both in the open air and in the laboratory. To reduce the influence of the smaller accuracy of the determination of $\triangle t$ with the Assmann thermometers I chose cases with great differences between the thermometers. As, however, the range of the psychrometer was only $|\triangle t| \leq 0^\circ.2$, a large resistance of 1000 Ω was inserted in the thermo current circle to diminish the deflexion of the galvanometer. Besides this extra resistance, which is only used for comparisons, the resistance in the thermopsycrometer is 9.1 Ω, in the galvanometer 25.0 Ω and in the cable 0.3 Ω, together 34.4 Ω.

*Example of comparison.*

Local: Laboratory "Maud"—Time 1/10 1923 11—11 1/2 a.

*Assmann temperature.*

Dry + 10°.92 (5 readings)
Wet + 6°.22 (5 — )
Difference 4°.70.

Extra resistance 1000 Ω. The entire resistance in the thermocircuit = 1034.4 Ω. The mean difference in 40 telescope readings before and after reversing the current is 40.7 (about 4.1 cm).

Calculated difference for 1°, no resistance being inserted $= \dfrac{1034.4 \cdot 40.7}{34.4 \cdot 4.70} = 260.$

From this it will be found that $C$ is $= 0.00384$, or 1 interval of the telescope scale $= 0^\circ.00384$.

As the scale was read off with an accuracy of 0.1 of an interval, the degree of exactness of the determination was $= 0^\circ.0004$. I have, however, never worked with more than 3 decimalplaces because the differences between consecutive readings may, have the order of magnitude $10^{-3}$ degrees.

The superiority of the thermopsychrometer over an Assmann aspiration psychrometer first of all exists in the circumstance that the former determines the difference in temperature between the "wet" and the "dry" temperature with a 100 times greater exactness. Suppose for instance that the fault in the difference in temperature when determined by an ordinary psychrometer amounts to 0°.2. This is at —40° equal to an error of 70 % in relative humidity. With the thermopsychrometer the error will be 1 %. Even if we could use a very long thermometer, from which we could read off up to 0°.01 — an accuracy to which we cannot attain with an alcohol thermometer — we should with an ordinary psychrometer get an error of 7 %. Furthermore, with a thermopsychrometer the differences in temperature are read off directly and at such a distance from the thermocylinders that the presence of the observer cannot have any effect on the readings. With an Assmann-psychrometer the thermometers are read off after each other and close to the bulbs. Brief, quick swingings in the temperature of the air, which often rises to several hundred parts of a degree, can here entirely destroy the determination of the humidity. With the thermopsychrometer changes of this kind in the temperature of the air should not make any difference, provided that both cylinders have the same surface and heat capacity, which is approximately the case.

However, it is quite possible, that the quick changes in temperature are followed by rapid changes in humidity. This also causes the readings of the telescope scale to vary slightly. These variations could at times rise to an amount equal to 0°.006. I have not been able to decide whether they are real, or if they depend upon imperfections in the instrument. The safest plan would be to regard the determinations of differences in temperature between wet and dry thermometers as uncertain at ± 0°.006. This is equal to an error in the relative humidity of about 2 % at —40°.

The disadvantage of a thermopsychrometer consists in the circumstance that the temperature must be decided with an extra thermometer. Further, an observation with this apparatus takes much longer than with an Assmann aspiration psychrometer. The observations which I have made took about 1/4 of an hour. With a stronger aspirator the time could probably be diminished.

### The computation of observations with the Thermopsychrometer.

If the difference between the telescope readings for both positions of the current reverser (*D*) is multiplied by the constant *C*, we get, as we have already seen, a fictitious difference in temperature $\triangle t$. $\triangle t$ gives the difference in temperature between an imaginary Assmann's wet and dry thermometer used on the same occasion ($\triangle t = T_w - T_t$, where $T_w$ is the "wet" and $T_t$ the "dry", Assmann temperature).

With the assistance of the calculated $\triangle t$ and the temperature of the air $T_t$, which must be read off from another thermometer we can from the tables for Assmann's psychrometer obtain the absolute and relative humidity at temperatures down to —30°.

Assume for example that $T_t = -28^\circ.4$ and $\triangle t = -0^\circ.093$ (the wet thermometer being colder). From the table we have for $T_w = -28^\circ.4$ and $T_w = -28^\circ.5$ respectively 0.3 mm —78 % and 0.3 mm —64 %. As our $T_w$ is $= -28^\circ.493$ we obtain through interpolation an absolute humidity of 0.3 mm and a relative one = 65 %. Without mentioning it, we have here made the assumption that the air temperature was precisely —28°.400. But it at once occurs that the result of the computation is not disturbed by the value distributed to the last two decimalplaces.

The same formula on which Assmann's tables for the calculation of the vapour tension (*e*) is based have also been used at temperatures below —30°. The formula was invented by Sprung, and can be written in the form given below if the wet thermometer is covered with ice. If $E'_i$ — is the maximum tension over ice at the wet temperature we have:

$$e = E'_i + \tfrac{1}{2} \triangle t.$$

When divided by $\frac{E_w}{100}$, where $E_w$ is the maximum tension over water at the "dry" temperature, we have the following expression where $R$ stands for the relative humidity

$$R = \frac{100\,e}{E_w} = \frac{100\,E'_i}{E_w} + \frac{100}{2}\,\frac{t}{E_w}.$$

$E'^i$ and $E_w$ have between —30° and —40° been computed from Thiesen's empirical formula:

$$\frac{\log E'_i}{4.5813} = 9.78\,\frac{T_w}{T_w + 273} \quad \text{and} \quad \frac{\log E_w}{4.5813} = \frac{T_t}{T_t + 273}\,\{8.628 - 0.00394\,T_t + 0.000002\,T_t^2\}.$$

All the logarithms used are Brigg's.

We really do not know how closely Sprung's formula gives us the proper values at such low temperatures. Neither do we know accurately the quantities $E'_i$ and $E_w$ at these temperatures. It is therefore possible that the computed relative humidity at temperatures below —30° will more and more deviate from the real ones.

To diminish the errors in the relative humidity deriving from errors in $E'_i$ and $E_w$ and from an error in the constant before $\triangle t$ in the Sprungian formula we will instead compute another relative humidity which we can expect to obtain with greater accuracy.

The quantity in question is a meteorological element that is named by A. Wegener *the relative humidity over ice.* According to definition the quantity ($R_i$) is $= \frac{100\ e}{E_i}$.

Using Sprung's formula we get:

$$R_i = \frac{100\ e}{E_i} = \frac{100\ E'_i}{E_i} + \frac{100 \triangle t}{2\ E_i}.$$

In the case where $\triangle t$ is small ($< 0°.1$) $E_i$ will become equal to $E'_i$, and we get:

$$R_i = 100 + \frac{50 \cdot \triangle t}{E_i}.$$

From this expression we at once see that if the wet cylinder of the thermopsycrometer has lower, equal or higher temperature than the dry one, $R_i$ will always become respectively smaller than, equal to, or greater than 100 %, independent of the value of $E'_i$ and $E_w$ and of the constant at $\triangle t$ in Sprung's formula.

Relative humidities over ice lying in the neighbourhood of 100 % can thus be looked upon as almost correct. This is of great importance in the Arctic Sea where from my experience $R_i$ always keeps in the neighbourhood of 100 %. We also know that $R_i = 100$ % is a strict limit for the different conditions of humidity of the air. Thus we shall see later on, that hoar-frost will regularly occur at a place where $R_i$ is greater than 100 %, especially during the Arctic winter.

In the following we always represent the relative humidity over ice by $R_i$ and the relative humidity over water by $R_w$.

## Results of Measurements with the Thermopsychrometer.

During the winters 1923—24 and 1924—25, 150 observations were made with the thermopsychrometer on about 120 different days. The observations themselves will be published in the coming scientific report of the "Maud"-expedition. The tables made for this paper are provisional and may to a slight extent be corrected by a later and more exact treatment of the subject.

The temperatures in the stastistics could be considered correct on ± 0°.3 C. The velocities of the wind derived from anemometric records are correct on ± 0.5 m/sec.

The reports concerning cloudiness and hydrometeors can be looked upon as definite.

The results which the study of the observations have given can be summarized in the following statements:

a. *During the winter, in the Arctic ocean, the relative humidity over ice ($R_i$) always keeps around 100 %.*

If all the observations are arranged in groups, in such a manner that the difference in humidity between two adjacent groups is 5 %, we obtain the following table. The figures in the table give the percentage of all occassions falling in a certain group:

| $R_i$ (%) | 83—87 | 88—92 | 93—97 | 98—102 | 103—107 | 108—112 | 113—117 | 118—122 |
|---|---|---|---|---|---|---|---|---|
| | 1 | 6 | 28 | 33 | 16 | 7 | 4 | 4 |

If the table is illustrated graphically we have the following figure (Fig. 4).

The curve has a marked maximum at 100 %. The smallest value for $R_i$ was 83 %, the largest 122 %.

b. *$R_i$ is dependent on the velocity of the wind in such a manner that a high velocity of wind gives a comparatively small humidity.*

In the following table, $R_i$ is divided in groups after the velocity of the wind and group medium of humidity and velocity of wind have been taken:

| Windveloc. m/sec. ........ | 0.6 | 2.0 | 4.0 | 5.9 | 9.2 |
|---|---|---|---|---|---|
| $R_i$ % .................. | 105.7 | 103.2 | 101.1 | 98.7 | 96.5 |
| Number of obs. ......... | 8 | 35 | 43 | 19 | 16 |

The conditions are illustrated in Fig. 5.

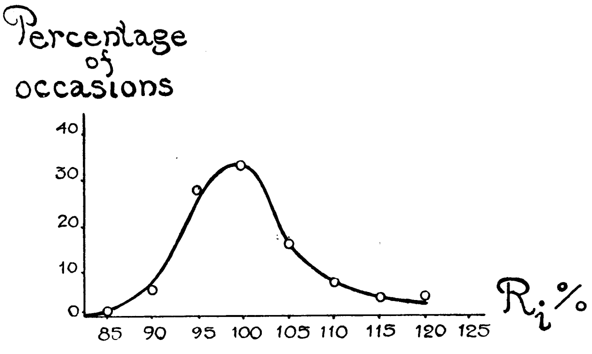


Fig. 4.

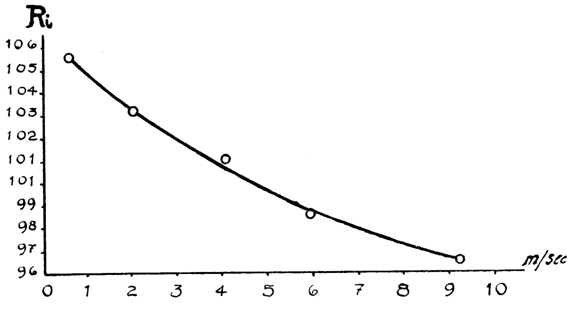


Fig. 5.

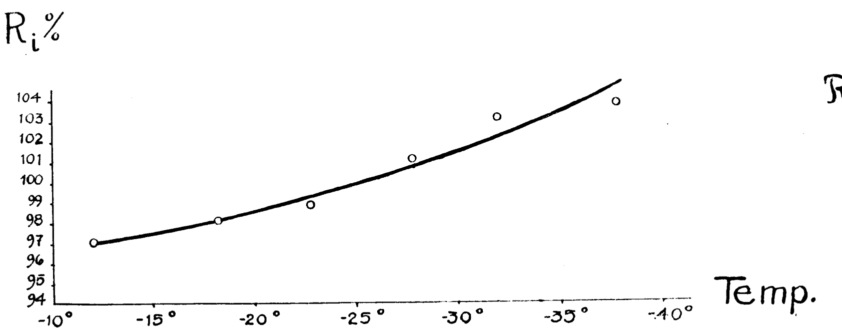


Fig. 6.

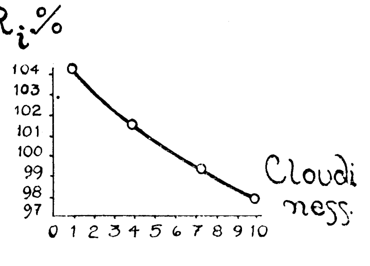


Fig. 7.

c. *$R_i$ is dependent on the temperature, high temperature being accompanied by little $R_i$.*

This is seen from the following table which is computed after arranging the observations in groups according to the temperature. In the table, the mediums of both elements in each group are put together.

| Temperatur °C ........ | —12.0 | —18.1 | —22.7 | —27.7 | —31.8 | —37.7 |
|---|---|---|---|---|---|---|
| $R_i$ % .................. | 97.1 | 98.1 | 98.9 | 101.1 | 103.2 | 103.9 |
| Number of obs. ......... | 16 | 15 | 18 | 31 | 21 | 21 |

In Fig. 6 we will see the same thing graphically.

d. *$R_i$ is dependent on the cloudiness. Slight cloudiness brings with it large $R_i$.*

To show this the observations are divided into 4 groups of cloudiness. The medium of cloudiness and of $R_i$ are taken from each group.

The result is seen from the table below and in Fig. 7.

| | | | | |
|---|---|---|---|---|
| Cloudiness | 0.9 | 3.9 | 7.2 | 9.9 |
| $R_i$ % | 104.3 | 101.6 | 99.2 | 97.9 |
| Number of obs. | 36 | 21 | 10 | 54 |

**Physical explanation of the results obtained.**

To be able to understand the changes in $R_i$ which are seen in the above tables, we must look at the conditions of temperature at the ice-surface and in the layer of air immediately above it.

The results of the kite ascensions during the expedition completed by a few balloon registrations, have shown that during the winter we have a layer of cold air close above the ice. The conditions are slightly different with a light breeze or calm than with a strong wind. In the first case the distribution of temperature is shown in the following diagram which is computed from five balloon registrations during the coldest season. (Fig. 8).

The temperature is lowest down by the ice and increases in the higher altitudes, first quickly than more slowly.

With a stronger wind the air nearest the surface of the ice gets mixed, the result being a lower layer of well mixed air with almost adiabatic distribution of temperature. Above this layer, which seldom becomes 200 meters thick, the warmer air floats without mixing to any considerable extent with the air below. (Fig. 9).

In both the above mentioned cases the stratification of temperature is very stable. The air lying close to the ice is either bound to the latter (1st case), or may mix with the above air up to a height of at the most 2 to 3 hundred meters (2nd case).

We may expect this lower layer of air to have a relative humidity over ice which remains in the neighbourhood of 100 %. It can never become very dry, because while the supply of falling air from considerable heights is impossible, the snow and ice try to saturate it from below. Furthermore, air arrives from the sides which has also for a long time been in contact with the snow and ice and is therefore also not dry. Neither can it be very oversaturated, the presence of the ice facilitating the falling out of hoar-frost, thus decreasing the humidity.

To explain the effect of wind, we will imagine the distribution of temperature to be that which is shown in Fig. 9. We will now let the wind calm down. The air mixing in the lower hundred meters ceases, because it was forced through vortices which were formed when the air glided over the rough surface of the drifting ice. The ice consequently becomes cut off from the heating supply from above, and as it continually loses the same quantity of heat through radiation, the temperature must decrease. This causes the air immediately above the ice to cool down, and we obtain a distribution of temperature which is demonstrated by the dotted line in the figure.

Regarding the relative humidity over ice, this must have increased at the same time as the temperature has fallen. If $R_i$ was $= 95$ % at $-29°.4$ during the time when the mixing still was going on in the lower 100 meters, it must now be 129 % at the temperature which took place when it grew calm (—33.3) provided that no form of precipitation took place. The last assumptions however fail. $R_i$ will certainly become greater when calm, but this as a rule followod by hoar-frost, and therefore such a high value as 129 % is never observed. $R_i$ may perhaps become 105 %. In that case it will also be seen that the relative humidity over water ($R_w$) has *decreased.* Thus this can also take place at decreasing temperatures if ($R_i$) was high from the beginning[1].

In the same way it can be shown that if wind arises after calm weather, we always will have a higher temperature and smaller $R_i$ in the air close to the ice. The same will take place if the velocity of the wind increases. From what has been found on the "Maud" expedition, this increase is accompanied by an increase in the thickness of the adiabatic layer, and we proceed from a distribution of temperature illustrated by the drawn line in Fig. 10, to one represented by the dotted line in the same figure.

As seen from the figure the temperature rises at the ice-surface, which causes a decrease in $R_i$. The opposite takes place if the wind decreases and we pass from the situation represented by the dotted line to another given by that fully drawn.

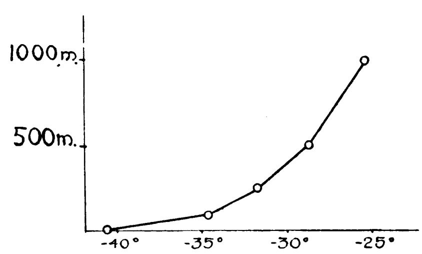

Fig. 8.

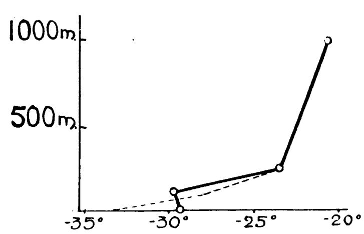

Fig. 9.

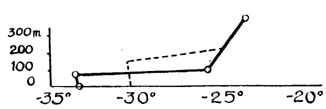

Fig. 10.

The result of these conditions must be that in the statistic $R_i$ falls with increasing velocity of wind.

From what has been said above concerning the influence of the wind on $R_i$ it may be regarded as certain that a decrease in cloudiness increases $R_i$. A decrease in the cloudiness, as we have seen above, is accompanied by an increase of the radiation of ice, which causes the air near the ice to become colder, and more humid. An increase in cloudiness gives an opposite result.

A decrease in the velocity of the wind as well as in cloudiness causes a decrease in temperature near the ice, which in its turn gives a greater relative humidity over the ice. The opposite takes place by an increase in wind and cloudiness. It is therefore to be expected that during the winter there must be a connection between temperature and $R_i$, which goes in such a direction that a low temperature corresponds to a great $R_i$ and vice versa.

We have now shown that the conclusions made through the observations with the thermopsycrometer are in full accordance with the special conditions existing during the winter in the Polar sea. Later on we shall see that they fully agree with the results gained through the records of hoar-frost.

In the meantime we will discuss the yearly and daily period of the humidity.

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1 This is the case during October and November according to the observations on the "Fram" expedition. Here we have a decreasing $R_w$ at falling temperatures so that the daily period both of temperature and of $R_w$ shows a minimum during the night and a maximum during the day. During the spring, on the contrary, the daily period of $R_w$ is the reverse to the period in temperature, which points to the fact that $R_i$ is smaller during the spring than during the autumn.

**The mean values of $R_i$ and $R_w$ during the winter months. Yearly period of humidity.**

In the following table the mean value of all humidity observations and the mean temperature at the time of observations during a certain month has been taken.

| Month and year | Number of obs. | Mean of $R_w$ | Mean of temperature | I Mean of $R_i$ | II Estimated $R_i$ | Difference II—I |
|---|---|---|---|---|---|---|
| Oct. 1923 | 25 | 85.6 | —14.2 | 98.0 | 97.4 | —0.6 |
| Nov. » | 23 | 80.3 | —24.8 | 102.3 | 99.7 | —2.6 |
| Dec. » | 9 | 72 6 | —34.9 | 101.6 | 103.8 | +2.2 |
| Jan. 1924 | 15 | 77.0 | —30 6 | 103.5 | 102.4 | —1.1 |
| Feb. » | 20 | 74.0 | —34.2 | 103.0 | 103.6 | +0.6 |
| Jan. 1925 | 14 | 77.9 | —23.5 | 97.6 | 99.2 | +1.2 |
| Feb. » | 17 | 74.6 | —28.8 | 98.4 | 101.6 | +3.2 |

We see from the table that the higher the mean temperature at the time of observation, the lower is generally $R_i$. This indicates that the earlier found relation between temperature and humidity also can be used for the mean values of long periods which could exist at any time during winter. We could therefore use the curve in Fig. 6 to work out the medium of $R_i$ from the mean temperature of the observations. The results are in the table under the heading "Estimated $R_i$". The estimated humidities are in close accordance with the values found. The mean difference is 1.6 %.

Basing our calculations on the mean temperature of the months, we can therefore expect to get the relative humidity over ice for a month with a similar accuracy, provided that the close accordance in the table is not accidental.

It is not as daring as it may appear to assume that such a close accordance between the media of temperature and humidity during the same month exists. We must always have in view that the meteorological conditions during the winter in the Arctic Ocean are connected with the thin local layer of cold air which lies close over the ice, and we have shown that the changes of humidity in this layer always are in connection with similar changes in temperature. We can also use the same relation between temperature and $R_i$ in other parts of the Polar Sea, the conditions in the whole Arctic Ocean being so uniform that a considerable difference in the relation is not to be expected. We will refer to this when later on we calculate monthly means of humidity during the "Fram" expedition.

In order to obtain the yearly period of $R_i$ in the Arctic Ocean we can thus during the winter use the media of temperature. During the warm season we can use the hygrograph records because they are then reliable. In that way the yearly period of humidity during the "Maud" expedition will be computed. The result of such a computation, however, can not yet be published as the hygrographic records from the warm season have not yet been compiled.

We wish instead to make a similar computation of the yearly period during the "Fram" expedition, which in the years 1893—96 crossed the Polar regions.

In the following table will be found the medium during the different winter months, of temperature ($t$) and relative humidity over water ($R_w$) taken from the scientific publications of the "Fram" expedition[1].

[1] The Norwegian North Polar Expedition 1893—1896. Scientific results, edited by Fridtjof Nansen, Vol. VI.

From these data the relalive humidity over ice has been calculated and added to the table (mean of $R_i$). This also contains an estimated $R_i$ which is computed from the mean temperature of the month, by the aid of the curve in Fig. 6 (estim. $R_i$) and last by the difference between the last two groups.

Relative humidity of the "Fram" expedition during winter.

| Month and year | $t$ | $R_w$ | $R_i$ from obs. | Estimated $R_i$ | Difference | Estimated $R_w$ |
|---|---|---|---|---|---|---|
| Nov. 1893 | —24.4 | 84.2 | 107 | 100 | — 7 | 79 |
| Dec. » | —29.1 | 89.2 | 119 | 102 | —17 | 76.5 |
| Jan. 1894 | —35.7 | 90.5 | 127 | 104 | —23 | 74 |
| Feb. » | —35.6 | 91.7 | 129 | 104 | —25 | 74 |
| Nov. » | —30.9 | 72.8 | 98 | 103 | + 5 | 76 |
| Dec. » | —35.0 | 72.6 | 102 | 104 | + 2 | 74 |
| Jan. 1895 | —33.7 | 71.6 | 99 | 104 | + 5 | 75 |
| Feb. » | —37.2 | 74.2 | 106 | 104 | — 2 | 73 |
| Nov. » | —30.9 | 83.3 | 112 | 103 | — 9 | 76 |
| Dec. » | —32.6 | 80.1 | 111 | 103 | — 8 | 75 |
| Jan. 1896 | —37.3 | 81.9 | 117 | 104 | —13 | 73 |
| Feb. » | —37.4 | 90.1 | 127 | 104 | —23 | 73 |
| Winter 1893—94 | —31.2 | 88.9 | 120 | 102 | —18 | |
| Winter 1894—95 | —34.2 | 72.8 | 101 | 104 | + 3 | |
| Winter 1895—96 | —34.6 | 83.8 | 117 | 103 | —14 | |

Taking the mean value of the 4 months of each winter, we obtain the figures which are found at the foot of the table.

The estimated humidity is in close accordance with that observed during the winter of 1894—1895, the difference being only 3 %. During the other two winters the difference is very great. The divergence must depend on a faulty correction used by the evaluation of the observations from the two hair hygrometers on the "Fram" expedition.

The reasons for this are:

1) We have only *one* determination of the correction for all the years during the months Dec.—Feb. It was made on the 1st of December 1893. The correction of $R_w$ was determined as + 8 %. The closest preceding determination was from the 11th of November, in the same year, when the correction was — 4 %, a difference of 12 % for a period of 20 days!

If the November correction had been used during the winter of 1893—94 we should have had a close agreement between the estimated and observed humidities during that winter.

2) It seems impossible that two winters in the Polar Sea can have so different relative humidities as the winters 1893—94 and 1894—95. The difference in the mean values of $R_w$ during the winters is here 16 % and this in a region where the meteorological conditions change very little from one year to another.

3) Such a high percentage of humidity as the *mean value* during the winter 1893—94 ($R_i$ = 119 %) has only been found in 4 % of all the observations made with "Maud's" thermo psychrometer. When it has occured it has been followed by very heavy hoar-frost — the Diary of the "Fram" expeditions, 1893—94, shows only a few occassions with hoar-frost.

After we have given these reasons for the omission of the "Fram's" observed humidities during the winter, we wish to discuss only those computed from a temperature that are probably very close to reality. We at first form the monthly average of $R_i$ and $R_w$ for the 3 years, and thus get:

| | $R_i$ | $R_w$ |
|---|---|---|
| November | 102 | 77 |
| December | 103 | 75 |
| January | 104 | 74 |
| February | 104 | 73 |

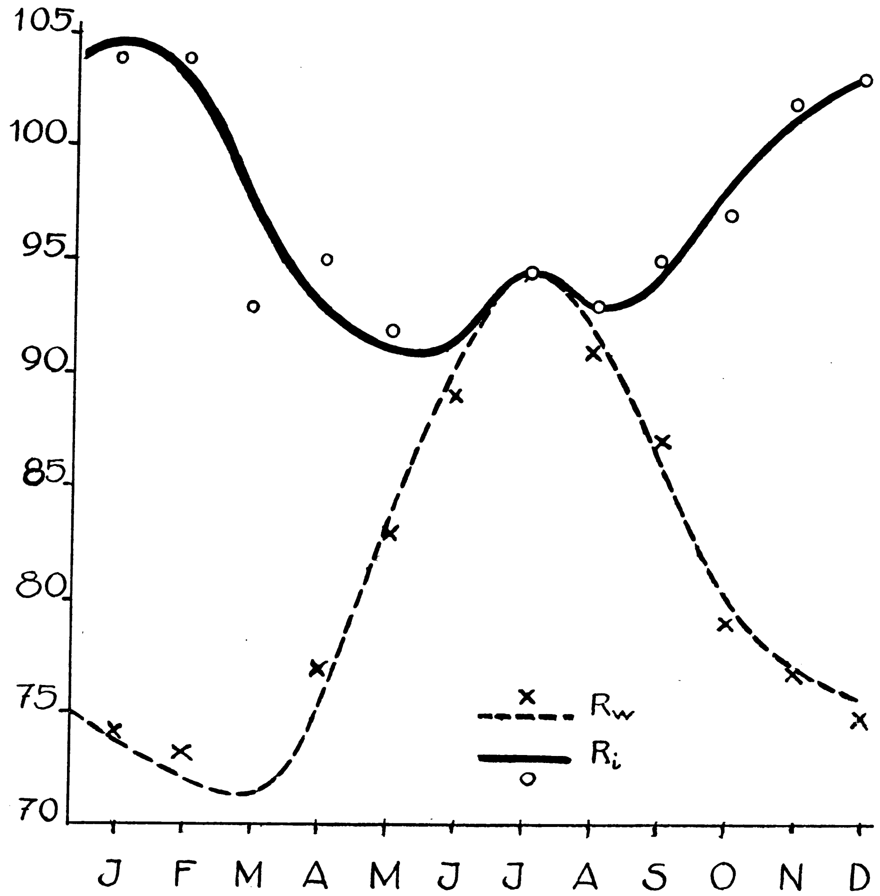


Fig. 11. Yearly period of the relative humidity over the Polar Sea.

$R_w$ has been computed from $R_i$ and the temperature.

If the humidities of the winter months are completed with the humidities for the other months derived from hygrometer observations, we shall have two tables, one for the relative humidity over ice and one for the same over water. The first, for the summer months, has been computed by the aid of Thiesen's formula.

Relative humidity over ice. Yearly period during the "Fram" expedition [1].

| Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 104 | 104 | (93) | (95) | 92 | 90.5 | 94.5 | 93 | 95 | 97 | 102 | 103 |

[1] The correction of the "Fram" obs. from February (—10 % on $R_w$) has been distributed to a certain extent also over the months March and April, so that the March corrections have been estimated to —7 % and the April corrections to —3 %. No correction has been made in May.

Relative humidity over water. Yearly period during the "Fram" expedition.

| Jan. | Feb. | Mar. | April | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | 73 | 69 | 77 | 83 | 89 | 94.5 | 91 | 87 | 79 | ·77 | 75 |

If the figures in the table are illustrated by two curves we obtain Fig. 11.

We see from the curves that $R_w$ has a marked maximum in July and a flat minimum during the winter. During the autumn $R_w$ is greater than during the spring. — $R_i$ has two maximums, a chief maximum during the winter and a secondary one during July. $R_i$ is also greater during the autumn than during the spring. The appearance of the curves is explained by the temperature and by the occurence of open water.

The temperature causes the winter minimum in $R_w$ as well as the winter maximum in $R_i$. On the other hand the difference between autumn and spring is based on the open water (pools) existing to a larger extent during the autumn than during the spring.

*The daily periods* of $R_w$ and $R_i$ during the spring and summer show a minimum at noon. During the autumn months of October and November the minimum of $R_i$ takes place during the night, while $R_w$ still shows a minimum during the day like the temperature. See pag. 11. During these seasons, the morning is always more humid than the evening. During the winter, the daily period must be extremely small. It is probable that $R_w$ follows the fluctuations in the temperature, while $R_i$ has an opposite period, depending on the high mean value of $R_i$.

The daily periods of $R_i$ and $R_w$ will not be further discussed until "Maud's" hygrometer records are calculated.

# II. Hoar-frost in the Arctic Ocean.

## The Hoar-frost Recorder.

We have found above that the medium of the relative humidity over ice during the entire winter keeps around 100%. We shall see later on that a relative humidity 100% as a rule is accompanied by hoar-frost, and that the amount of this hoar-frost is subject to certain laws which make possible a calulation of $R_i$. Thus we can from the hoar-frost records during long periods obtain valuable information of the humidity. The instrument, constructed to obtain the records (Fig. 12) is in reality only a registrating balance[1]. It registers the weight of the hoar-frost which is formed on a cylinder. The cylinder hangs on one of the arms of the balance. On the opposite one there is a counter-weight which together with a spiral spring gives equalibrium. The counter-weight is fitted in such a manner that it almost balances the cylinder when the latter is free from hoar-frost. A deposition of hoar-frost causes the cylinder to sink a little and a new state of equalibrium is attained through the lengthening of the spiral spring. The angle described by the weight arms (always small) is registered by a clockwork, the time of revolution being 7 days. The cylinder hangs in a steel rod (*s*), which at the same time keeps the cylinder from swinging out to the sides when wind is blowing. The steering arrangement is protected against hoar-frost by an interior tube (*r*) which is fastened to the hanging cylinder.

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1 The instrument was very well contrived out after my design by the Norwegian aviator Mr. Odd Dahl, who during the "Maud" expedition proved himself to be an exellent mechanic and instrument maker.

Fig. 13 shows the moving parts seen from above. The weight balances on two pin tips $a$ and $a_1$. $M$ is the counter-weight and $C$ is the place for the suspension of the cylinder.

The cylinders effective area[1] was 16 $cm^2$.

This figure is not very well determined. Nor is it certain that the deposition of hoar-frost on a cylindrical surface on all occasions in proportional to the deposition on a plane one. I have therefore not reduced the quantity of hoar-frost to an area of 1 $cm^2$, but kept as a measure of the amount of hoar-frost the deposition on the cylinder during 2 hours. If these amounts are divided by 16, however, we have the approximate value of the quantity of hoar-frost at 1 $cm^2$ area during 2 hours.

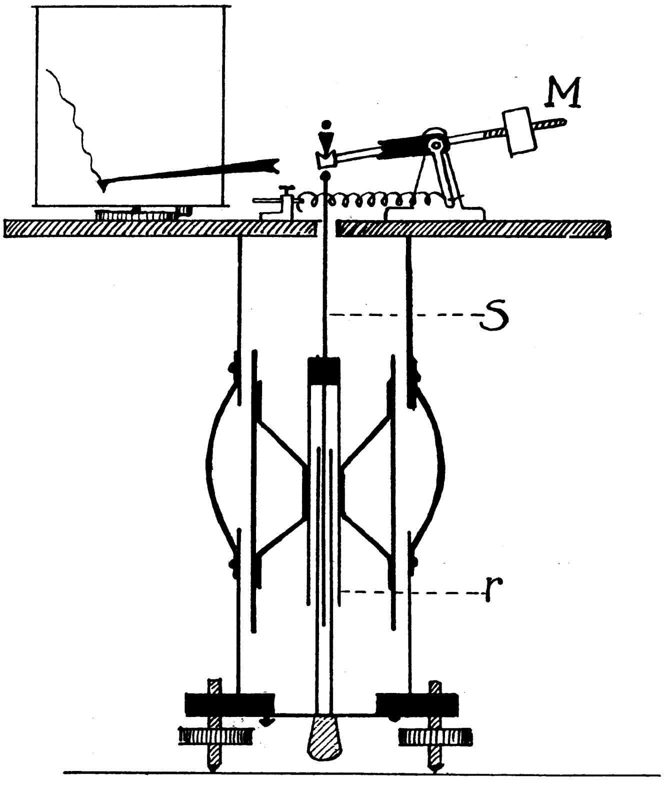


Fig. 12.

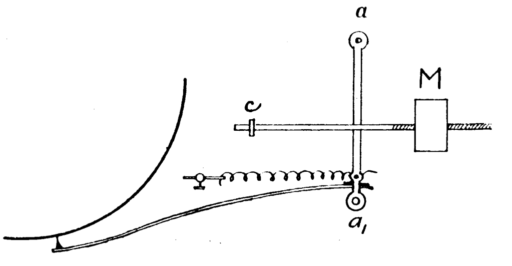


Fig. 13.

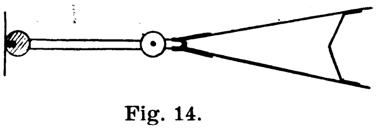

Fig. 14.

The sensibility of the instrument was about 2 cm for each gram of hoar-frost. The determining factor was decided by loading the cylinder with more and more weights. For each amount a mark was put on the paper with the registration pen.

The amount of hoar-frost during two hours was later determined by reading the distance of the pen from the top of the registration paper at two adjacent odd hours, and multiplying the difference between these distances by the factor of determination for the mean position of the pen. This factor was almost constant for the whole interval.

## Results of the Records of the Hoar-frost.

As before, we designate by $\triangle t$ the fictitious difference between an ordinary Assmann psychrometer's wet and dry thermometers. ($\triangle t = T_w - T_t$). The difference is determined by means of the thermo psychrometer.

[1] By this is meant that with hoar-frost a similar amount of hoar-frost is deposited on the cylinder as on a circular plane area 16 cm in size which stands perpendicular to the direction of the wind.

The result of a comparison between the thermo psychrometer and the hoar-frost recorder will then be the following, $R_i$ still being the relative humidity over ice.

*Hoar-frost is generally formed when $R_i$ is $> 100\%$ but never when $R_i$ is $< 100\%$.* The exceptions are very few, and can be explained partly by imperfections in the instruments and partly by poor simultaneousness in the observations, the amount of hoar-frost being taken during two hours, while the psychrometer determination only is valid for the short time of the observation.

*The amount of hoar-frost is dependent on $R_i$, temperature (t) and velocity of the wind (V).* The effect of the two first mentioned above can be summed up by presuming the hoar-frost deposition to be proportional to $\triangle t$. This presumption must be correct, as the deposition of hoar-frost is analogous to the deposition of ice on the wet Assmann thermometer, and the amount of this during the unit of time in its turn is proportional to $\triangle t$.

If $m$ is the weight of the hoar-frost formed on 1 cm$^2$ during one second, we thus have:

$$m = M_0 \cdot \triangle t \cdot f(V)$$

where $f(V)$ is presumed to be $= 1$, for a velocity of wind of 1 m/sec. and $M_0$ thus means, the amount of hoar-frost deposited on 1 cm$^2$ during 1 second when the difference in temperature is 1° and the velocity of wind is 1 m/sec.

During $\tau$ seconds and an effective area of $q$ cm$^2$ we obtain for the amount of hoar-frost ($M$) the following expression:

$$M = M_0 \, f(V) \cdot \tau \cdot \triangle t \cdot q \qquad \text{(I)}$$

In order to determine the different values of $f(V)$ the amount of hoar-frost during the dark season was grouped according to velocity of wind.

The mean value of these amounts ($M_r$) and of $\triangle t$ ($\triangle t_r$) were taken in each group. The result of this grouping is given in the following table ($q = 16$ cm$^2$, $\tau = 7200$ sec.):

| Windvelocity m/sec. | 0.25 | 1 | 2 | 3 | 4 | 6 |
|---|---|---|---|---|---|---|
| $M_r$ gr. | 0.086 | 0.054 | 0.060 | 0.112 | 0.150 | 0.181 |
| $\triangle t_r$ centigr. | 0.0447 | 0.0367 | 0.0312 | 0.0282 | 0.0263 | 0.0251 |
| Number of observ. | 12 | 36 | 34 | 28 | 23 | 12 |

If the equation (I) is used for the values in the second column of this table, we have:

$$M_0 = 1.3 \cdot 10^{-5} \text{ gr.},$$

where as before $\triangle t$ is counted in °C, $\tau$ in seconds, $V$ in m/sec. and $q$ in cm$^2$.

By using this value for $M_0$ the table gives the following values for $f(V)$:

| m/sec. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| $f(V)$ | 1.40 | 1.00 | 1.37 | 2.53 | 3.73 | 4.47 | 4.86 | 5.10 | 5.27 |

Five more precise determinations of $M_0$ were made, by fastning circular brass plates to the counter-weight of the wind-vane, so that one side of the plate would always stand perpendicular to the wind. (See Fig. 14).

The amount of hoar-frost during a certain period was determined directly by weighing the plate before and after the exposition. $\triangle t$ was decided by means of numerous simultaneous observations with the thermo psychrometer. The velocity of the wind was reduced to 1 m/sec. by the aid of the above table over $f(V)$.

The results of the determination which gives a $M_0 = 1.6 \cdot 10^{-5}$ are summarized below:

| $T$ mean | $Mg$ | $q$ cm² | sec. | $V$ m/sec. | $M_0$ | |
|---|---|---|---|---|---|---|
| 0.081 | 2.40 | 66.5 | 6600 | 4.3 | 1.7 | $10^{-5}$ |
| 0.048 | 1.75 | 66.5 | 7200 | 5.5 | 1.6 | » |
| 0.020 | 0.50 | 59.4 | 21600 | 1.8 | 1.6 | » |
| 0.064 | 1.24 | 59.4 | 57600 | 3.5 | 1.8 | » |
| 0.045 | 1.35 | 59.4 | 33300 | 1.6 | 1.4 | » |

From the table over $f(V)$ on page 17, we see that with the same $\triangle t$ (for instance with the same temperature and relative humidity) the amount of hoar-frost deposited as a rule rises when the velocity of the wind increases. This is explained by the fact that the hoar-frost in the Polar sea chiefly consists of "Rauhfrost". ("Rauhfrost" is hoar-frost which is deposited on the windward side of hindrance, often during foggy or misty weather).

On closer examining the values in the table for $f(V)$ we find that $f(V)$ has a minimum at 1 m/sec. This probably depends on the circumstance that in extremely calm weather (0 m/sec.) hoar-frost which is *not* "Rauhfrost" may occur in the Polar sea. Between 2 and 6 m/sec. the deposition is approximately proportional to the velocity of the wind. This is a result which might have been expected, as in the formula $M = M_0 f(V) \triangle t \tau q$. $\triangle t$ is proportional to the oversaturation in vapour pressure $(E' - E'_i)$. Here $E'_i$ is the vapour pressure by saturation and $E'$ is the real one.

If now $f(V)$ is also proportional to $V$, we obtain the formula

$$M = C \cdot V (E' - E'_i) \tau q, \text{ where } C \text{ is a constant.}$$

For small velocities of wind, we now know that the amount of air ($L$) which during a second comes in direct contact with the cylinder of the hoar-frost recorder can be regarded as proportional to $V$. The above formula then only states that $M$ is proportional to the weight of the surplus of the water vapour existing in $L$.

We have previously found that the amount of hoar-frost increases with an increase of velocity of wind. *The probability for hoar-frost building*, on the contrary, decreases quickly with the strengthening of the wind.

During the dark hours of January, February, November and December 1924 the probability was as follows at different velocities of wind:

| | | | | | |
|---|---|---|---|---|---|
| Velocity of wind m/sec. .......... | 0—1 | 2 | 3 | 4—5 | over 5 |
| Probability for building of hoar-frost | 62 | 51 | 42 | 28 | 12 |

This proves very well that the relative humidity over ice — as we have seen before — decreases with increasing velocity of wind.

*The influence of temperature on the building of hoar-frost* has been discussed after all amounts of hoar-frost for 2 hours have been reduced to a velocity of wind of 1 m/sec.

The probability of hoar-frost at different temperatures is shown on Fig. 15. The probability rises at falling temperatures, down to —32°. After this the probability again decreases, possibly depending upon the circumstance that the amount of hoar-frost grows so small at very low temperatures, that it cannot be recorded without difficulty. This is especially the case when $R_i$ is only a little over 100%.

The amount of hoar-frost at different temperatures and a velocity of wind of m/sec. is seen on Fig. 16.

The amount of hoar-frost is largest at —28° to —29° C. It falls quickly with lower temperatures, depending upon the circumstance that the humidity of the air grows small. It is also low at high temperatures, which is in accordance with what was seen above, viz. that $R_i$, is small at high temperatures during winter.

*The yearly period of hoar-frost.* According to what has been mentioned above, the yearly period of the hoar-frost chiefly depends upon the surplus of water vapour (in grams pr. cm³) and upon the velocity of the wind. The water surplus, during the

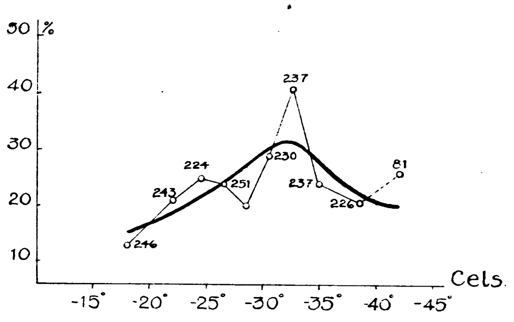


Fig. 15.

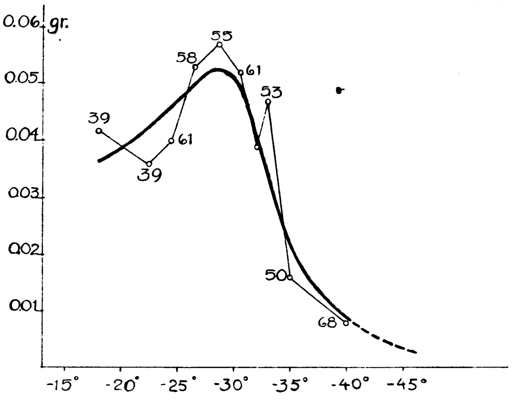


Fig. 16.

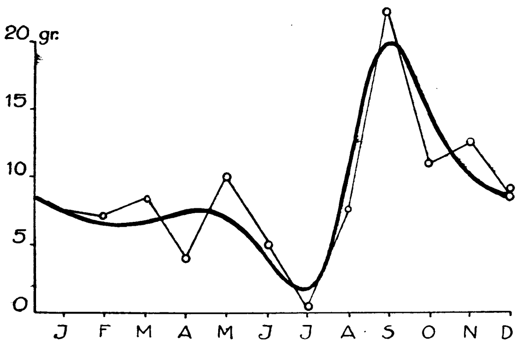


Fig. 17.

coldest season according to temperature, is very small even though $R_i$ is large. This causes a minimum in the amount of hoar-frost during January and February. During the spring, and especially during the autumn, the surplus is greater although the medium of $R_i$ is smaller. We therefore have a larger amount of hoar-frost during these seasons. During July the temperature is mostly above the freezing point, and on account of this hoar-frost is impossible. This causes a new minimum during that month. The conditions are shown on the curve of Fig. 17.

We also see from the curve that there is more hoar-frost during the antumn than during the spring. This is both dependent upon a greater surplus of water vapour and upon a greater velocity of wind during the autumn. The greater surplus of water vapour is caused by a more frequent occurence of open water.

*Daily period of the hoar-frost.* The period is very small during the *dark season.* Later, when the sun rises over the horizon during the day, the hoar-frost will more or less completely disappear during the light hours of the day. We get a marked minimum at noon. The minimum grows flatter and flatter as the day grows longer. The formation of hoar-frost is stronger early in the morning than in the evening. We have previously found the same in the case of humidity.

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We have now found that the conclusions drawn from the hoar-frost records agree in all respects with the results of the measurements with the thermo psychrometer during winter and with the hygrometer during summer.

In future when all the scientific material from the "Maud" expedition can be published, we shall see, that the daily and yearly periods of frequency of fog, cloudiness and precipitation will be in full accordance with the daily and yearly period of humidity and hoar-frost, here shown.