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SAMPLING ATMOSPHERIC SEA-SALT NUCLEI OVER THE OCEAN¹

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Atmospheric hygroscopic nuclei are of primary interest to meteorologists in studies of haze, fog, clouds, etc. (Simpson, 1941; Middleton, 1941; Sheppard, 1947). The sea surface is presumed to be an important source of these nuclei in the form of drops of concentrated sea water arising from spray. Gautier (1899), Jacobs (1939) and others have made measurements of total air-borne chlorides by use of filtering methods; Wright (1940b) and Neiburger and Wurtele (1948) have related changes in visibility and relative humidity to the number and average size of hygroscopic nuclei. However, no information seems to be available which gives the measured weights and numbers of sea-salt nuclei² at various heights in clear air over the open sea (see summaries by Landsberg, 1938; Wright, 1940a; Simpson, 1941).

The primary purpose of this paper is to describe the methods used to sample sea-salt nuclei in air over the sea and to measure the weight of chloride³ in these nuclei. Data are shown giving the weight and number of salt nuclei sampled from aircraft at various heights over the open sea.

The following methods of sampling and measuring air-borne nuclei containing chlorides are modifications of those used by Cunningham (1942). The sampling of aerosols by exposing small glass slides to an air stream has been used by Houghton and Radford (1938), Cunningham (1942), May (1945), Schaefer (1946) and many others. The present authors used 1 x 15 mm glass surfaces cut from microscope slides that were ground to size on a lens-grinding wheel; these slides were cleaned and then coated with hydrophobic Dri-film⁴ in the manner

¹ Contribution No. 458 of the Woods Hole Oceanographic Institution. This study was supported by the Office of Naval Research, under contract number N6onr-277TO11.

² Hereafter these nuclei, whether in the crystalline or liquid phase, will be termed "salt nuclei" or simply "nuclei."

³ When chloride, chlorinity or Cl is used, reference is made to chlorine present as chloride or chloride ion.

⁴ Dri-film No. 9987, made by the General Electric Co., Schenectady, New York.

suggested by Langmuir (1944). A Dri-film coating causes drops of water to become hemispheric on the slides, as shown in Fig. 1, where sprayed sea-water nuclei and sampled atmospheric nuclei are seen as crystalline masses and as liquid hemispheres viewed from top and side. In this study it is assumed that the nuclei, when liquid, are hemispheres. Fig. 2A shows the vane used to expose the slides normal to the air stream.

Following exposure, the slides were brought to the laboratory and placed in a lucite box which is mounted upon a microscope stage (Fig. 3). A 50 ml sample of sulfuric acid and water was introduced for vapor pressure control, after which the box was sealed. Temperature was thermostatically controlled. When the temperature of the air around the microscope and that of the acid solution inside the lucite box were equal (within $\pm 0.1^\circ \text{C}$), and when the drops on the slides ceased changing in diameter, it was assumed that the air in the chamber had reached water vapor saturation. The hygroscopic nuclei immersed in this air gain or lose water vapor, thus causing changes in nuclei salt concentration. At the point of equilibrium the water vapor pressure over the nuclei⁵ will equal that over the acid solution, which is known. This method, which is an adaptation of a chemical technique for determining the concentration of solutions, is referred to by Glasstone (1940) as the "isopiestic" or equal pressure method.

After equilibrium was established, counts and diameter measurements of the nuclei were made. Since the vapor pressures and densities of concentrated sea water are known, it is possible to determine the weight of the chloride in the individual nuclei.

The weight, in grams, of the total chloride in all of the measured nuclei on a slide (W_{Cl}) is derived as follows:

$$W_{Cl} = V d Cl, \quad (1)$$

where V = volume of nuclei in μ^3 , d = density of nuclei in g/cm^3 and Cl = chlorinity of nuclei expressed as weight fraction. In the equation, volume is computed from nuclei diameters; chlorinity is read from Fig. 5, using the vapor pressure and temperature of the acid solution; acid solution vapor pressures are read from Fig. 6, nuclei densities are

⁵ Curvature effects upon vapor pressure over the nuclei are not generally significant when using the above method of determining the Cl present in the nuclei. This is due to the fact that the nuclei, when in equilibrium with a 16% solution of $\text{H}_2\text{SO}_4 + \text{H}_2\text{O}$, are hygroscopic solutions of sea salt with a concentration of Cl about 75 % by weight. In these nuclei small increases in vapor pressure due to surface tension are readily balanced by decreases in vapor pressure produced by small increases in the salt concentration (see Fig. 5).

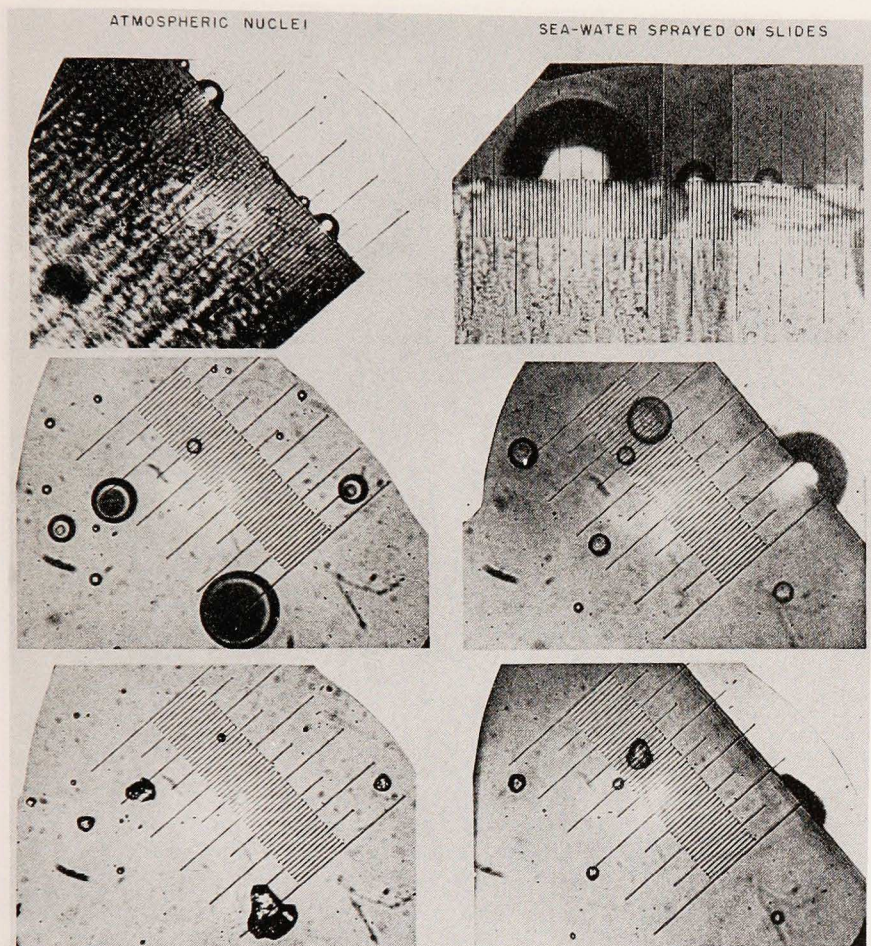


Figure 1. Photomicrographs of sea-water nuclei and sampled atmospheric nuclei as crystalline masses and as liquid hemispheres viewed from the top and side. Scale: one division = 2.2μ

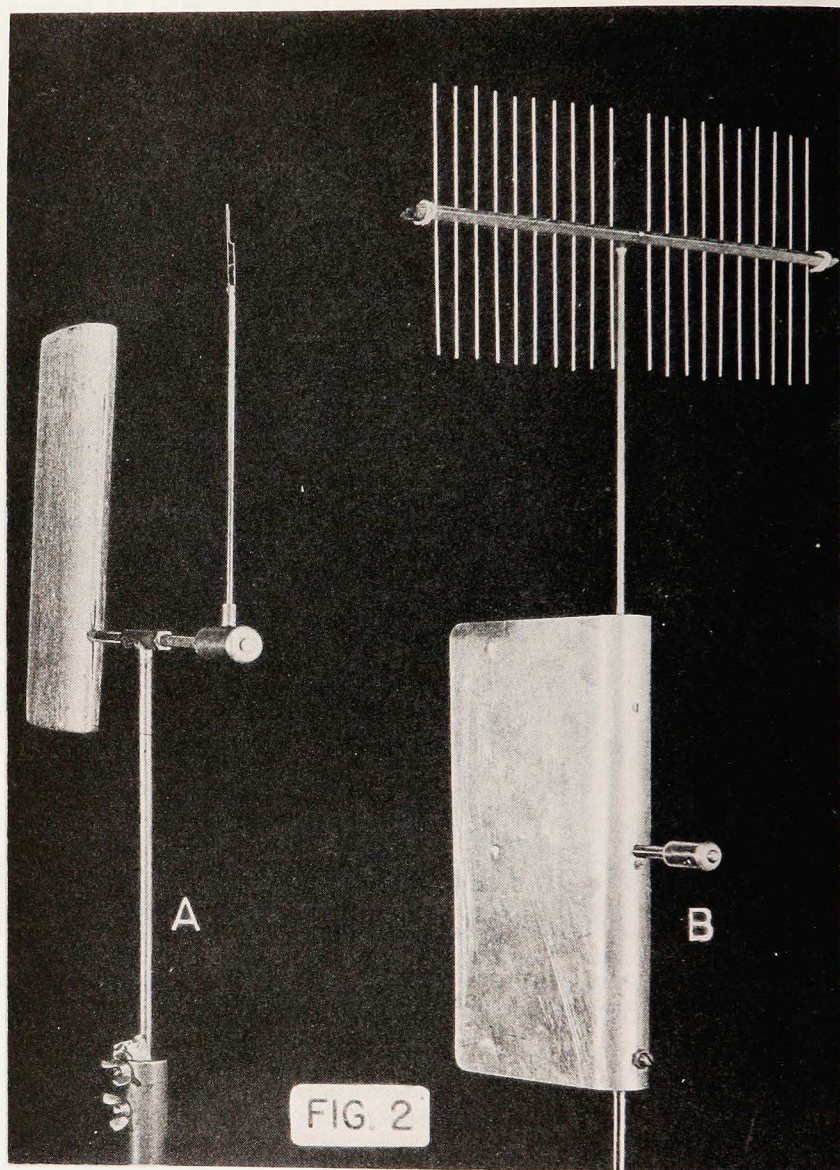


Figure 2. The glass slide and silver rod sampling surfaces and the vanes used to hold them normal to the air stream.

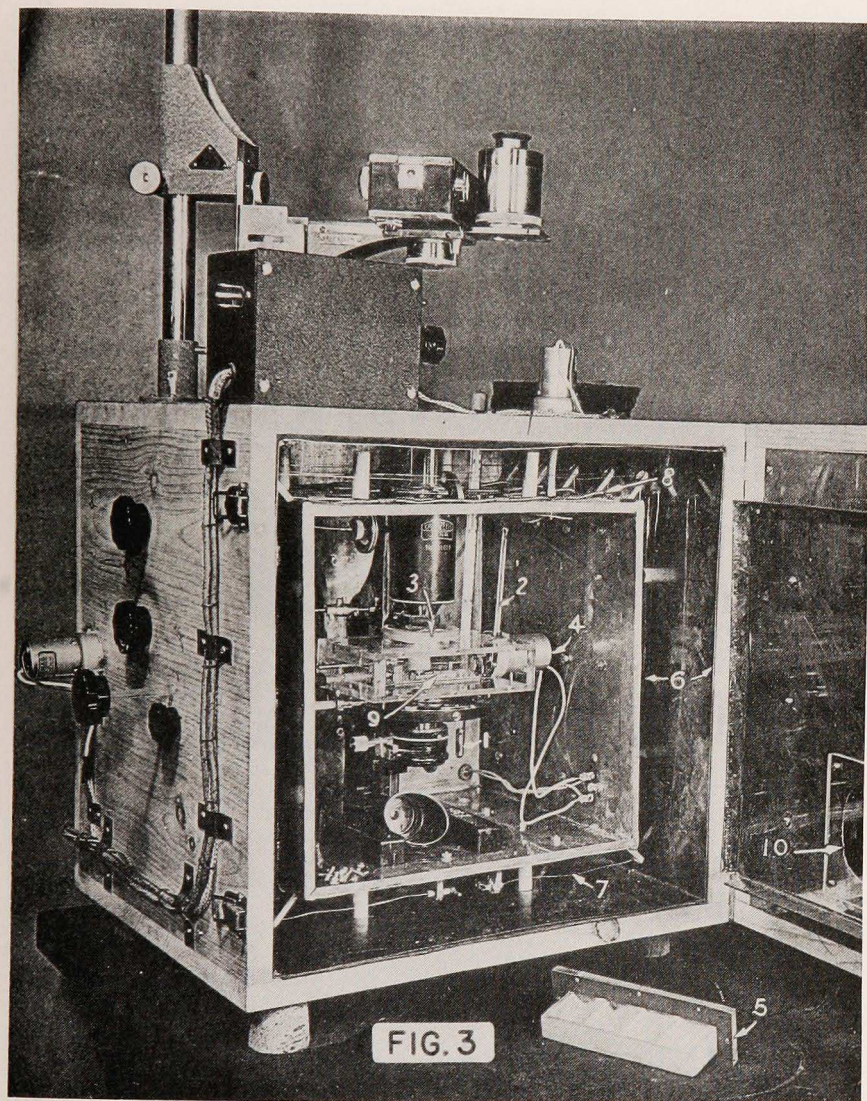


FIG. 3

Figure 3. The lucite box and accessory apparatus used to control temperature and water vapor pressure over the nuclei. 1. Thermometer for measuring temperature of ambient air. 2. Thermometer for measuring temperature of vapor pressure control solutions. 3. Rubber diaphragm producing a flexible seal between microscope objective and lucite chamber. 4. Six volt stirring motor. 5. Container for vapor pressure control solutions which is attached to front side of lucite box. 6. Sheet copper boxes to facilitate uniform distribution of temperature. 7. Heating wires for temperature control (power source: 6 volt battery). 8. Thermometer tube of temperature control device. 9. Stage for glass slides. 10. Double lucite window in housing door for admitting light.

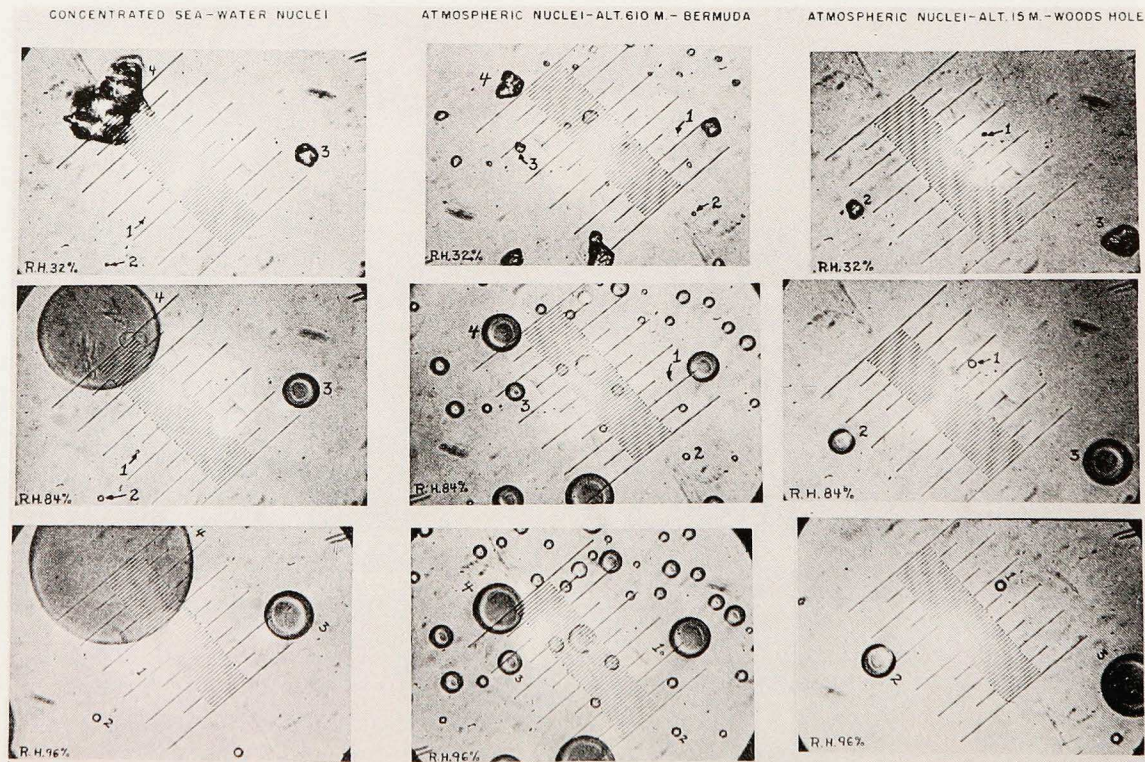


Figure 4. Photomicrographs showing changes in the appearance of nuclei as the relative humidity is increased. The nuclei at the left were sprayed on the slide.

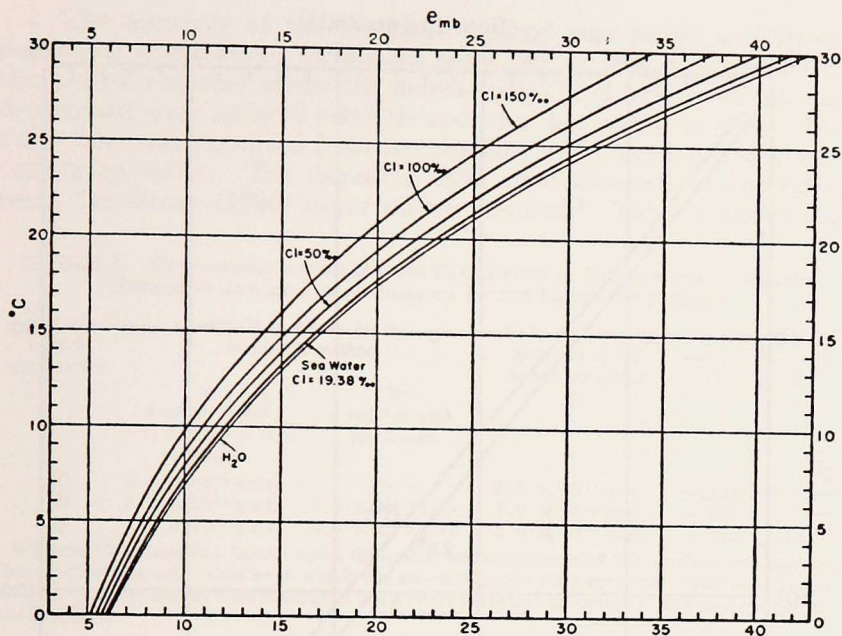


Figure 5. Saturation vapor pressure over water, sea water and concentrated sea water. Sources of data for this graph: Vapor pressure over water, from table 79 in Smithsonian Meteorological Tables; vapor pressure over sea water, from table 29 in Sverdrup, et al., 1942: 116; vapor pressure over concentrated sea water, from table 6 and chart 3 in Higashi, et al., 1931: 171, 172.

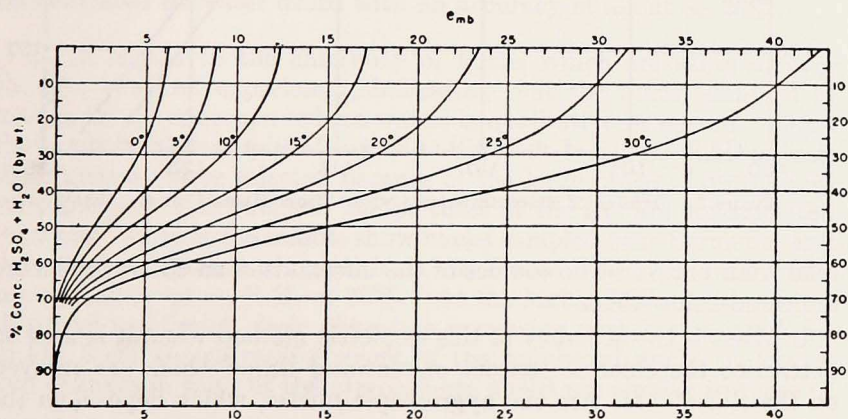


Figure 6. Water vapor pressure over solutions of H₂SO₄ + H₂O (from International Critical Tables, vol. III: 302).

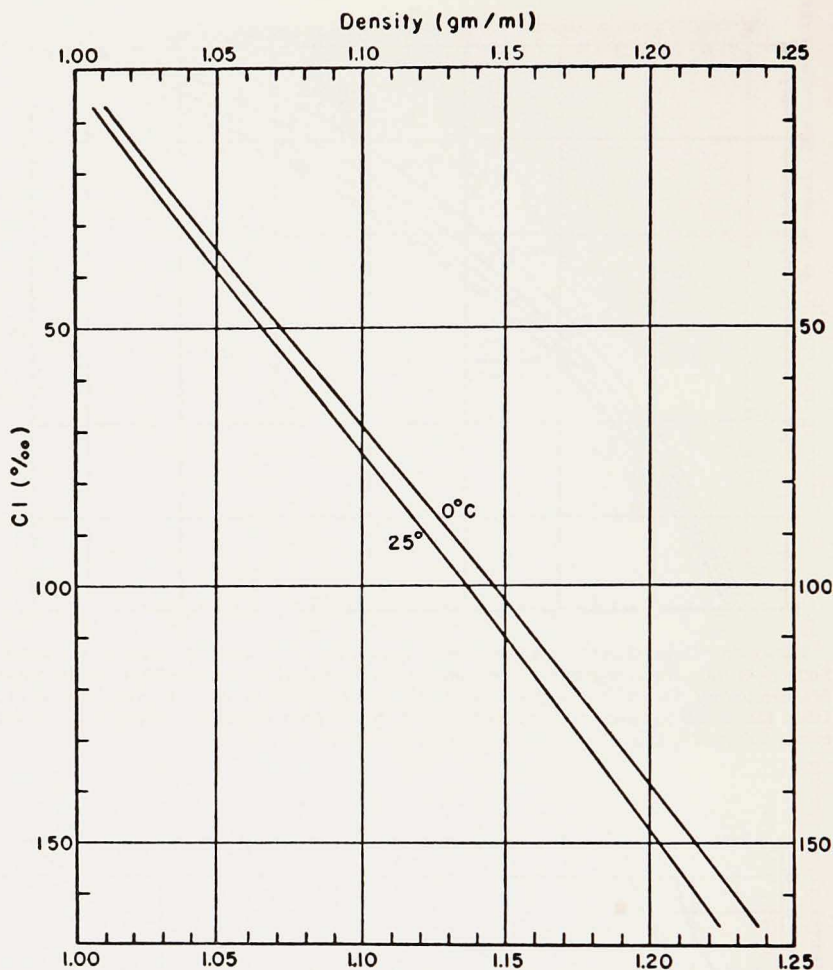


Figure 7. Density of concentrated sea water (from Higashi, et al., 1931).

read from Fig. 7. The sources of the information on these graphs are indicated below them.

I. What is the accuracy of this isopiestic method when it is used to determine the chloride content of seawater drops which are sprayed on the slides? II. Are the hygroscopic nuclei, which deposit on the slides in marine air, composed of concentrated sea water? These questions will be discussed in this order.

I. The accuracy of the isopiestic method was tested as follows. Sea water was sprayed on several slides, which were then placed in the control chamber under the microscope; the chloride content was determined over an acid solution and over sea water as well. The slides were then removed from the chamber and placed in a test tube containing water. The dissolved salts were titrated for chlorides, using the Oxner (1920) silver nitrate method.⁶ Table I shows the

TABLE I. COMPARISON OF THE NUCLEI Cl CONTENT AS DETERMINED BY DIRECT TITRATION AND BY A MODIFICATION OF THE ISOPIESTIC METHOD

No. of nuclei measured*	Total Cl on slides by the isopiestic method		Cl by titration of solution of all nuclei on slides C	C - A C	C - B C
	A e control with 16% H ₂ SO ₄ + H ₂ O solution	B e control with sea water			
160	4.1×10^{-4} gms.	—	3.5×10^{-4} gms.	-.171	—
565	2.1×10^{-4} gms.	1.5×10^{-4} gms.	2.0×10^{-4} gms.	-.050	.25
586	2.9×10^{-4} gms.	2.0×10^{-4} gms.	2.6×10^{-4} gms.	-.115	.23

* These Cl values are based upon diameter measurements of the nuclei deposited on about 1% of the total area over which the sea-salt nuclei were sprayed. The assumption is made that the nuclei thus measured are a representative sampling of the nuclei over the total surface.

results of three of these experiments. Computed chloride values are given in columns A and B, titrated values in column C and percent errors in the last columns. Titration values are assumed to be correct.

Thus the isopiestic method can be used to measure the chlorides in concentrated seawater drops with an accuracy of about $\pm 20\%$.

II. In regard to the chlorinity of nuclei which are sampled over the sea, the first experiment, indicating that the nuclei sampled in marine air are concentrated sea water, is qualitative in nature. Fig. 4 shows photomicrographs of nuclei at different indicated R.H. values; these pictures were selected because of the large range of drop diameters shown. The nuclei in the pictures at the left are concentrated sea water, those in the middle show nuclei sampled near Bermuda, and those on the right are of nuclei from the Woods Hole area. All nuclei are crystalline at an R.H. of 32%. At the higher R.H. values shown all nuclei are liquid, their diameters increasing with increasing R.H. In Fig. 8 are shown radii changes of the numbered nuclei in Fig. 4. The changes in radii of the atmospheric nuclei are similar to those of

⁶ The accuracy of the Oxner method for titrating these small quantities of chloride was found to be $\pm 10\%$.

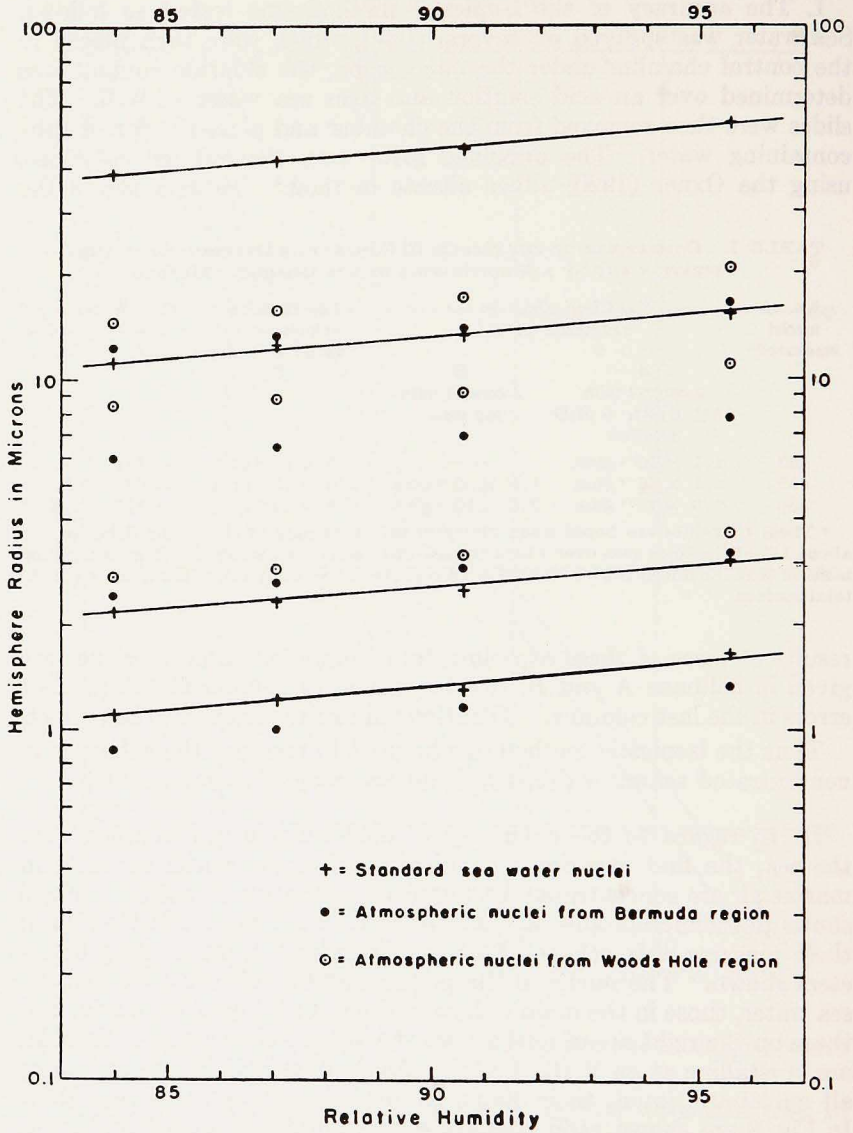


Figure 8. Changes of nuclei radii occurring as the relative humidity is increased.

the known seawater nuclei. Thus these nuclei are similarly hygroscopic and all show crystalline masses⁷ at the low R.H. values.

A more quantitative method of indicating the nature of these airborne nuclei will now be described. Hard-drawn silver rods, 1 mm square, were exposed to the air at the end of a dock in Woods Hole (see Fig. 2B). These rods were usually exposed during the passage of about 100,000 meters of air, and glass slides were exposed beside the silver rods to about 2,000 meters of air. Three slide samples were taken—at the beginning, near the middle and at the end of the period of exposure of the silver rods. After exposure, the salt-encrusted silver rods were placed in water, and the dissolved salts were then titrated for chlorides. (Deposition of nuclei on the side and rear surfaces of the rods was not significant.) The samples taken on the glass slides were measured by the isopiestic method. Table II shows

TABLE II. A COMPARISON OF THE CHLORIDE CONTENT OF THE AIR, AS DETERMINED BY THE ISOPIESTIC AND TITRATION METHODS. SAMPLING HEIGHT 4 METERS OVER THE SEA SURFACE. LOCATION: THE SEAWARD END OF THE MARINE BIOLOGICAL LABORATORY DOCK, WOODS HOLE, MASSACHUSETTS

Date	Wind Velocity	Total nuclei measured on three slides	R_i^*	A	B	$B - A$	R_{Cl}^\dagger
				Av. Cl by isopiestic method (g/cm^3 of air)	Cl by titration of a solution of nuclei from silver rods (g/cm^3 of air)		
VI.14.48	4.9 m/s SW	458	.06	0.54×10^{-12}	1.05×10^{-12}	+ .49	.46
VI.17.48	6.3 m/s SW	883	.05	1.17×10^{-12}	1.51×10^{-12}	+ .23	.42
VI.18.48	5.3 m/s SSW	426	.03	0.55×10^{-12}	0.68×10^{-12}	+ .28	.14
VI.30.48	7.6 m/s SW	1532	.03	2.73×10^{-12}	2.72×10^{-12}	0	.80

* R_i = Ratio of total exposure length of three glass slides to exposure length of silver rods.

† R_{Cl} = Ratio of minimum value to maximum value for atmospheric chlorides measured by the glass-slide isopiestic method.

the results of these measurements; column A gives the average chloride computed from the drops on the three slides, column B the values for chloride in the nuclei deposited upon the silver rods, the next to last column the percent error of the glass-slide isopiestic method, assuming

⁷ It may be supposed that crystalline nuclei will fail to adhere to the glass slides upon impact, thus producing unknown errors in this method of sampling. It is probable, however, that the presence of the highly soluble magnesium and calcium chlorides in sea salt will cause crystalline material of lower solubility in a nucleus to remain wet at relative humidities as low as 33% (see International Critical Tables, Vol. 3: 367, 368 for vapor pressures over saturated aqueous solutions of $MgCl_2$ and $CaCl_2$). For this reason it is assumed here that crystalline sea-salt nuclei, at relative humidities above about 30%, will adhere to the glass slides upon impact as readily as they do when completely liquified.

that the titration values are correct. The difference between the two methods is not great in consideration of the small quantities measured and of the rather large maximum variations of chloride shown by the individual slides (see column R_{Cl}). The largest percent error, 0.49, is attributed to these variations within the air stream. (The relatively short exposure lengths of the slides, indicated by column R_i , were used in order to measure the size distribution of the nuclei, as it was not thought at the time that there would be so much variability of salt content within the air stream.)

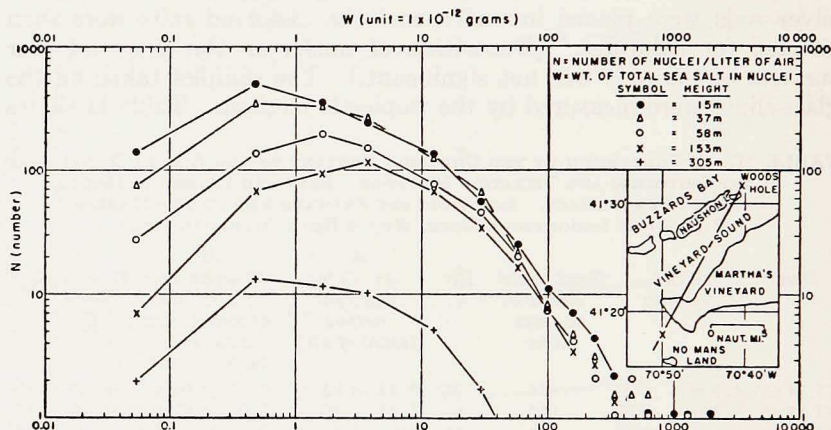


Figure 9. The numbers and weights of sea-salt nuclei sampled in the lower atmosphere over the sea (see Table III for position, time, etc.).

Thus the isopiestic method indicates a chlorinity of atmospheric nuclei approximately the same as the chlorinities derived by titration of deposited salts. The method also indicates that the atmospheric nuclei are similarly hygroscopic when compared to concentrated sea-water nuclei, and show similar crystalline masses at low R.H. values. Therefore, the isopiestic method seems useful in measuring the weights and numbers of atmospheric nuclei which are sampled.

Fig. 9 shows the numbers and weights of nuclei that were sampled from an aircraft in air which had passed over about 150 miles of sea surface. The lines are added to aid the eye in following the trend of the observed points. The weights of the nuclei represent the total sea salts present, assuming that the total salts are equal to $1.805 \times$ chlorinity, expressed as parts per thousand by weight. Each set of symbols represents the weight and number distribution at some specified height. (The weight of the smallest nucleus shown is based

upon an estimated drop diameter.) The "X" mark on the insert chart shows the location of the sampling area.

Fig. 10 shows the data in Fig. 9 corrected for deposition error; that is, correction has been made for the fact that some of the air-borne

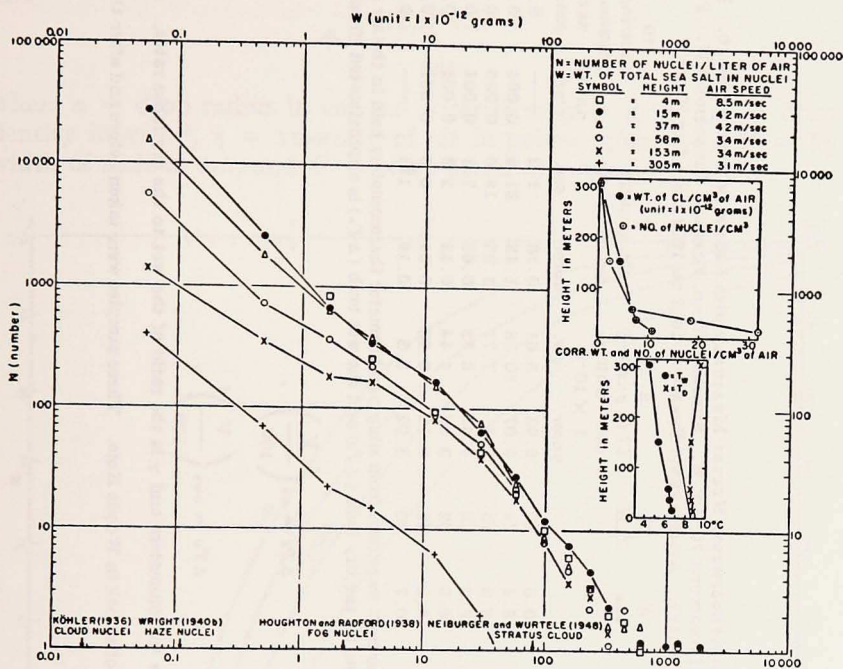


Figure 10. The data in Fig. 9 corrected for deposition error (E). The square symbols represent the corrected deposition of nuclei on two slides exposed at wind speed before and after the airplane samples were taken. Above the lower W scale are shown the average or mean values for sea-salt nuclei weight as derived by various authors.

nuclei are deflected by the flow of air around the slides and hence fail to impinge upon them. This error, for the very small nuclei, is large, and there is some uncertainty as to its magnitude for the smallest nucleus shown. The inserts in Fig. 10 show variations with height of air temperature and of nuclei weight and number. Table III shows other information concerning the data in Figs. 9 and 10.

For correction of deposition error, reference was made to a mathematical study by Langmuir and Blodgett (1945) on water droplet trajectories and deposition. They found the maximum total efficiency of drop deposition on ribbons, assuming ideal fluid flow. Drop

TABLE III. ADDITIONAL DATA RELATIVE TO ATMOSPHERIC NUCLEI MEASUREMENTS SHOWN IN FIGS. 9 AND 10. DATE, APRIL 30, 1948. POSITION, LATITUDE 41° 18' N., LONGITUDE 70° 50' W. SURFACE WIND, FORCE 4, DIRECTION SW. PROBABLE FETCH, < 200 NAUTICAL MILES. ATMOSPHERIC PRESSURE 1002 TO 1006 MB. SKY, CLEAR

1	2	3	4	5	6	7	8		9		10		11
Time (EDT)	Height (m.)	Air speed (m/sec)	T_D^*	T_W^*	e_{mb}	R.H.	Cl in μ/cm^3 of air. Unit = 1×10^{-12}		No. of nuclei per cm^3 of air		Covering fraction		No. of nuclei counted
							uncor.	cor.	uncor.	cor.	nuclei cryst.	nuclei conc. 7%	
1350†	4	9	9.9	8.8	10.5	86	2.98	5.01	0.16	1.2	—	0.009	386
1500	15	42	8.8	6.7	8.4	74	9.07	10.93	1.48	31.9	0.004	0.023	662
1508	37	42	8.7	6.5	8.2	73	6.1	7.77	1.25	18.6	0.005	0.029	795
1515	58	34	8.5	6.4	8.2	73	5.43	6.82	0.68	7.1	0.004	0.025	635
1520	153	34	8.5	5.3	6.9	62	3.56	4.44	0.43	2.3	0.004	0.024	612
1528	305	31	9.4	4.3	5.0	42	0.12	0.23	0.045	0.5	0.001	0.003	516
1740†	4	8	9.5	8.7	10.7	90	5.92	8.3	0.19	1.4	—	0.013	456

* All T_D and T_W measurements made from aircraft were read from sling psychrometer thermometers held in the air stream. Correction for temperature rise due to dynamic heating on the dry bulb (ΔT_d) and the wet bulb (ΔT_w) is approximated (from Spilhaus, 1943) as follows:

$$\Delta T_d = a_d \left(\frac{V}{100} \right)^2,$$

and

$$\Delta T_w = a_w \gamma \left(\frac{V}{100} \right)^2,$$

where a_d and a_w depend upon the form of the thermometers and γ is the ratio of the wet to the dry lapse rates. A value of 0.85 is used for both a_d and a_w .

† At this time slides were exposed at the end of a dock in Woods Hole. These samples were taken before and after the flight on which the other samples were obtained.

deposition efficiencies (E) are given in terms of two dimensionless parameters K and Φ , which are defined in the following equation:

$$K = \frac{2\rho_s a^2 U}{9\eta C}, \quad (2)$$

and

$$\Phi = \frac{18\rho a^2 C U}{\eta \rho_s},$$

where a = drop radius in cm, ρa = air density in g/cm³, ρ_s = drop density in g/cm³, η = viscosity of air in poises (g/cm sec), C = $\frac{1}{2}$ width of slide in cm, and U = wind speed in cm/sec.

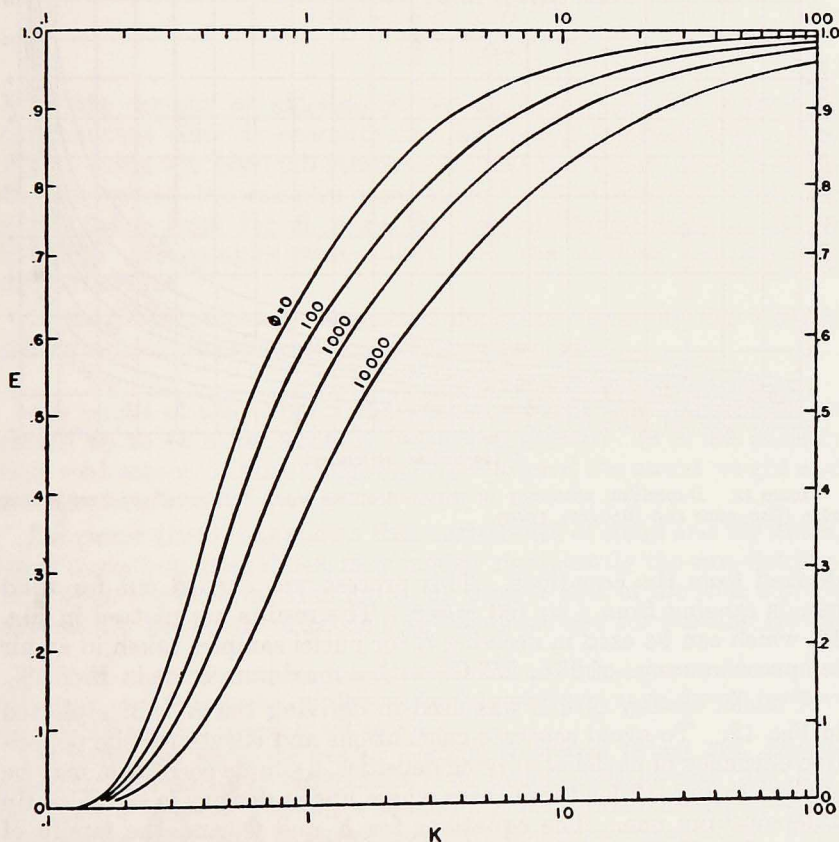


Figure 11. Efficiency of rime deposition on ribbons with ideal fluid flow (from Langmuir and Blodgett, 1945).

Constant values for drop density, air density, air viscosity and width of ribbon were substituted in these equations, leaving drop radius and wind speed as the two variables. Wind speed was fixed arbitrarily, while Φ and K were calculated for drop radii varying from 0.3 to 14 microns. Deposition error (E) was then taken from the results of Langmuir and Blodgett (see Fig. 11), using the Φ and K values

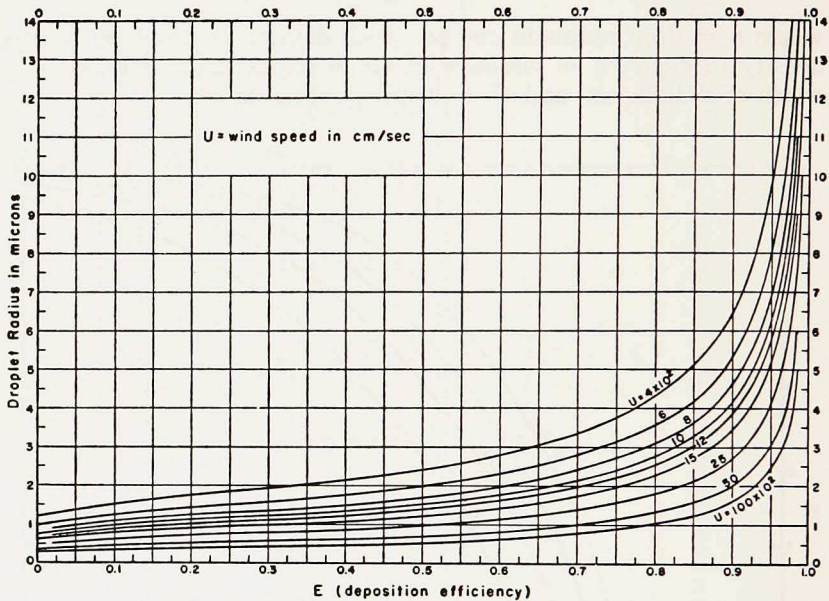


Figure 12. Deposition efficiency of water droplets upon "ribbons" one millimeter wide (Langmuir and Blodgett, 1945).

derived from the equations. This process was carried out for wind speeds ranging from 4 to 100 m/sec. The results are plotted in Fig. 12, which can be used in deriving E for nuclei samples taken in an air temperature range of 0° to 25° C., with a maximum error in E of 3%.

A nuclei density of one was used in deriving the E values plotted in Fig. 12. To avoid separate calculations and curves for the deposition efficiency of nuclei of varying densities, a simple correction may be applied to Fig. 12 for those cases where nuclei density is significantly different from one. The equations for K and Φ , and the family of curves for K , Φ and E (see Fig. 11), indicate that proportionate changes of density or wind speed affect the resulting computed value

of E similarly. Thus, doubling the value of ρ_a gives about the same value of E as does the doubling of U . As a specific example of the use of Fig. 12, assume that nuclei of 1μ radius are sampled at an air speed of 30 m/sec and at a time when their density in the free air is 1.2 [see equation (3) for the method used to derive nuclei radii in the free air]. In this case the modified value for air speed is 1.2×30 , or 36 m/sec. A nucleus of 1μ radius which was sampled on a 1 mm wide ribbon and at a modified air speed of 36 m/sec has a deposition efficiency of about 0.6 (see Fig. 12).⁸

The radius (R) of the nuclei in the free air at the time of sampling is derived as follows:

$$R = \sqrt[3]{\frac{W}{\frac{c D}{4/3\pi}}} \quad (3)$$

W = the weight of chloride in the nucleus (unit = 1×10^{-12} g).
 c = nucleus chloride concentration by weight fraction; taken from Fig. 3, using the dry-bulb temperature and the vapor pressure of the free air where the samples were taken.⁹ D = nucleus density in g/cm³; taken from Fig. 6, using the dry-bulb temperature of the air in which the samples were taken and the nucleus concentration derived above.

It has been necessary to discuss deposition error at this time in order to point out the errors of impact sampling.

Are nuclei of the weights and numbers which were sampled at air speeds up to 42 m/sec actually present in the air? Is it not possible that coalescence or shattering may have altered the nuclei weight and number distribution?

Langmuir (1944) has shown that coalescence of cloud and fog drops, upon impact on glass slides, may modify significantly the size distribution when the covering fraction (i. e., the per cent of the slide surface covered by the drops) exceeds 0.1. A direct test for possible coales-

⁸ For the ranges of sampling speed, nuclei radii and nuclei density discussed in this paper, the above method of allowing for the variation of nuclei density produces a value of E which is correct to within 3%.

⁹ In those cases where the free air humidity is between 78 and 70%, chloride concentration is derived by extrapolation of the results of Higashi et al. (1931) (Fig. 3). Below a humidity of 70% it is assumed that the nuclei are mostly crystalline (from Owens, 1926) with a density of about 2.2. In deriving deposition error E it is also assumed that these crystalline nuclei deposit on the slides as would spherical droplets of the same density (see footnote 7).

cence and shattering was made at an R.H. of 82%, when the nuclei are always liquid.

Six glass slides were exposed at constant altitude over the sea—three at higher and three at lower air speeds. Fig. 13 shows the distribution of weights and numbers of the nuclei sampled. It can be

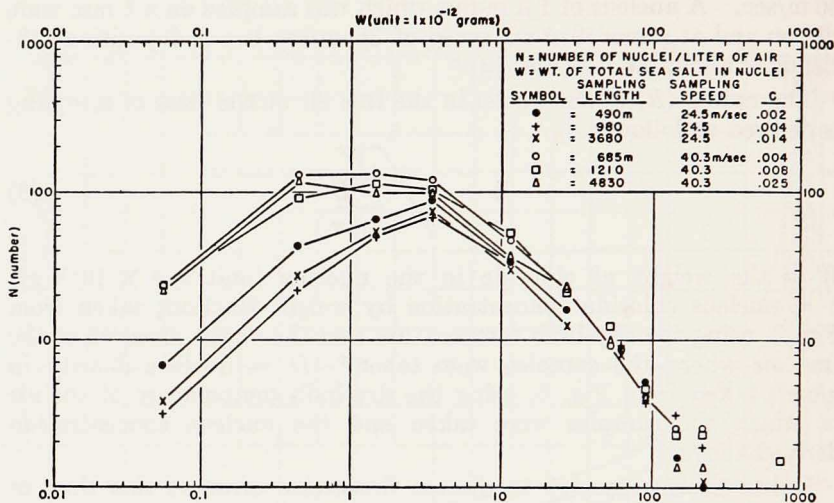


Figure 13. Variations of nuclei weight and number with different sampling lengths and speeds (see Table IV for further data).

seen on this slide that there is little difference in the numbers and weights of nuclei sampled on three slides of increasing covering fraction (C) exposed at a speed of 24.5 m/sec (see the lower plotted symbols). Similarly, Fig. 13 shows little difference in the number and weight of nuclei sampled at an air speed of 40.3 m/sec.

If a significant amount of coalescence of nuclei had occurred at constant air speed, Fig. 13 should show an increasing proportion of larger nuclei and a decreasing proportion of smaller nuclei associated with increasing values of C . Fig. 13 shows no trend towards larger nuclei which is related to increasing covering fraction. It is concluded as improbable, therefore, that coalescence of nuclei was a significant factor in producing the weight range shown.

Do the nuclei become shattered by impact? Fig. 13 indicates an increase in the numbers of nuclei sampled with a speed increase. Differences in deposition efficiency account for much of this discrepancy in number. In Fig. 14 are plotted average N values (from

Fig. 13) to which the deposition error correction has been added. The remaining difference in the average N at the two sampling speeds is attributed to changes, between sampling periods, in the amount of chlorides present in the air, as shown in Table IV. Note that the

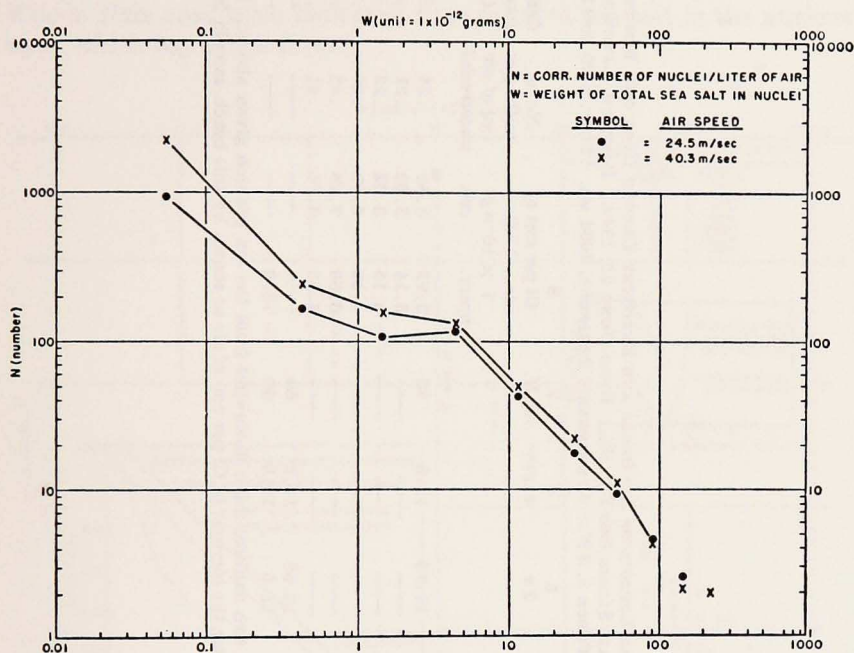


Figure 14. Average N values, from Fig. 13, which have been corrected for deposition error.

largest values in column 8, corrected and uncorrected, correspond to the higher air speed (column 2). This change can be due to variations of N with time or to slight variations in sampling height.

Shattering tests have also been made when nuclei are crystalline, at an R.H. of 43%. No shattering has been observed.

The sampling results which have been shown and discussed indicate that neither coalescence nor shattering of nuclei upon impact is a significant factor in the production of the nuclei weight and number distributions shown. This conclusion gains further support from the similarity of the corrected deposition of nuclei on slides exposed at an average wind speed of 8.5 m/sec and at 42 m/sec (see Fig. 10). The square symbols represent samples taken near the surface at Woods

TABLE IV. DATA RELATIVE TO A TEST OF THE EFFECTS OF AIR SPEED AND EXPOSURE LENGTH UPON THE WEIGHT AND NUMBER DISTRIBUTION OF NUCLEI DEPOSITED ON GLASS SLIDES (see Fig. 13). DATE, JUNE 25, 1948. POSITION, LATITUDE 41° 18' N., LONGITUDE 70° 50' W. SURFACE WIND, FORCE 3, SW. ATMOSPHERIC PRESSURE, 1006 MB. TIME, 1700 TO 1720 EDT

1 Height (m)	2 Air speed	3 Slide exposure length in:		4 T_D	5 T_W	6 e_{mb}	7 R.H.	8 Cl per cm^3 of air. Unit = 1×10^{-12} g		9 No. of nuclei per cm^3 of air uncorrected	10 Covering fraction (%)	11 No. of nuclei counted
		sec	m					uncor.	cor.			
15	24.5	20	490	18.75	16.75	17.6	82	2.92	3.48	.26	.002	517
15	24.5	40	980	—	—	—	—	3.14	3.60	.21	.004	558
15	24.5	150	3680	—	—	—	—	3.16	3.62	.22	.014	581
15	40.3	17	685	—	—	—	—	4.42	5.00	.49	.004	597
15	40.3	30	1210	—	—	—	—	6.66	7.26	.43	.008	563
15	40.3	120	4830	—	—	—	—	4.25	4.74	.41	.025	608
61	24.5	—	—	23.35	18.05	17.0	60	—	—	—	—	—
2*	4	60	240	17.9	17.5	19.5	95	78.0	—	—	—	544

* These measurements were made on a beach two nautical miles downwind from the sea position given above. Nuclei produced by the local surf probably account in large part for the increase in Cl per cm^3 of air as shown by this beach sample (see column 8).

Hole after the lower air had been mixed in passing over small islands (see insert, Fig. 9). The close agreement is evident. Sea fog nuclei, sampled at 7 m/sec, also show a closely similar distribution in the weight range of 5×10^{-12} g and less, again indicating the presence of the smaller salt nuclei in the sea air. (Sea fog nuclei samples from the Woods Hole area have indicated thus far that sea salt is the nucleus upon which fog drops form.)

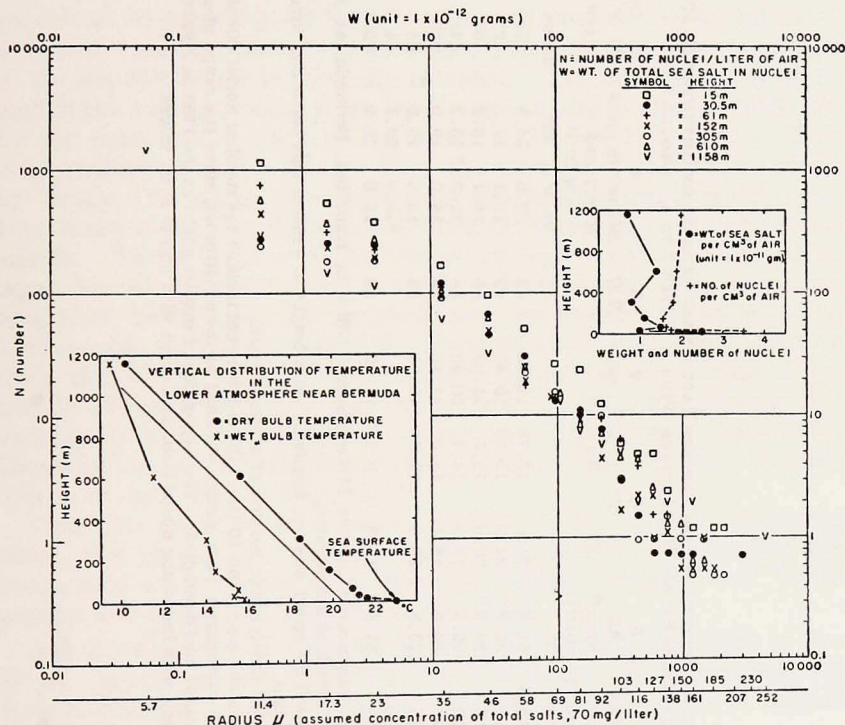


Figure 15. The numbers and weights of sea-salt nuclei sampled in the lower atmosphere over the sea in the Bermuda area (see Table V for additional information).

Finally, Fig. 15 shows the corrected weight and number of nuclei sampled near Bermuda in air which had passed over at least 600 miles of sea surface. Table V shows further data from this area.

It is interesting to compare the vertical distribution of weight and number of nuclei in the mixed air near Bermuda with the vertical distribution of weight and number of nuclei in thermally stable air near Woods Hole (Fig. 10). In the thermally stable air the total

TABLE V. DATA CONCERNING AIR-BORNE SEA-SALT SAMPLES TAKEN NEAR BERMUDA ON NOVEMBER 26, 1948. POSITION, LATITUDE 32° 23' N. LONGITUDE 64° 55' W. SURFACE WIND N, FORCE 3 TO 4. CLOUDS 2 CU.

1	2	3	4	5	6	7	8	9	10	11	12	
Time (zone 5)	Height (m)	Slide exposure (secs)	Atmos- pheric pressure‡ (mb)	Air speed [§] (m/sec)	T_d	T_w	e_{mb}	R.H.	Sea salt in g/cm ³ of air; unit = 1×10^{-12}	No. of nuclei per cm ³ of air	Covering fraction (%)	No. of nuclei meas- ured
									uncor. cor.	uncor. cor.		
1535	15.2	30	1016.5	31.8	21.6	15.75	10.80	42	30.6 34.6	.70 2.5	.004	738
1540	30.5	60	1015	26.8	21.2	15.30	10.43	42	15.1 17.2	.409 1.0	.004	580
1546	61	60	1012	26.8	20.9	15.5	11.23	45	14.1 16.3	.407 1.5	.004	552
1555	152	120	1000	26.8	19.8	14.4	10.42	45	13.5 15.3	.34 1.1	.006	640
1603	305	120	983	26.8	18.4	14.0	11.45	54	16.0 18.0	.313 0.8	.007	670
1612	610	120	946	26.8	15.6	11.5	10.28	58	16.8 19.3	.44 1.4	.008	723
									*19.8 20.1	.54 .7		
1620	1158	90	883	31.3	10.2	9.5	11.46	92	19.8 20.2	.69 2.1	.093	667

‡ Sea level pressure (1018 mb) was recorded at the Meteorological Office in Hamilton, Bermuda, at 1600. Pressures at other heights are based upon the U. S. standard atmosphere.

§ Altitude correction of indicated air speed was not applied. At a height of 1158 m this correction amounts to about 2.1 m/sec. At lower altitudes it is not significant.

† T_d and T_w values are corrected for dynamic heating of thermometers.

* The upper of the two values in columns 9 and 10 (alt. 1158 m.) does not include the smallest nuclei sampled at this height. These upper figures should be used for comparison with values obtained at lower altitudes, since the range of nuclei weight is the same. The lower value includes the smallest nuclei sampled. The deposition of smaller nuclei at the 1158 m. height (see Fig. 15) results from an increase in deposition efficiency with increasing nuclei radii associated with higher R.H. values.

number and total weight of sea-salt nuclei decreased rapidly with height. Near Bermuda, in well mixed air overlying warmer water, there is relatively little change with altitude in nuclei number and weight (see inserts, Fig. 15). This difference in vertical distribution of nuclei is probably a result of the difference in vertical mixing in the two air masses concerned.

At the base of Fig. 15 a second scale is drawn showing the computed radii of the nuclei, assuming spherical drops with a concentration of sea salt of 70 mg/l (7×10^{-17} g/ μ^3). In each case the radius indicated is that of a nucleus containing a weight of sea salt equal to the weight of the sea salt in nuclei actually sampled. The concentration of 70 mg/l is the average value given by Houghton and Radford (1938: 30) for the total salt content of fog water at Round Hill, Mass. This concentration is much greater than the average of the figures given by Wright (1940a) in his summary of the measurements which have been made of the chloride concentration of snow, rime, rain and cloud waters. Therefore, a concentration of 70 mg/l seems a conservative figure for salt concentrations in marine cloud drops. The computed drop sizes, based upon this concentration, are therefore assumed to be a reasonable approximation of the eventual cloud drop sizes resulting from the lifting of the air containing these nuclei. Cloud drops having the radii shown at the base of Fig. 15 will have rates of fall varying from about 0.3 to 200 cm/sec (see Humphreys, 1940: 280). Drops of the larger sizes (radius 50 μ or more) are classified as mist, drizzle or light rain by Humphreys.

Thus this great range of nuclei weight at the base of an oceanic cloud, if it proves to obtain generally over the seas, may explain the occurrence of rain from thin layers of stratus clouds ($T > 0^\circ$ C.) in oceanic areas (Kotsch, 1947; Schaefer, 1949).

Acknowledgment of valuable aid in carrying out this work is due R. M. Cunningham, J. S. Coles, Irving Langmuir, W. S. von Arx and Henry Stommel. Instrumentation is due, in major part, to Robert G. Walden and Kenneth G. McCasland.

SUMMARY

A method of sampling air-borne sea-salt nuclei over the open ocean is described. Data are given showing the distribution of the weight and number of nuclei sampled at various heights. It is suggested that these sea-salt nuclei act as condensation nuclei in the formation of sea fogs and clouds, and that the presence of the larger nuclei at cloud bases may account for the production of rain from small clouds in marine locations at temperatures above 0° C. The range of the

weights of these nuclei is comparable to the range of the average weights of salt nuclei which have been measured at shore stations by other authors.

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