ON WATER IN THE CLOUDS

BY *HILDING KÖHLER*

WHITH 9 FIGURES AND 5 TABLES

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Of the older measurements of the amount of water in the clouds only those of Conrad (1) and Wagner (2) are really satisfactory. The autor of the present investigation began his researches in 1920. During the years 1920 and 1921 some measurements were carried out which, however, later proved to be affected by a constant error, presumably due to faulty rubber tubing. This error was of such magnitude that it is doubtful whether they should be considered[1].

It was not until 1925 that these determinations were resumed, using a better and surer method, due partly to the acquisition of two oil pumps by the Observatory and partly to the obtaining of first-class rubber connections. Unfortunately it was necessary to discontinue these investigations after a few months even though they should have been conducted over a period of many years and required at least two people. During the time which they were undertaken the air was especially poor in thick clouds. The data that I have been able to collect are therefore *rather scanty*. That they seem on the whole worthy of publication rests on the fact that I have been able to draw some conclusions from them, with the support of the measurements of Conrad and Wagner, which plainly show the great importance of putting the determination of the water content in clouds in the place on the program of meteorologists that this important problem deserves.

Measurements of Humidity.

Concerning the estimation of the accuracy with which the measurements of water content in fogs and clouds can be carried out, it is of fundamental importance to know the accuracy with which one can measure the quantity of water vapor present.

Conrad used for his determinations first an Assmann psychrometer and then a hair hygrometer. Wagner used the hair hygrometer throughout. The author used the Assmann psychrometer exclusively. Conrad obtained on three occasions at *Sonnblick* surprisingly low humidities with his hair hygrometer. On the other hand, Wagner obtained astonishingly high humidities, often over 100 %.

Concerning the use of hair hygrometer in general, it has been my experience that with frequent corrections and comparison with a similar stationary instrument indoors it gives very good results as compared to the Assmann type. However, it reaches equlibrium very slowly at low temperatures, At —10°, for example, the time required for attaining constancy with a Koppe hair hygrometer is about 20 minutes. For fog this

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[1] The value published for the water content in Met. Zeitschr. p. 168, 1921 and in Geof. Publ. p. 5 Vol. II, No. 1 is therefore much too high, and the probable value is about 2 g. per m^3.

long time required is particularly dangerous. Especially in wet fogs — neither Conrad nor Wagner characterize fog from this point of view — the whole hygrometer, hair, counterpoise, suspension for the counterpoise, and wheel finally become coated with a film of water. Besides the resulting change in weight it seems that the effect upon the hygroscopic properties of the hair should be considered, an effect which to my knowledge was not investigated; namely, whether a hair having condensed water on its surface reacts in the same way toward the water vapor in the air as does a dry filament. A reaction under these assumptions appears very improbable. On this account and on theoretical grounds which are not given here, I do not think that Wagner's supersaturations could be considered to correspond to the actual facts. I have therefore, in the use I have made of his investigations, recalculated the quantity of condensed water which Wagner obtained at this supersaturation by the assumption that the relative humidity was 100 %. Another reason for this procedure is emphasized later in this paper.

Very little is known relative to the accuracy attainable in the use of the Assmann aspiration psychrometer for humidity measurements in clouds. In cloudless air it is known that the calculation of the degree of humidity from Sprung's formula gives erroneous values for high and low humidities. For humidities near the saturation point too high vapor pressures are obtained. Moreover, it seems to me that Sprung's determination of the constant in August's formula was made on a basis of all to few measurements over too small a temperature interval.

Regnault (3) long age proposed to substitute for August's formula a more complete formula with two constants, which were to be determined experimentally. He made this recommendation only after a series of experiments which were conducted — as usual, where Regnault is concerned — with great accuracy at different air velocities past the thermometers. He thought that August's theoretical considerations were not tenable.

In the present time as we penetrate deeper into the fundamental laws of hydrodynamics, we must acknowledge without reservation the correctness of Regnault's views. The introduction of the second coefficient that Regnault proposed certainly has a deeper theoretical meaning than has the one proposed by Ekholm[1].

A. Svensson (4) has carried out a series of very painstaking investigations to determine both constants in the formula proposed by Regnault. These studies included a very large number of measurements over a temperature interval from + 26.25° to — 12.96°. Therefore his results, which form the basis for she so-called Svensson-Ekholm formula that was used by Bruno Rolf in the compilation of his "Tables Psychrométriques portative", are probably much more certain than Sprung's. The author of the present work has for this reason used the same formula for the calculation of the amount of water vapor in the clouds. It should be noticed that Svensson (5) assigns ± 0.12 mm as the average error of his investigations. After the calculation of the average value for his observed vapor pressure, 5.76 mm, the error is found to be nearly 2 %.

Proceeding on the assumption that humidity determinations in clouds by Assmann's psykrometer can be made with the same degree of accuracy as in cloudless air, I have in the short table 1 following calculated from temperatures from — 5° to + 10° the error $\triangle$ m in percent of the total quantity m of vapor per m^3 air that an observational error of 0.1° in the psychrometer temperature difference would cause. The average value obtained was 1.49 %.

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[1] In addition Svensson [l. c. 5] has shown through his most recent researches the untenability of Ekholm's hypothesis.

Table 1.

t	$\frac{100\,\Delta m}{m}$	Δm g
— 5	2.02	0.067
— 4	1.94	0.069
— 3	1.82	0.070
— 2	1.75	0.072
— 1	1.68	0.074
± 0	1.61	0.076
+ 1	1.54	0.978
+ 2	1.48	0.080
+ 3	1.41	0.082
+ 4	1.35	0.084
+ 5	1.30	0.087
+ 6	1.25	0.089
+ 7	1.23	0.092
+ 8	1.19	0.095
+ 9	1.14	0.098
+ 10	1.11	0.102

Since one knows from experience to what rapid fluctuations with time both the temperature and humidity of the atmosphere are subjected, one should assume a possible error of at least 4 % for humidity measurements in cloudless air.

In clouds Assmann's aspiration psychrometer must give even more uncertain results because droplets are deposited on both thermometers. An error of possibly 5 % cannot be avoided in the determination of the quantity of water present as vapor in the air of the clouds. If a strong hoarfrost (Rauhfrost) deposition occurs, or at lower temperatures, the error may be appreciably greater.

Perhaps one might be tempted on this account always to assume a humidity of 100 % in fog without further thought. That this is not permissible, however, is shown by Conrad's measurements as well as by Wagner's and many others'. Furthermore, we know very well that the droplets adsorb ions, radioactive emanations, etc., all of which decrease the vapor pressure and may reduce it to less than 100 %. This does not contradict a previous investigation (6) made by the author where he demonstrated that the vapor tension of the droplets at a certain stage of their growth — supposing continual condensation — passes through a maximum which is greater than 100 %.

From the foregoing considerations the following result is obvious: Since Conrad and Wagner's measurements showed that the densest clouds contain hardly more than 5 g. water per m^3 air and that clouds of relative density such that the distance of visibility is not greater than 100 meters often contain 0.3 g. water or less per m^3 air, and since at an air temperature of 0° an error of 5 % in the measurement of the vapor content per m^3 introduces an error of approximately 0.2 g. per m^3, consequently at a distance of visibility of 100 meters an error is caused in the determination of the content of condensed water equal to 67 %. It is also evident from this that the error in the determination of the quantity of condensed water increases very rapidly with temperature and rarity of the cloud. Since there is absolutely no proof of any relation between temperature and water content of the clouds, one may say that the accuracy of these measurements must rise with decreasing temperature and increasing cloud density.

Visibility in Clouds.

Both Conrad (1) and Wagner (2) indicated for every measurement of the water content in clouds the distance of visibility, the distance in meters that the observer must place himself from an object so that the outline of the object just disappears. Trabert (7) has developed a formula from theoretical considerations giving a relation between the radius of the cloud droplets, water content per unit of volume, and distance of visibility:

$$C \cdot \frac{r}{m} = l$$

l = visibility in meters
r = radius of droplets in μ
m = water content in g. per m^3

L. F. Richardson (8) obtained the same formula in another manner and from the measurements of the size of droplets which Conrad and Wagner made on the occasion of their sojourn on *Sonnblick* for the determination of water contents, he arrived at the following relation:

$$2.9 = \frac{(\text{Distance of Visibility}) \times (\text{volume of water per volume of cloud})}{(\text{Diameter of cloud particle})}$$

Several scientists, such as Wiener (9), Schuster (10), Mie (11), Mecke (12), and most recently Blumer (13), have conducted theoretical investigations on the passage of light through a foggy atmosphere. Most of them have studied the case where the fog particles are very small. Their researches deal with the scattering of light on passing through fog. This phenomenon has not been taken into consideration by Trabert. Without further proof it is not evident that this scattering can be neglected. If, however, one considers that the visibility of a nonluminous body depends on its contrast to the surroundings and thus that the direct rays from the object do not noticeably alter the diffuse light in the cloud, then it is evident that Trabert's formula can approximately be applied to this case where there is no directed light[1].

Since the clouds investigated by Conrad and Wagner were so dense that one can hardly suppose the presence of directed light, Trabert's formula should be valid for their measurements.

The author endeavored as far as possible to measure the size of droplets simultaneously to the determination of water content. Distance of visibility was estimated. When one has lived for a long time at a station one becomes skilled in estimating cloud densities in dim light. It is only necessary in the daytime to notice how a nearby object decreases in distinctness at a definite distance of visibility. I have in this way estimated the distance of visibility *approximately* on several occasions. Values thus obtained are not so exact as those that Wagner got by direct measurement, but later on we shall see how well Conrad's, Wagner's, and the present measurements agree.

Methods for the determination of the water content in clouds.

Conrad was the first to work out a method for obtaining exact values of the quantity of water — vapor + droplets — present in a definite volume. One of his methods was used by Wagner. The author also has adopted Conrad's methods. The one that gave the data published herewith was the same as that which Wagner employed, but appreciably greater volumes were used in the present work.

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[1] Strictly it is applicable only to dark bodies.

Tanks used.

Ordinary tanks for distilled water were closed by stoppers bearing three tubes equipped with stopcocks: one large tube — inner diameter 2 cm — and two small — inner diameter 1 cm. For sealing, an asphalt-like substance, "compound", was employed which is much used for insulation of joints in electric cables. It was melted and poured over the top of the bottle as is shown in Fig. 1. First a tin collar A was put over the neck of the bottle. This was then filled with melted "compound". When the "compound" hardened, another collar B was placed outside of A and also filled with "compound". After it hardened the tank was tight. With a vacuum of 1 mm established, during a day there was rarely more than a few tenths of a millimeter change. Four such tanks were used, hereafter designated as A, B, C, and D. Their volums are given in Table 2.

Table 2.

Tank	A	B	C	D
Volume in cm³	53 894	63 910	62 215	52 688

Fig. 2 is a photograph of one of the bottles, and Fig. 3 another photograph taken in the vicinity of the place where the bottle was usually filled with cloud air.

It is necessary to wrap the bottle with burlap or other material, for the danger is always present of the bottom being forced in during strong evacuation and being thrown upward. This is due to the bottom of the tanks being curved up. An explosion which also happened on one occasion may be very unpleasant.

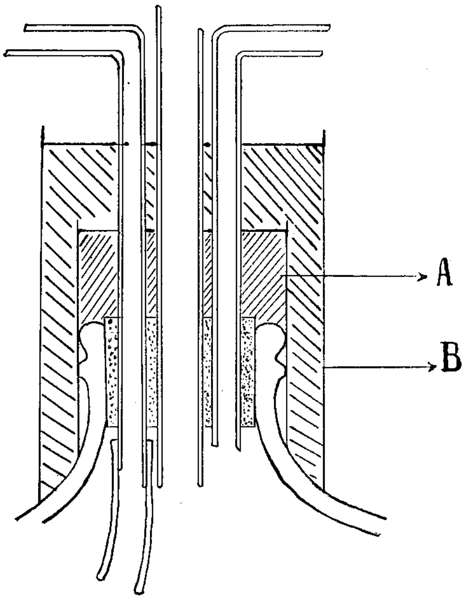

Fig. 1.

Evacuation and absorption of water.

Evacuation was accomplished by means of two oil pumps connected in series, driven by an electric motor. About thirty minutes were required to obtain a vacuum of a few tenths of a millimeter; the time increased, however, as the pumps aged.

Measurement of vacuum.

Measurement of vacuum was performed with an apparatus (Fig. 4) on the same principle as the McLeod (14) gauge. It accompanied a mercury pump from the firm of Nerlien Ltd., Oslo. The volume A, from *d* to *e* was 53 cc and when the mercury leveling tube *b* stood on the floor the pressure in both A and B was equal to p_ε. A scale was etched on tube *c* so that the number of cubic centimeters from the closed end could be read off. Then by lifting C so that the mercury rose in tubes B and C the pressure could be determined with great accuracy by reading off the difference in level of the mercury in arms B and C on the brass scale behind the arms, since p_ε in B was not changed.

After the cloud air had been admitted to the tank, dry air was sucked in by the same pumps through the tank and a series of U-tubes filled with phosphorus pentoxide (P_2O_5). This was accomplished in the following manner. First the bottle was evacuated through the U-tubes. During this operation the pressure was measured on both sides of the U-tube chain to make sure that the resistance was not too great. As soon as the pressure in the tank had decreased to 10—50 mm, air was admitted through phosphorous pentoxide to the tank while the pumps continued to suck out air through the U-tubes. The rate at which the pressure in the tank increased depended entirely on the difference between the resistance offered by the phosphorous pentoxide through which the air was admitted to the thank and the resistance in the U-tube chain. It usually required about thirty minutes for the pressure to rise to 300—600 mm. Then the stopcock through which the air entered was closed and evacuation started anew. This was repeated several times. Such a procedure was necessary to free the bottle of the water which is always adsorbed on glass walls. By replacing the U-tube closest to the tank each time it was easily established that two times for the admission of dried air and subsequent evacuation were quite sufficient to ensure the removal of water from the thank.

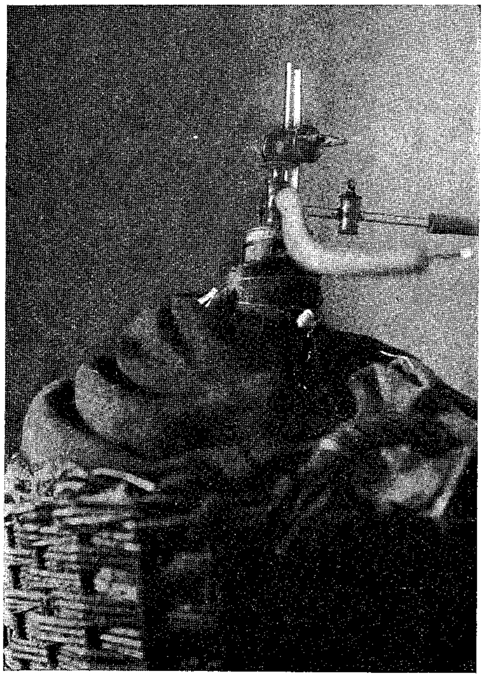

Fig. 2.

A little calculation shows that since the average atmospheric pressure was 680 mm, after an evacuation to 10 mm, admission of air to 300 mm and another evacuation to 10 mm, not more than 1/68 × 1/30 = 1/2040 of the original air could remain in the bottle. Since the pumps were in operation during the whole time of admission of air, about thirty minutes, the same length of time as that required for complete evacuation of the tank if no U-tubes were present, it is apparant that the P_2O_5 in the U-tubes must have absorbed all the moisture of the cloud air that was admitted into the tank at the start. The whole process was very protacted the resistanse of the U-tubes increased the time of evacuation very materially. The collection of water in the U-tubes required a total time of about four hours. Fig. 5 shows a photograph of the arrangement used for the determinations. α is the McLeod gauge and B, the manometer between the U-tubes and pump, If necessary, several tanks could be connected at the same time in series or in parallel.

Before the U-tubes were weighed dry air was admitted to them so that they would have the same pressure as the outer air. Then they were allowed to hang for at least one hour in a desicator before weighing. Both of these precautions are absolutely necessary and neglect of them may introduce a considerable error.

Sources of error in the method.

It is, of course, necessary in this method that all the stopcocks be absolutely tight and dry. It is of greatest importance to make sure that the joints between the rubber tubing and glass tubes are tight, so they should be covered with "compound" or similar material. Moreover, the rubber tubing should be of best quality so that it does not give off water. If these precautions are observed then the moisture taken up by the P_2O_5 should correspond to that which entered the bottle when the tap was opened directly to the cloud.

During the admission of air there occurs, however, a source of error that apparently was not adequately considered. With a strong wind blowing a rarefaction of the air in the bottle will take place, so that the influx of the outer air stops before a volume of air equal to that of the bottle and of the same density as the atmosphere has entered. In the last determinations of Table 3 such an equilibrium was established so that the influx ceased at a pressure 31.5 mm lower than atmospheric. On several other occasions where the water content corresponded to just the measured vapor content of the air this same phenomenon was probably the cause. It is possible that the two obviously incorrect values that Conrad obtained in a storm on Sonnblick (loc. cit. 1, p. 11) can be explained through such a rarefaction of the air. It is also possible tha the direct aspiration method that Schlagintweit, Pernter, and others employed miscarried on account of a similar reduced pressure. It is hardly conceivable that the effect could be caused by the inertia of the cloud particles.

Another chance for error is present in this method because the air is admitted through an opening which is very small in proportion to the surrounding cloud air. One soon notices during a sojourn in the mountains that the density of the clouds undergoes very great changes and sometimes holes actually occur. There is danger that the tap may be opened into such a hole.

The above-mentioned sources of error, together with those that were emphasized in connection with the remarks on the determination of the vapor pressure serve to account for the great difficulty one often experiences in attempting the quantity of condensed water in clouds.

On a few occasions the distance of visibility was estimated. The uncertainties of the procedure adopted have already been referred to.

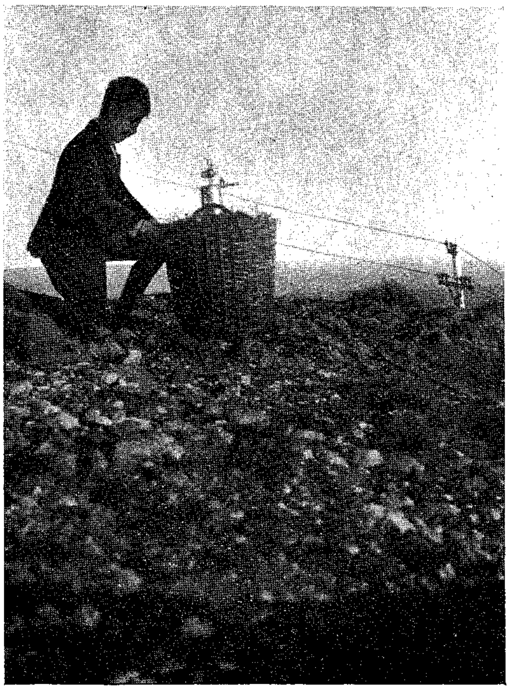

Fig. 3.

On several occasions the size of droplets was determined by measuring the corona around a light source. Sometimes a searchlight (Fig. 6, 7) was used as the light source and sometimes simply an ordinary electric light. The searchlight and measuring instrument were the same as the author used in his earlier studies (15) on cloud particles.

The writer always personally tended the tank for collection of cloud air and took the observations on the Assmann aspiration psychrometer. In the meantime Mr. Fagermo, first assistant, measured the coronas[1]. The weighings of the U-tubes and the care of the apparatus during the pumping of the moist air through the P_2O_5 was carried out by myself. The searchlight was operated by Mr. Lukkassen, the second assistant. I wish to express my thanks at this point for the aid rendered me by my assistants during this very trying work.

Results.

The results of the investigation are assembled in Table 3. The highest value, 1.84 g per m^3 of air, and the lowest, 0.12 g per m^3 are indicated in full-faced type.

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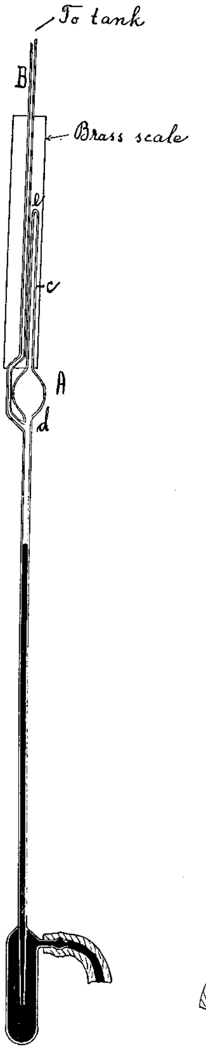
[1] On the method (l. c. 15).

Tables 3, 4 and 5 also have several colums of theoretical values, calculated from the measurements of Conrad and Wagner. It is evident at once that clouds investigated by these scientists, especially Conrad, were much denser. As mentioned before, those values that Wagner obtained with a humidity of over 100 % have been recalculated and appear in the column reduced values.

From the approximate values obtained for the distance of visibility in the present investigation, the constant C was calculated for the formula $\frac{r}{m} \cdot C = 1$. Then from this formula the radius was computed of the particles in the clouds studied by Conrad and Wagner and, surprisingly enough, the values obtained fell for the most part in the neighborhood of the radii of the so-called 7-group, and a smaller fraction fell in the 8-group, determined in a previous investigation by the author (15). Taking into consideration the circumstance that the writer previously showed the existance of these groups to be at least probable in rain at Innsbruck, it was deemed legitimate to assume that the deviation from the exact radii in these groups could be due to errors in the determination either of the distance of visibility or of water content. Therefore in place of the values which lay close to these groups the exact values were substituted and are found in the colums corresponding 7-groups and corresponding 8-group in the tables. Then C was determined by the method of least squares, yielding C = 6.11. Richardson (8) had previously obtained the value 2.9, using the diameter as the measure of particle size, and the value for that diameter which was obtained by Conrad and Wagner through corona measurements on Sonnblick. This value of 2.9 gives to C the value 2 × 2.9 = 5.8, very close to the author's value for C calculated n an entirely different way. This fact substantiates markedly the correctness of the author's apparently bold assumption.

According to the constant, 6.11, found by the writer, an object in the cloud should disappear when its visibility becomes $e^{-\frac{3}{4} \times 6{,}11} = 1/98$ of its visibility in clear air. This seems to agree with Fechner's physiological law. By experiment it was found that an object should disappear when its distinctness decreases to 1/64—1/131 of its original value (16) (Helmholtz). Tigerstedt (17) cites an experiment with a Masson disc giving values between 1/100 and 1/120 but adds that larger values and smaller (down to 1/250) were observed. Therefore it seems that the value obtained in clouds agrees very well with the values considered by these two authorities to be the most usual.



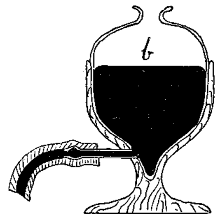


Fig. 4.

On the assumption of exact 7-group radii the exact distances of visibility were next calculated, in part for the visibilities to which Conrad assigned approximate values and in part for the visibilities in the clouds investigated by the author. These values appear in the column calculated distance of visibility. In the column calculated radius are found the values of r which satisfy the equation $\frac{r}{m} \cdot C = 1$. It will be noticed that the calculated distances of visibility in the table, based on Conrad's measurements, lie close to the middle value in the majority of cases of the limits given by

Table 3. *Köhler's measurements.*

Date	Time	Tank	Dry bulb. thermom.	Wet bulb. thermom.	Water vapour pressure	Rel. humidity	Vacuum in mm Hg	Effekt volume in cc	Amount water vapour in g per m^3	Increas in weight in g	Amount water in g per m^3	Amount condensed water in g pr. m^3	Character of cloud	Estimated distance of visibility	Calculated distance of visib.	Radius measured	Radius calculated	Corresp. 7-group	Corresp. 8-group
11/8	6^{30} p.	C	+ 8.9	+ 8,8	8.23	97 0/0	—	62 215	8.45	0.6154	9.89	1.44	moist	150	120	—	28.1	28.13	—
14/8	1^{30} p.	C	+ 9.8	+ 9.3	8.36	92 »	--	62 215	8.55	0.5919	9.51	0.96	dry	125	113	—	17.7	17.72	—
14/8	9^{27} p.	C	+ 7.4	+ 7.2	7.34	95 »	—	62 215	7.57	0.4992	8.02	0.45	dry	120	120	—	8.8	8.86	—
16/8	1^{00} a.	B	+ 5.5	+ 5.5	6.60	97 »	—	63 910	6.85	0.4956	7.77	0.91	wet	—	127	18.9	18.9	—	—
17/8	midd.	C	+ 7.2	+ 7.0	7.24	95 »	—	62 215	7.47	0.4851	7.80	0.33	wet	100	100	—	5.4	5.58	—
18/8	11^{55} a.	B	+ 7.1	+ 6.9	7.19	95 »	1.90	63 740	7.42	0.4902	7.69	0.27	wet	125	125	—	5.5	5.58	—
19/8	2^{57} a.	C	+ 2.9	+ 2.8	5.42	96 »	3.22	61 920	5.68	0.4184	6.76	1.08	wet	70	63	—	11.2	11.16	—
2/9	0^{17} p.	B	+ 6.4	+ 6.25	6.89	96 »	1.80	63 736	7.14	0.5103	8.01	0.87	dry	40	40	—	5.7	5.58	—
3/9	11^{28} p.	B	+ 4.2	+ 4.1	5.94	96 »	1.03	63 811	6.20	0.4034	6.32	**0.12**	dry	—	372	7.2	7.2	7.03	—
4/9	9^{12} p.	B	+ 4.2	+ 4.1	5.94	96 »	1.47	63 767	6.20	0.4156	6.52	0.32	dry	200	214	11.2	11.2	11.16	—
5/9	0^{05} a.	C	+ 3.9	+ 3.7	5.74	95 »	1.70	62 058	5.99	0.4235	6.82	0.83	dry	—	80	10.9	10.9	11.16	—
6/9	1^{35} a.	C	+ 3.9	+ 3.9	5.90	97 »	2.50	61 983	6.16	0.3966	6.40	0.24	wet	—	385	15.1	15.1	—	(15.52)
9/9	3^{05} a.	B	+ 2.2	+ 2.2	5.23	97 »	4.00	63 534	5.50	0.3647	5.73	0.23	moist	—	403	15.2	15.2	—	(15.52)
10/9	0^{11} a.	C	+ 2.4	+ 2.3	5.23	96 »	2.76	61 963	5.49	0.3578	5.78	0.28	moist	—	363	16.6	16.6	—	—
21/9	8^{57} p.	C	+ 0.9	+ 0.9	4.76	97 »	3.00	61 937	5.03	0.3453	5.58	0.55	Δ	—	128	11.5	11.5	11.16	—
24/9	4^{40} p.	D	+ 3.1	+ 2.9	5.42	95 »	1.72	52 553	5.67	0.3496	6.65	0.98	moist	100	139	—	22.3	22.32	—
24/9	5^{15} p.	A	+ 3.0	+ 2.8	5.38	95 »	1.50	53 773	5.64	0.3371	6.27	0.63	dry	100	109	—	11.2	11.16	—
24/9	8^{20} p.	C	+ 3.0	+ 2.8	5.38	95 »	2.48	61 985	5.64	0.3640	5.88	0.24	dry	ca. 100	140	5.5	5.5	5.58	—
24/9	10^{18} p.	A	+ 2.9	+ 2.8	5.42	96 »	0.57	53 843	5.68	0.3164	5.88	0.20	dry	—	259	8.5	8.5	8.85	—
25/9	2^{42} p.	D	+ 3.0	+ 2.9	5.45	96 »	0.33	52 662	5.72	0.3182	6.04	0.32	chang.	—	210	11.0	11.0	11.16	—
26/9	11^{55} p.	D	+ 2.6	+ 2.6	5.38	97 »	2.04	52 529	5.65	0.3932	7.49	**1.84**	wet	—	53	15.9	15.9	--	15.52
27/9	10^{13} p.	A	— 1.9	— 1.9	3.81	96 »	1.04	53 811	4.06	0.2476	4.60	0.54	wet ∼	—	360	31.9	31.9	—	31.03
28/9	10^{21} p.	D	— 1.3	— 1.25	4.00	96 »	1.36	50 111	4.26	0.2489	4.97	0.71	° ∼	ca. 150	121	14.0	14.0	14.06	—

Table 4. *Conrad's measurements.*

Date	Time	Temp.	Water vapour g per m^3	Total water obtained in g per m^3	Cond. water in g per m^3	Measured dist. of visibility	Calculated dist. of visibility	Radius (calcul.)	Corresp. 7-group	Corresp. 8-group
1/7	4^{30} p.	+ 8.4	8.24	11.28	3.04	22—30	**28.2**	**14.06**	14.06	—
2/7	5^{00} p.	+ 8.3	8.28	11.05	2.77	22—30	**24.6**	**11.16**	11.16	—
2/7	7^{40} p.	+ 7.2	7.76	10.38	2.62	30	30	12.8	—	—
2/7	3^{00} p.	+ 8.0	8.22	9.76	1.54	33--38	35.5	8.9	8.86	—
2/7	4^{30} p.	+ 8.3	8.28	9.36	1.08	38—60	**50.1**	**8.86**	8.86	—
2/7	9^{30} p.	+ 7.8	7.73	8.15	0.42	ca. 80	**83.6**	5.58	5.58	—
19/8	10^{00} a.	+ 1.4	5.32	9.89	4.57	19	19	14.2	14.06	—
20/8	11^{00} a.	+ 4,0	6.34	10.70	4.36	20	20	14.3	14.06	—
19/8	11^{62} a.	+ 3.0	5.93	8.87	2.94	24—30	**29.2**	14.06	14.06	—
20/8	8^{45} a.	+ 2.2	5.63	6.53	0.90	40—53	**47.7**	7.03	7.03	—
22/6	5^{10} p.	— 0.9	4.61	6.95	2.34	27	27	10.3	—	—
29/6	8^{15} p.	+ 0.5	5.01	7.88	2.87	30	30	14.1	14.06	
29/6	11^{15} a.	— 1.0	2.28	3.98	1.70	34	34	9.5	—	9.78
20/6	7^{00} p.	+ 5.5	6.99	8.48	1.49	35	35	8.5	8.86	—
29/6	1^{30} p.	— 1.0	3.20	3.70	0.50	75	75	6.1	—	6.16
29/6	5^{30} p.	± 0.0	3.36	3.71	0.35	80	80	4.6	4.43	—

Table 5. *Wagner's measurements.*

Date	Time	Temp.	Rel. humidity	Water apour in g per m^3	Total amount of water in g per m^3	Condensed water in g per m^3	Measured dist. of visibility	Reduced values	Radius (calcul.)	Corresp. 7-groups	Corresp. 8-group
13/7	4^{00} p. m.	+ 2.1	103	5.79	6.19	0.40	80	0.57	7.5	—	7.76
14/7	6^{10} p. m.	+ 0.5	103	5.19	5.98	0.79	80	0.95	12.4	—	12.20
16/7	6^{30} p. m.	— 4.3	101	3.60	4.17	0.57	90	0.61	9.0	8.86	—
17/7	8^{45} p. m.	+ 1.2	102	5.39	8.59	3.20	30	3.31	16.2	—	—
17/7	10^{15} p. m.	+ 0.8	100	5.14	9.98	4.84	—	4.84	—	—	—
19/7	11^{20} p. m.	— 0.1	99	4.79	7.42	2.63	30	2.63	12.9	—	—
19/7	4^{10} p. m.	— 0.2	95	4.56	7.12	2.56	45	2.56	18.8	—	—
19/7	6^{45} p. m.	— 0.4	103	4.89	8.30	3.41	30	3.55	17.4	17.72	—
19/7	9^{15} p. m.	— 0.4	103	4.89	7.91	3.02	—	3.16	—	—	—
20/7	2^{15} p. m.	+ 1.2	91	4.80	6.93	2.13	50	2.13	17.4	17.72	—
21/7	2^{10} p. m.	— 0.2	90	4.32	5.17	0.85	70	0.85	9.7	—	9.78
21/7	7^{00} p. m.	— 0.4	103	4.89	5.48	0.59	70	0.73	8.4	8.86	—
21/7	9^{00} p. m.	— 0.4	102	4.83	6.44	1.61	50	1.71	14.0	14.06	—
22/7	4^{30} p. m.	+ 2.8	74	4.35	5.95	1.60	5	1.60	17.0	—	—
24/7	10^{30} p. m.	— 2.1	103	4.32	4.55	0.23	90	0.36	5.3	5.58	—
24/7	12^{30} p. m.	— 1.4	103	4.53	5.47	0.94	65	1.08	11.5	11.16	—
25/7	10^{15} p. m.	— 0.2	101	4.85	6.30	1.45	40	1.50	9.8	—	9.78
25/7	1^{30} p. m.	+ 0.5	98	4.94	5.20	0.26	100	0.26	4.2	4.43	—
25/7	4^{00} p. m.	+ 0.8	103	5.29	5.41	0.12	100	0.28	4.6	4.43	—
25/7	6^{00} p. m.	+ 0.7	103	5.26	5.60	0.34	80	0.50	6.5	—	—
27/7	8^{30} p. m.	+ 1.5	103	5.54	9.98	4.44	25	4.60	18.8	—	—
27/7	10^{30} p. m.	+ 1.6	101	5.47	9.85	3.38	35	3.43	19.6	—	19.55

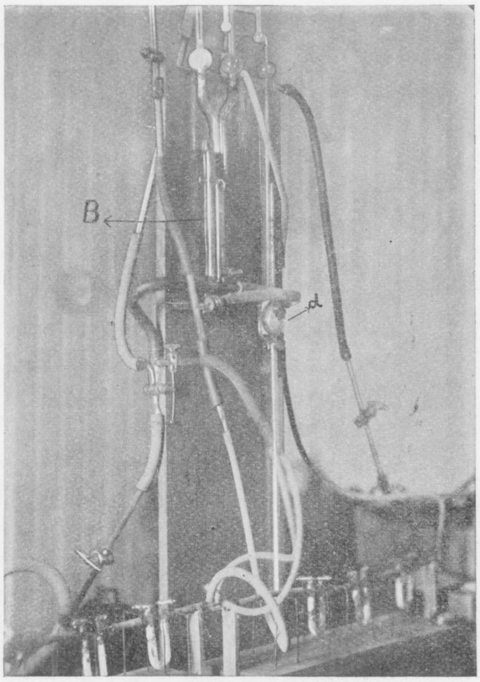


Fig. 5.

Fig. 6.

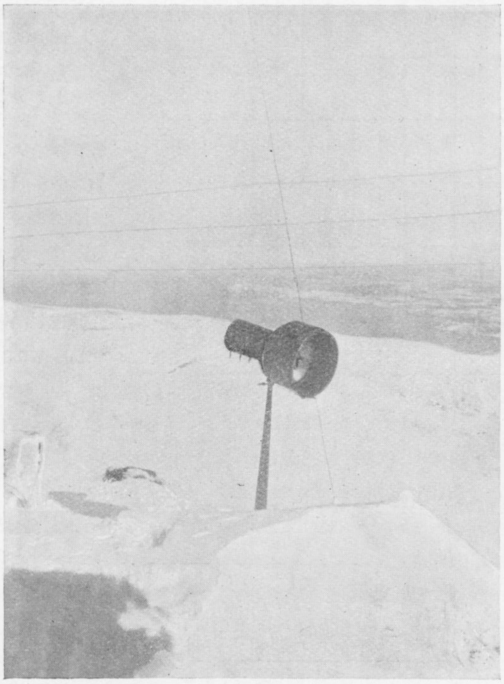


Fig. 7.

Conrad. The calculated distances of visibility in the tables 3 (Köhler's measurements) certainly agree very closely with the visibilities which must actually have existed.

If now the same formula is applied to Wagner's measurements, it is found water content calculated from the unreduced values for the date $^{25}/_7$ 4 : 00 P. M. gives improbably small radii, a fact which supports the procedure adopted by the author of reducing the values of the water content.

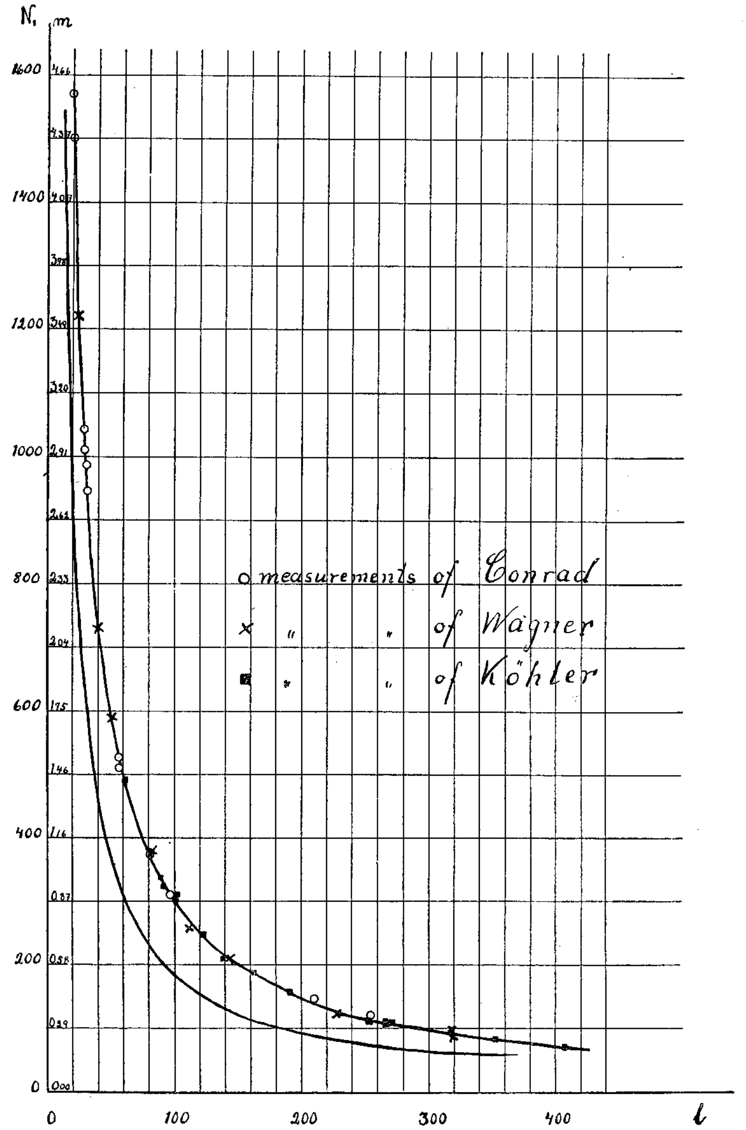


Fig. 8.

Both Conrad and Wagner constructed curves showing the relation of the distance of visibility to water content. Such a curve can naturally be found from a large number of measurements, but it is evident from the formula employed here that the distance of visibility must also be a function of r. If the measurements are all reduced to the same radius, the required relation is easily obtained. Only those measurements where the cloud contained droplets of radii belonging to the 7-group were used. The radii are reduced to the value which came closest to the average of all the droplet measurements made by the author at *Haldde*, namely 8.86 μ. The other radii are expressed here according to the formula $8.86 \times 2^{\frac{n}{3}}$ where n is a whole number when only the 7-group is used. If now it is assumed that a combination of droplets takes place by two's then the number has decreased to half. Letting N_1 designate the number of droplets with radius $r_1 = 8.86\,\mu$, we have, if $r = r_1 \cdot 2^{\frac{n}{3}}$

$$N = N_1 \cdot 2^{-n}$$

We know in addition that $m = N \cdot \frac{4}{3} \pi r^3$

$$l = C \frac{r}{N \cdot \frac{4}{3} \pi r^3} = C \frac{1}{N \cdot \frac{4}{3} \pi r^2}$$

or

$$l = \frac{C}{N_1 \cdot 2^{-n} \frac{4}{3} \pi r_1^2 \cdot 2^{\frac{2}{3} n}} = \frac{18587}{N_1 \cdot 2^{-\frac{n}{3}}}$$

$$\therefore N_1 = \frac{18587}{l \cdot 2^{-\frac{n}{3}}}$$

The curve is therefore established on theoretical grounds.

Since at the *Sonnblick* station the radii appear to have been much larger on the average than 8.86 μ an since the clouds the author measured at *Haldde* often had larger droplets, a curve was also constructed to give the relation between the water content actually found and the distance of visibility, after the droplets had heen reduced to 14.06 μ. This curve is a measure of the accuracy with which the formula $C \cdot \frac{r}{m} = 1$ holds for the 7-group, when the exact radii in the 7-group (not the observed radii) and the experimentally found values for the condensed water per m^3 are used. (Fig. 8 the curve to right).

The most important conclusions to be drawn from this curve are that a distribution of droplets occurred at *Sonnblick* — like that proviously demonstrated at *Haldde* — according to the formula $r_1 \cdot 2^{\frac{n}{3}}$ (where n $= \pm 1, 2, - - -$) and that it is probable that $r_1 = 8.859$ closely.

To what extent the deviations found from the 7- and 8-groups are due to the presence of other groups, to occasional inhomogenities in the clouds, or to errors in measurements (see pages 5 and 9) cannot be decided.

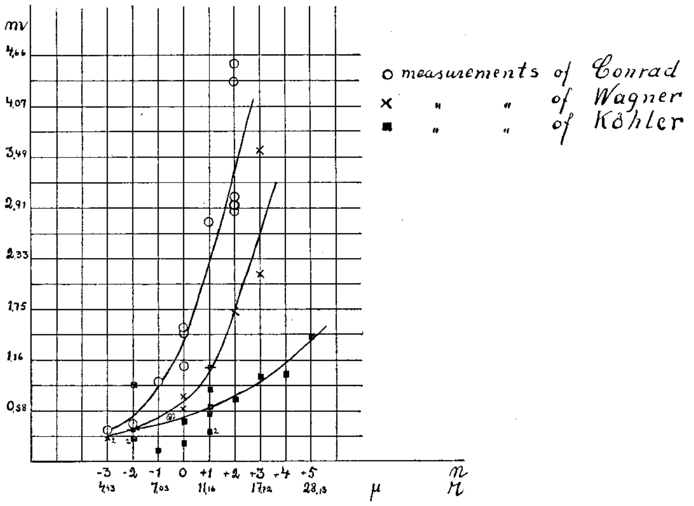


Fig. 9.

It is evident from the tables that a relation also exists between distance of visibility and radius of cloud particles. The author therefore computed the coefficients of correlation *q* between *r* and N_1 with the following results:

For Conrad's measurements $q = 0.90 \pm 0.058$
For Wagner's » $q = 0.86 \pm 0.092$
For Köhler's » $q = 0.71 \pm 0.124$

If it is now considered that Conrad's investigations were conducted in the thickest clouds and Köhler's in the thinnest, the result ensues that *q* decreases with decreasing cloud density. In Fig. 9 the relation is reproduced graphically with *r* as abscissas and N_1 as ordinates.

The fact that there is a relation between r and m and that this becomes less pronounced as the density of the cloud decreases indicates that C in reality should be a function of cloud density. If, however, the behavior may be assumed to be on the average in agreement with the findings of the author in his droplet measurements then it can be explained quite rationally. In a foregoing work the author (15) showed that very probably the droplets always begin to condense at the same size of radius r. It follows immediately that the more droplets of this size present, that is, the greater the water content, the more easily and quickly will they attain another determined size. The fewer the drops of radius r, the greater the variation in the relation between N_1 and r obtained at the end of a certain time condensation. These considerations would seem to account for both the existence of a relation between these quantities and that this relation becomes less marked with decreasing density of the cloud.

This relation between radius and water content explains why neither Conrad nor Wagner obtained hyperbolas in general for the relation between m and l. Their curves approach the coordinate axes more rapidly. For values of about 1 g per m^3, nevertheless, they agree very well with the author's curves in Fig. 8.

These properties should be studied more thoroughly, however, and it is very desirable that several, more accurate, determinations be made simultaneously of water content, drop size, and distance of visibility.

Sumary.

1. At Haldde the water content of the clouds *appears* to be of the same order of magnitude as that found by Conrad and Wagner in Austria. The sources in the methods, discussed, may be observed.
2. The author has given reasons for the probability that the 7-group and possibly the 8-group also are found to a rather great extent in the clouds investigated by Conrad and Wagner as well as by the author at Haldde. The assumption required for this conclusion is that Trabert's equation holds for the relation between distance of visibility, radius of droplets, and water content. It is the opinion of the author that the formula is valid if the light is not directed but is completely scattered in the cloud and if the object is distinct and dark in cloudless air.
3. On this basis a relation has been developed between water content and distance of visibility.
4. A relation between drop size and water content has been established.
5. The author expresses his wish that studies of condensation and the general properties of water in the atmosphere may receive greater consideration from meteorologists and that more refined methods may be developed for the measurement of vapor tensions and the total water content in clouds.

References.

1. Dr. V. Conrad, Über den Wassergehalt der Wolken, Denkschriften der mathematisch-naturwissenschaftlichen Classe der K. Akad. der Wissenschaften B. 73 p. 1—17, Wien 1901.
2. Dr. Arthur Wagner, Untersuchung der Wolkenelemente auf dem Hohen Sonnblick (3106 m), Sitz-ber. der Math.-Naturw. Klasse der k. Akad. der Wissensch. B. 117, Abt. 2 a, p. 1281, Wien 1908.
3. M. V. Regnault, Études sur l'hygrométrie, Annales de chemie et de Phys. Tome 15, p. (212) 1845.
4. Aron Svensson, Zur Kenntniss des ventilierten Psykrometers, Akad. Abh., Stockholm 1898.
5. — Zur Psykrometerfrage, Met. Zeitschr. B. 43, p. 140, 1926.
6. Hilding Köhler, Zur Thermodynamik der Kondensation an hygroskopischen Kernen und Bemerkungen über das Zusammenfließen der Tropfen, Medd. från Statens Met.-Hydrogr. Anstalt. B. 3 No. 8, Stockholm 1926.
7. W. Trabert, Die Extinktion des Lichtes in einem trühen Medium (Sehweite in Wolken), Met. Zeitschr. B. 18, p. 518, 1901.
8. L. F. Richardson, Measurement of Water in Clouds, Proc. of the Royal Soc. Ser. A. Vol. 46 p. 19, 1919.
9. Chr. Wiener, Abh. d. Kais.-Leop.-Carol. Deutsch. Akad. der Naturf. B. *73*, 1907, B. *91* 1909; after Blumer (13).
10. Arthur Schuster, Radiation through a foggy Atmosphere, Astroph. Journ. Vol. 21, p. 1, 1905.
11. G. Mie, Ann. d. Phys. B. 25 p. 377, 1908.
12. R. Mecke, ,Über Zerstreuung und Beugung des Lichtes durch Nebel und Wolken, Ann. d. Phys. V. 65 p. 257, 1921.
13. Hans Blumer, Strahlungsdiagramms kleiner dielektrischer Kugeln II, ZS. f. Phys. Vol. *32*, p. 119, 1925, Vol. 38, p. 304, 1926.
14. Mc Leod, Phil. Mag. Vol. 48, p. 110, 1874.
15. Hilding Köhler, Untersuchungen über die Elemente des Nebels und der Wolken, Medd. från Statens Meteor.-Hydrogr. Anstalt Vol. 2. No. 5. Stockholm 1925.
16. H. von Helmholz, Handbuch der physiologischen Optik, Hamburg u. Leipzig 1911, p. 146.
17. Robert Tigerstedt, Lehrbuch der Physiologie des Menschen, p. 89.

the pressure in the tank had decreased to 10—50 mm, air was admitted through phosphorous pentoxide to the tank while the pumps continued to suck out air through the U-tubes. The rate at which the pressure in the tank increased depended entirely on the difference between the resistance offered by the phosphorous pentoxide through which the air was admitted to the thank and the resistance in the U-tube chain. It usually required about thirty minutes for the pressure to rise to 300—600 mm. Then the stopcock through which the air entered was closed and evacuation started anew. This was repeated several times. Such a procedure was necessary to free the bottle of the water which is always adsorbed on glass walls. By replacing the U-tube closest to the tank each time it was easily established that two times for the admission of dried air and subsequent evacuation were quite sufficient to ensure the removal of water from the thank.

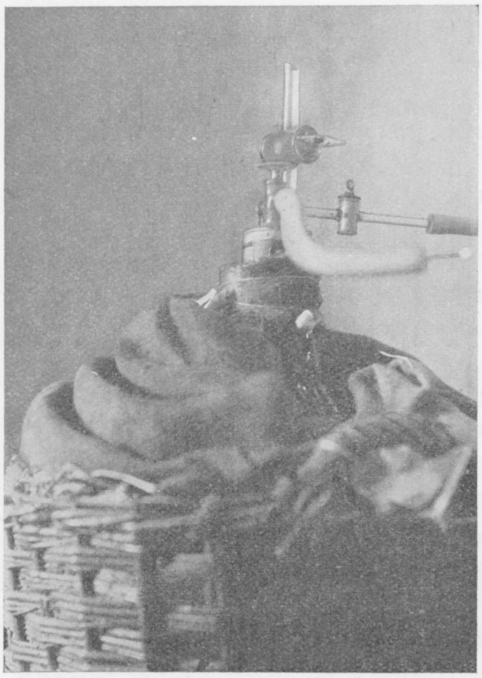


Fig. 2.

A little calculation shows that since the average atmospheric pressure was 680 mm, after an evacuation to 10 mm, admission of air to 300 mm and another evacuation to 10 mm, not more than $1/68 \times 1/30 = 1/2040$ of the original air could remain in the bottle. Since the pumps were in operation during the whole time of admission of air, about thirty minutes, the same length of time as that required for complete evacuation of the tank if no U-tubes were present, it is apparant that the P_2O_5 in the U-tubes must have absorbed all the moisture of the cloud air that was admitted into the tank at the start. The whole process was very protacted the resistanse of the U-tubes increased the time of evacuation very materially. The collection of water in the U-tubes required a total time of about four hours. Fig. 5 shows a photograph of the arrangement used for the determinations. α is the McLeod gauge and B, the manometer between the U-tubes and pump, If necessary, several tanks could be connected at the same time in series or in parallel.

Before the U-tubes were weighed dry air was admitted to them so that they would have the same pressure as the outer air. Then they were allowed to hang for at least one hour in a desicator before weighing. Both of these precautions are absolutely necessary and neglect of them may introduce a considerable error.

Sources of error in the method.

It is, of course, necessary in this method that all the stopcocks be absolutely tight and dry. It is of greatest importance to make sure that the joints between the rubber tubing and glass tubes are tight, so they should be covered with "compound" or similar material. Moreover, the rubber tubing should be of best quality so that it does not give off water. If these precautions are observed then the moisture taken up by the P_2O_5 should correspond to that which entered the bottle when the tap was opened directly to the cloud.

During the admission of air there occurs, however, a source of error that apparently was not adequately considered. With a strong wind blowing a rarefaction of the air in the bottle will take place, so that the influx of the outer air stops before a volume of air equal to that of the bottle and of the same density as the atmosphere has entered. In the last determinations of Table 3 such an equilibrium was established so that the influx ceased at a pressure 31.5 mm lower than atmospheric. On several other occasions where the water content corresponded to just the measured vapor content of the air this same phenomenon was probably the cause. It is possible that the two obviously incorrect values that Conrad obtained in a storm on Sonnblick (loc. cit. 1, p. 11) can be explained through such a rarefaction of the air. It is also possible tha the direct aspiration method that Schlagintweit, Pernter, and others employed miscarried on account of a similar reduced pressure. It is hardly conceivable that the effect could be caused by the inertia of the cloud particles.

Another chance for error is present in this method because the air is admitted through an opening which is very small in proportion to the surrounding cloud air. One soon notices during a sojourn in the mountains that the density of the clouds undergoes very great changes and sometimes holes actually occur. There is danger that the tap may be opened into such a hole.

The above-mentioned sources of error, together with those that were emphasized in connection with the remarks on the determination of the vapor pressure serve to account for the great difficulty one often experiences in attempting the quantity of condensed water in clouds.

On a few occasions the distance of visibility was estimated. The uncertainties of the procedure adopted have already been referred to.

Fig. 3.

On several occasions the size of droplets was determined by measuring the corona around a light source. Sometimes a searchlight (Fig. 6, 7) was used as the light source and sometimes simply an ordinary electric light. The searchlight and measuring instrument were the same as the author used in his earlier studies (15) on cloud particles.

The writer always personally tended the tank for collection of cloud air and took the observations on the Assmann aspiration psychrometer. In the meantime Mr. Fagermo, first assistant, measured the coronas[1]. The weighings of the U-tubes and the care of the apparatus during the pumping of the moist air through the P_2O_5 was carried out by myself. The searchlight was operated by Mr. Lukkassen, the second assistant. I wish to express my thanks at this point for the aid rendered me by my assistants during this very trying work.

Results.

The results of the investigation are assembled in Table 3. The highest value, 1.84 g per m^3 of air, and the lowest, 0.12 g per m^3 are indicated in full-faced type.

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[1] On the method (l. c. 15).