The Release of Latent Heat in Tropical Storms Due to the Fall-Out of Sea-Salt Particles

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Abstract

Observations of atmospheric sea salt in a hurricane are used to estimate the weight of salt in the clear air at cloud levels. These quantities are then used to determine the rate of release of heat in the moist air layers below, due to condensation on this salt as it falls from the relatively dry air at higher levels. This rate is found adequate to alter significantly the distribution of heat and water vapor in the cloud-layer air and to explain much of the observed potential temperature increase in the lower air converging upon the central regions of hurricanes.

1. Introduction

In meteorology computations involving the release of latent heat of vaporization of water assume that no significant amount of condensation occurs in the atmosphere until the relative humidity reaches 100 per cent. In fact the assumption of dry-adiabatic conditions in well-mixed sub-saturated air below cloud base is sometimes used as a basis for judging the probable accuracy of temperature measurements made in this air (JORDAN, 1952). In air containing certain quantities of hygroscopic particles, this assumption is probably not valid. The author has shown that condensation on sea salt particles in ascending air can bring about a significant release of latent heat in the sub-cloud layer at relative humidities less than 100 per cent (WOODCOCK, 1950).

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The previous attempt to use measurements of sea-salt particles to estimate the role of the salt in the release of latent heat in the sub-cloud layer was not very conclusive. This was due primarily to uncertainty about the maximum amounts of salt to be expected in storms at sea, and to a failure to realize that salt falling from higher levels might also be important. Recently developed techniques (WOODCOCK, 1950a, 1952) (WOODCOCK and SPENCER, 1957), designed to sample the larger salt particles, have shown the presence in strong winds of particles having a weight of nearly 10^{-6} grams. These measurements have also shown that the glass slide technique averages quantities of salt, in one to ten kilometer sampling lengths over the sea, which may vary by a factor of two to ten within these lengths. Thus for this and other reasons (see section 8), one need not regard the averaged hurricane data used here as limiting quantities, since they result from application of the older glass-slide sampling

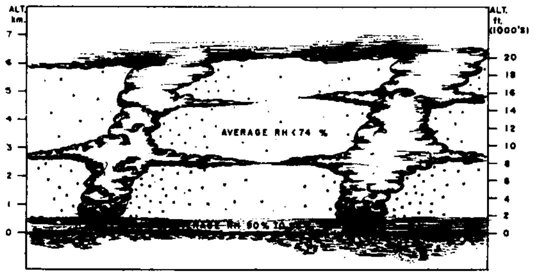

Fig. 1. Diagram illustrating the idea of the fall-out of large salt particles associated with clouds. This figure is intended to represent a cross-section normal to two cloud lines. It is assumed that the average relative humidity in the clear air at cloud levels above 5,000 feet is less than 74 per cent.

technique. No new measurements have thus far been made in these storms using the new techniques, but for present purposes the earlier observations are useful.

The current interest in expanding our knowledge of tropical storms and the improved facilities for doing so caused the author to hazard a second attempt to show that the quantity of airborne sea-salt is important in these storms. The primary purpose of the present paper is to discuss the role of salt which is carried upward by the clouds, in subsequently altering the distribution of heat and water vapor as it falls back towards the sea. It is hoped that hurricane-research aircraft will be able to test some of the conclusions of this study through direct measurements.

Byers (1944, p. 432) and Riehl (1951 and 1954) have discussed the near-isothermal expansion of the sub-cloud air flowing in towards the central low-pressure areas of tropical cyclones. Riehl emphasized the basic role of this phenomenon in altering the stability of the atmosphere in the central areas of hurricanes (Riehl, 1954, p. 313—316). Both of the above authors assumed that the sensible heat required to compensate for the adiabatic cooling as the pressure falls in the converging air (roughly 1° C per 10 mb of pressure decrease), is derived from the greatly agitated sea surface waters.

The following sections of this paper are intended to show that a large part of this heat can come from latent heat released by condensation of water vapor on salt particles. It is pictured that these particles, which are produced by bursting bubbles at the sea surface (Blanchard, Woodcock, 1957) (Kientzler et al., 1954) are carried up in the clouds, are distributed laterally by shear and turbulence and fall into or are mixed into the relatively clear air between the clouds. Here the particles will alter the vapor and heat distributions as they fall in and out of layers of air having different relative humidities on their way down towards the sub-cloud layer, as suggested by Figure 1. In falling from an area where the RH averages < 74 per cent, to one in which the average RH is 90 per cent or 96 per cent, condensation releases heat at a rate which is sufficient to account for the observed warming of the air flowing into tropical cyclones, if one assumes a salt fall-out of a certain average intensity over the whole area of the observed isothermal expansion.

2. Preliminary description of the model proposed

The purpose here is the initial clarification of the primary problem, which is to demonstrate that the transport of salt between the sea, the sub-cloud and cloud layers can result in a sensible heating of the sub-cloud air through the release of latent heat.

The spray particles entering the atmosphere from the sea can be divided, for present purposes, into two groups: 1), those particles which fall back into the sea without being carried out of the sub-cloud air, and 2), those which return to the sea after ascending in clouds and falling through relatively dry regions of the cloud-layer atmosphere.

Group one particles will produce a net cooling of the sub-cloud air due to evaporation. The amount of this cooling will be directly related to the difference in the salinity of the droplets which are ejected into the air from the bubbles in the sea and their salinity upon falling from the air and re-entering the sea. The relative humidity over spray droplets of sea water is about 98 %. Since surface-air relative humidities of 90 % and 96 % are assumed in the discussion below, the spray droplets will evaporate to some extent (see Fig. 2) before returning to the sea. Thus evaporation from these group one spray particles will tend to stabilize thermally the lower part of the sub-cloud layer, which

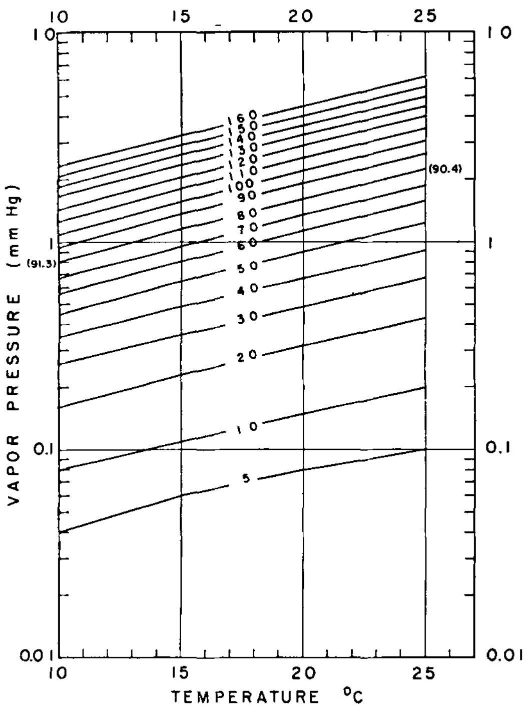

Fig. 2. Vapor pressure lowering over concentrated sea water at various temperatures and salt concentrations. Concentrations represent chloride in parts per thousand, by weight. (From ARONS and KIENTZLER, 1954).

contains the dryest air in this usually well-mixed section of the trade-wind or hurricane atmospheres (BUNKER et al. 1949) (RIEHL, 1954). The sensible heat required for this evaporation is assumed to come from the sea surface.

Group two particles are carried upwards into the clouds through the sub-cloud layer. They are assumed to enter cloud base having a salinity equal to that existing when they were ejected from the sea (i.e. equilibrium at RH 98 %). From the time of their production to the time when they enter cloud base, this group of particles could thus cause no net change in the total heat of the sub-cloud air. After being carried upwards to various altitudes in the clouds, the particles are mixed or fall into the dryer inter-cloud air and eventually fall back into the sub-cloud layer as relatively dry salt particles. The heat required to vaporize the water from the group-two particles is thus derived from high in the cloud-layer air. The quantity of latent heat released in the sub-cloud layer by condensation as these particles re-enter the layer, will be inversely proportional to their salinity as they subsequently fall into the sea or re-enter the clouds. In this cycle of vertical motions group-two particles will cool the cloud layer air and will warm the sub-cloud air, adding to the instability of each.

With the above model in mind, the author will now try to show that the range of increase of potential temperature observed in converging lower air in hurricanes may be computed, at least in part, from the quantities of salt found in these storms.

3. Sea salt in lower air

During the tropical storm which passed near Miami, Florida on September 22, 1949, the author made measurements of the average weight and number of the salt particles of certain size ranges present at an altitude of 40 meters above the sea at Hillsboro Lighthouse (WOODCOCK, 1950). Fig. 3, curve 12, shows the number and size of the salt particles found, presented as a cumulative-number distribution curve. For comparison other observations are shown which were made from aircraft at cloud levels in trade-wind

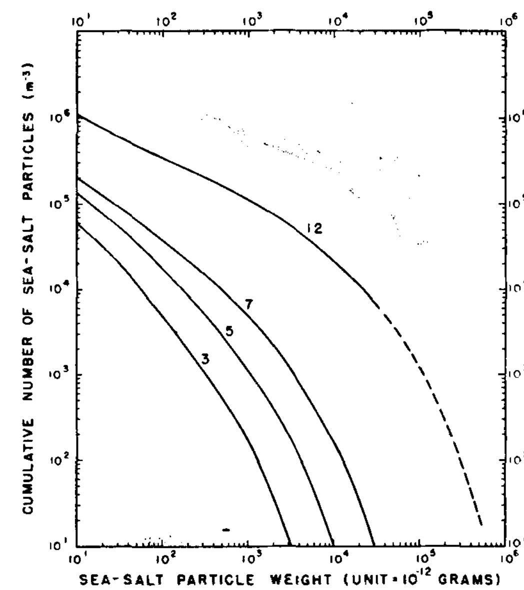

Fig. 3. Cumulative number distribution curves for averaged obs^rvations during wind forces 3, 5, 7 and 12.

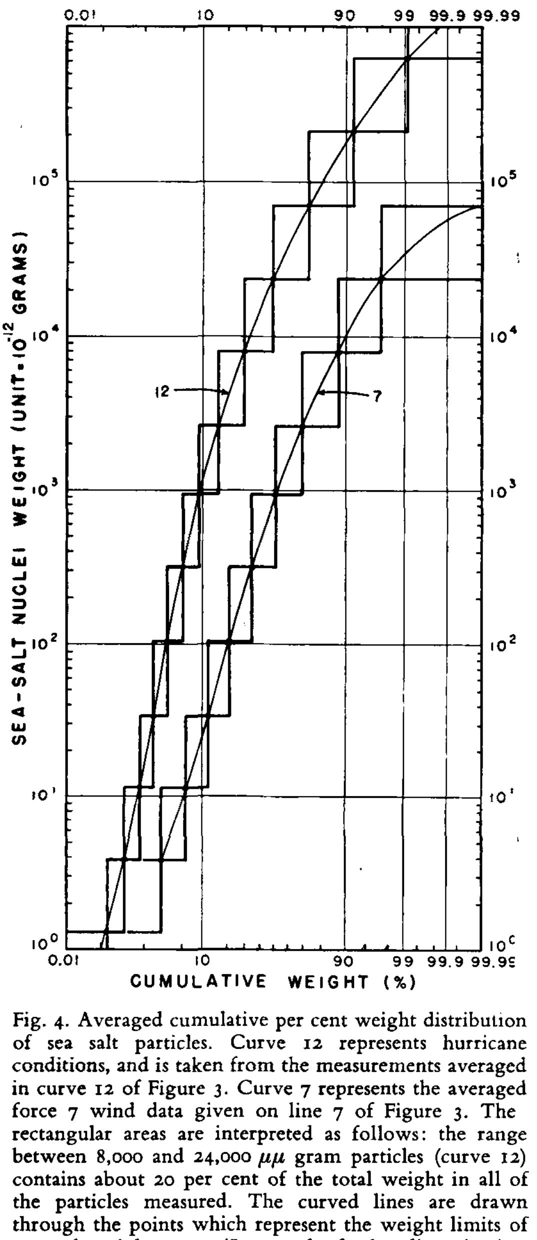

Fig. 4. Averaged cumulative per cent weight distribution of sea salt particles. Curve 12 represents hurricane conditions, and is taken from the measurements averaged in curve 12 of Figure 3. Curve 7 represents the averaged force 7 wind data given on line 7 of Figure 3. The rectangular areas are interpreted as follows: the range between 8,000 and 24,000 $\mu\mu$ gram particles (curve 12) contains about 20 per cent of the total weight in all of the particles measured. The curved lines are drawn through the points which represent the weight limits of each weight range. (See text for further discussion.)

areas under more moderate wind conditions. The broken portion of curve 12 is a reasonable extrapolation, based upon the author's wide experience in salt-aerosol sampling.[1]

The cumulative number distribution curve, which was originally derived from thirty-one size range measurements, was divided into fourteen weight ranges in accordance with the convenient size steps of the Porton eyepiece graticule (MAY, 1945). The product of the total number in each weight range and the median-number weight, approximates the weight of salt in each range. The ratios of these individual weights to their sum were used to derive the cumulative per cent weight distribution values shown on Figure 4. The sum of weights of sea salt represented by the force 12 curves on Figures 3 and 4 is 1.2 mg m^{-3}. As a test of the accuracy of this weight estimate, a further division of each of these fourteen steps into five, making a total of seventy size ranges, increased this value by only 0.1 mg m^{-3}. Thus curve 12 of Figure 4 is, for present purposes, a close approximation of the total salt represented by curve 12 of Fig. 3.

On Table I, column 1 shows the particle weights represented by curve 12 of Figure 3, divided into 20 weight range categories. Each of these weight ranges contains about 5 per cent of the total mass of sea salt present in all of the particles. The particle weights were taken from curve 12, Figures 3 and 4 as follows: Note on curve 12, Figure 4, that the salt particles in the weight range of about 320 to 1,200 $\mu\mu$ grams contain about 5 per cent of the total salt. In this weight range the cumulative number distribution curve (on Figure 3) crosses the mid-point of this selected 5 per cent interval at the nuclei weight of about 600 $\mu\mu$ grams. This and other similarly derived nuclei weights are shown in column 1 of Table I. Columns 2, 3 and 4 of Table I give the radii and the rates of fall of these nuclei as relatively dry salt particles.

Amounts of salt near cloud-base altitudes have been found to be about the same as those a few hundred feet over the sea surface, under a wide range of wind conditions. On the assumption that a similar mixing of

[1] The hurricane samples were unfortunately taken prior to the development by the author of the "multi-strip sampling" technique (WOODCOCK, 1952). This sampling method which utilizes the low sampling efficiency of wide slides or "ribbons" (LANGMUIR, 1945), makes it possible to selectively sample the large sparsely distributed nuclei, despite the presence in the air of great numbers of the small nuclei. See the discussion section of this paper for further remarks about salt in hurricane winds.

TABLE I

The sea-salt particle distribution represented by curve 12, Figure 3, divided into 20 equal weight categories. The nuclei weights given in column 1 are those of the median number particle and are used to compute the distribution of salt and condensed water at severals levels in the atmosphere. Inital weight of salt in each 5 % interval is 60 μ gms m^{-3}. See the text for more information.

Sea-salt nuclei as crystalline particles near sea surface				Sea-salt nuclei as droplets upon arrival at cloud base				
Weight 10^{-12} g	Radius μ	Fall Rate cm sec^{-1}	Amount of salt falling $\mu gms.m^{-2} sec^{-1}$	Radius μ	Fall Rate cm. sec^{-1}	Amount of salt & water falling μ gms.m^{-2} sec^{-1} salt	water	Wt. of salt in each size range μ gms. m^{-3}
1	2	3	4	5	6	7	8	9
50	1.8	0.084	0.05	9	1.0	0.6	36	60.5
600	4.0	0.42	0.25	17	3.5	2.2	74	61.9
1,750	5.8	0.86	0.52	22	5.8	3.7	90	63.0
3,200	7.0	1.27	0.76	26	8.0	5.2	113	64.5
4,800	8.0	1.63	0.98	29	9.7	6.3	128	65.4
7,100	9.2	2.15	1.29	32	11.4	7.5	137	66.0
9,900	10.2	2.72	1.63	35	13.4	9.0	147	66.8
13,100	11.2	3.25	1.95	37	15.0	10.2	155	68.2
16,700	12.2	3.85	2.31	40	17	11.8	170	69.5
21,800	13.3	4.50	2.70	42	19	13.4	177	70.7
28,000	14.5	5.45	3.27	45	22	15.6	196	72.3
36,000	15.7	6.40	3.84	48	24	17.7	210	73.9
44,000	16.8	7.30	4.38	51	26	20.0	224	75.6
54,000	18.0	8.40	5.04	54	29	22.4	244	77.4
68,000	19.4	9.70	5.82	57	32	25.4	257	79.5
88,000	21.2	11.6	6.9	61	36	29.9	293	83.0
114,000	23.1	13.8	8.3	65	40	33.8	307	85.6
152,000	25.4	16.7	10.0	70	44	39.2	331	89.0
223,000	29.0	22.0	13.2	77	50	46.7	345	93.5
410,000	35.4	33.0	19.8	90	63	68.5	441	108.7
			93.0			379.1	4,075	1,495.0

aerosols exists in hurricanes, the quantity of salt derived above can be used to estimate amounts carried upwards by clouds.

4. Transport of salt by ascending clouds

Using a reasonable average rate of rise of air in the cumulus clouds of 4 m sec^{-1} (MALKUS) and a weight of salt at cloud base altitudes of 1.2 mg m^{-3}, the estimated ascent of salt is 4.8 mg m^{-2} sec^{-1}.

What proportion of a storm area contains such actively growing cumuli? Wexler found in a study of numerous radar (PPI) scope photographs of hurricane spiral rain bands, that the width of these bands was about the same as the width of the spacing between them (WEXLER, 1947). If these rain bands roughly delineate the size of the areas of major ascent of moist cloud air, one might estimate that the areas of ascent are about the same size as the areas between.

It seems excessive to suppose however that one-half of a storm area contains actively ascending cloud material. A more conservative ratio of active cloud area to relatively clear inter-cloud area of one to ten is tentatively used. Sea salt ascending in the clouds at a rate of 4.8 mg m^{-2} sec^{-1} will, on this assumption, be sufficient to produce an average fall over ten square meters of 0.48 mg m^{-2} sec^{-1}.

What proportion of this salt is subtracted from the cloud layer air, by the various rain mechanisms (MIYAKE, SUGUIRA, 1950) (WOODCOCK, 1952) (WOODCOCK, BLANCHARD, 1955) which cause the salt particles to be carried back to the sea in solution in the falling raindrops? Miyake and Suguira (1954) have shown that the rate of precipitation of chloride during the passage of typhoon "Kitty" in Japan ranged

TABLE 2

Rates of fall of sea salt in hurricane at equilibrium concentration at different relative humidities.* Quantities of salt taken from Table I, column 1 and from Figure 4.

Wt. of sea salt in particles 10^{-12} g	RH 90 %			RH 96 %			RH 98 %		
	Particle radii μ	Particle fall rate cm sec^{-1}	Sea salt falling μ gms m^{-2} sec^{-1}	Particle radii μ	Particle fall rate cm sec^{-1}	Sea salt falling μ gms m^{-2} sec^{-1}	Particle radii μ	Particle fall rate cm sec^{-1}	Sea salt falling μ gms m^{-2} sec^{-1}
50	4.2	0.3	0.2	5.3	0.4	0.2	7.0	0.6	0.4
600	9.6	1.3	0.8	12.1	1.9	1.1	15.8	3.0	1.8
1,750	13.6	2.5	1.5	17.4	3.9	2.3	22.6	6.0	3.6
3,200	16.7	3.7	2.2	21.2	5.7	3.4	27.7	8.8	5.3
4,800	19.0	4.8	2.9	24.3	7.4	4.4	31.8	11.3	6.8
7,100	21.7	6.1	3.7	27.6	9.3	5.6	36.2	14.5	8.7
9,900	24.2	7.6	4.6	31.0	11.5	6.9	40.5	17.8	10.7
13,100	26.6	9.0	5.4	34.0	13.6	8.2	44.5	21.0	12.6
16,700	28.8	10.4	6.2	37.0	15.0	9.0	48.3	24.5	14.7
21,800	31.5	12.4	7.4	40.0	18.2	10.9	52.5	28.5	17.1
28,000	34.2	14.5	8.7	44.0	21.5	12.9	57.5	32.7	19.6
36,000	37.2	17.0	10.2	47.5	25.0	15.0	62.5	37.0	22.2
44,000	39.8	18.8	11.3	51.0	28.5	17.1	66.6	41.0	24.6
54,000	42.6	21.6	12.9	54.5	31.7	19.0	72.0	46.0	27.6
68,000	46.1	25.0	15.0	59.0	36.0	21.6	77.5	51.0	30.6
88,000	50.2	29.0	17.4	64.0	40.0	24.0	84.0	57.5	34.4
114,000	54.7	33.0	19.8	69.8	46.0	27.6	92.0	65.0	39.0
152,000	60.3	39.0	23.4	76.5	53.0	31.8	102.0	74.5	44.7
223,000	68.5	46.5	27.9	87.5	63.0	37.8	113.0	84.0	50.4
410,000	83.9	62.0	37.2	110.0	84.0	50.4	140.0	108.0	65.0
			217.7			308.2			439.8

* It is assumed here that the amount of salt is constant as the RH is varied. The original data (WOODCOCK, 1950, p. 398) are inadequate to test this assumption. Sampled amounts of salt differed by a factor of 2.4, while the RH varied from 82 % to 91 %. These RH values are thought to be too low however, due to the necessity to expose the thermometers inside the lighthouse enclosure (with several windows open). Thermometers exposed outside were immediately coated with a briny film, thus making the readings uncertain.

from about 0.003 to 0.08 mg m^{-2} sec^{-1}, with an average of about .02. This range of values agrees very well with one estimated from the average rainfall in moving storms (RIEHL, 1954, p. 295) and from the chloride concentration in typhoon and hurricane rains (MIYAKE, SUGUIRA, 1954) (HARRISON, WILLIAMS, 1897).

Thus the estimated fall-out of chloride transported up in the clouds (about 0.27 mg m^{-2} sec^{-1}) exceeds by a factor of more than ten the average observed rate of chloride fall in rains.

If, for the moment, one assumes that within the storm area sufficient salt has been carried up in the clouds to establish a steady state, then the average fall of briny particles through the relatively clear inter-cloud air (S_f) is simply derived as follows:

$$S_f = \frac{S_a - S_r}{10} \quad (1)$$

where S_f = sea salt falling (mg m^{-2} sec^{-1})
S_a = sea salt ascending in clouds (4.8 mg m^{-2} sec^{-1})
S_r = sea salt carried down in rains (0.04 mg m^{-2} sec^{-1})

Using equation (1) it is found that a fall-out of salt aerosols from the inter-cloud air of about 0.44 mg m^{-2} sec^{-1} should occur. (It will be noted that this quantity is very similar to the fall of salt computed on Table 2 from the observed values. This similarity is presumably due to a realistic choice of variables in estimating fall-out from the inter-cloud air.)

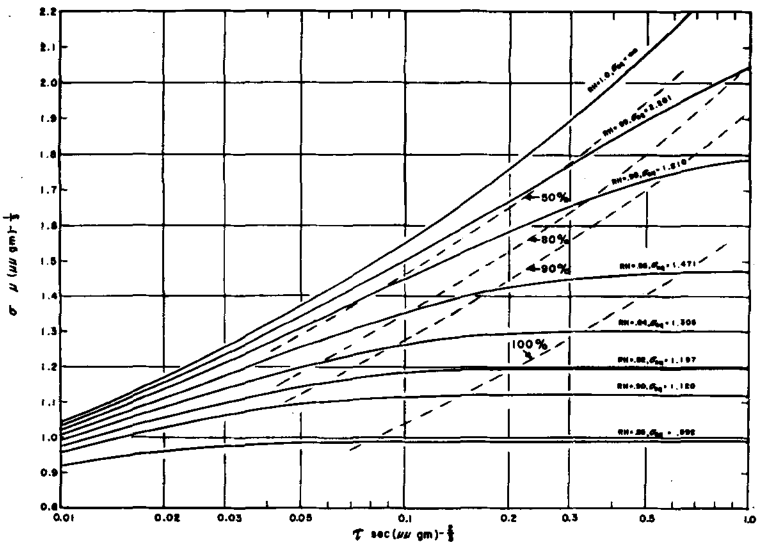

Fig. 5. Sea-salt particle-growth curves at various fractional humidities and a temperature of 25 C. Multiplication of τ by the cube root of nucleus mass, and of σ by the nucleus mass raised to the 2/3 power, converts coordinates to droplet radius in microns and time in seconds (from KEITH and ARONS, 1954). The dashed lines have been added by the present author to estimate the time required to establish various fractions of the equilibrium volume of the droplets.

When the salt particles fall from the relatively dry inter-cloud air into the moist sub-cloud air, condensation occurs and heat is released.

5. Heating of unsatured sub-cloud air by condensation on falling salt

The amount of water which will condense (W_L) as the falling salt particles enter the moist air, is computed from the equation

$$W_L = S_f \frac{1}{c} \tag{2}$$

where W_L is expressed as mg m^{-2} sec^{-1}
S_f = weight of salt falling (mg m^{-2} sec^{-1})
c = concentration of sea salt in particles by weight fraction (from ARONS and KIENTZLER, 1954).

Utilizing the relationships given in equation (2) and the salt fall-out, the weights of condensed water were computed. The heating of the air resulting from this condensation was then derived as follows:

$$T = m_L / C_p \tag{3}$$

where T = temperature change (°C gm^{-1} sec^{-1})
m = weight of water condensed (gms gm^{-1} sec^{-1})
L = latent heat of vaporization of water (585 cal gm^{-1})
C_p = specific heat of moist air (0.245 cal gm^{-1})

Assuming that 0.44 mg m^{-2} sec^{-1} of sea salt are falling from an air layer having a RH of < 74 per cent,[1] into regions where the RH is 90, 96 and 98 per cent, equation (2) is used to derive the amount of water condensed. In so doing the data on Figure 2 are used. It is found that water is condensed at a rate of 12.6 mg m^{-2} sec^{-1}, if the moist layer RH is 98 per cent, 5.9 mg m^{-2} sec^{-1} if it is 96 per cent and 2.9 mg m^{-2} sec^{-1}, if it is 90 per cent. This assumes that a steady state exists and that condensation on all particles proceeds to a

[1] In a recent series of temperature soundings by the Woods Hole Oceanographic Institution aircraft (August 1956), the relative humidity in the clear air above 5,500 feet was 72 per cent or less in several locations in the West Indian region. It is supposed that it is the more or less normal trade-wind air and clouds of this time of year which are drawn into tropical cyclones (see discussion of this point by Wexler, 1947).

state of vapor pressure equilibrium in the moist air. In the time required to fall 200 meters, most of these particles will reach more than 90 % of their equilibrium size at these relative humidities (see Fig. 5; GUNN and KINZER, 1949; and Stoke's law).

The computed heating of the moist layer of air resulting from the above amounts of condensed water, utilizing equation (3), is shown in Table 3 below. The degree of this heating in any given mass of air depends of course upon the average relative humidity there. The air-layer depths selected for tabulation[1] lie in the range of those reported for the sub-cloud layer in tropical storms. It is this layer which contains most of the air spirally converging upon the rain-area. The extent to which the assumed relative humidities of this air are realistic is uncertain. Similar high values have however been reported and utilized in other hurricane studies (see TANNEHILL, 1943, Fig. 10; SIMPSON, 1947, and RIEHL, 1954, Fig. 11–29).

Riehl has indicated the potential temperature as a function of surface pressure in hurricanes (RIEHL, 1954, p. 287). It is concluded from his study of available data that the average pressure drop is about 50 mb, and that the average amount of sensible heating of the converging air is about 4° C.

Using Hughes' Figure 8 (HUGHES, 1952), which shows the average trajectories and rates of convergence of surface air to a point within 0.5° latitude (30 nautical miles) of the moving storm center, it is estimated that the heating of this air occurs in from 12 to 22 hours, with an average of about 18 hours. In other words 4° C is the approximate temperature increase in the air within the range of time required for it to move into the 0.5° latitude point from a distance of 240 nautical miles out from the center. On Table 3 it can be seen that the latent heat released due to condensation upon salt particles produces temperature increases which range from about 0.5 to 9 °C, depending upon the time used, the average relative humidity of the sub-cloud layer and the thickness of this layer. It is assumed of course that the high relative humidities are maintained by evaporation from the sea surface. As a rough first approximation, the similarity of this range of heating computed from the salt fall-out, to the range given in Riehl's study (see RIEHL, 1954, p. 287), encourages further work in this direction.

[1] A cubic meter of air is assumed to weigh one kilogram. No corrections have been made in this paper for pressure effects upon particle distributions or fall rates, since the condensation processes discussed are thought to occur largely at low altitudes.

6. Effects of salt fall-out from undiluted aerosols

The fall-out of salt into the moist lower air from the cloud layer will not, of course, be in a steady state, since the clouds which transport most of the salt are so unsteady (KESSLER) (SIMPSON). In order to estimate the average heating effects of this salt fall upon the sub-cloud layer as a whole, it was necessary in the previous section to assume a steady state and a ten times dilution of the salt transported by the clouds. It is of interest to consider some effects, of shorter duration, which might arise in areas where the aerosol population might remain undiluted. In order to do this it becomes necessary to estimate the aerosol concentrations to be expected in inter-cloud areas near active cloud systems.

Below it will be shown that condensational growth of the salt nuclei in ascent to cloud base and within the clouds will result in a "compression" of their spacial distribution.

TABLE 3

Computed air temperature increases, in layers of various vertical thickness, due to condensation on falling salt

Height of layer Meters	Air temperature increase in 18 hours (°C)		
	RH 90	RH 96	RH 98
200	1.0	2.9	9.4
400	0.5	1.5	4.7

The largest increase in concentration occurs as the nuclei fall from the clouds into relatively dry inter-cloud air. The cloud and its local environment thus become an area of concentration of salt.

a) *Ascent of salt-laden air to cloud base.* Columns 5 through 9, Table I, show the changes which occur as a result of the lifting of air from near the surface up to cloud base.

The radii in column 5 are taken from the sea-salt nuclei growth measurements of Kieth and Arons, and they represent the sizes of the salt particles of column 1 at cloud base, assuming dry adiabatic ascent at a rate of one meter per second (see Figure 6).[1] The rates of fall of individual particles, which are given in column 6, are taken directly from Stoke's law and, for the larger particles, from the measurements of GUNN and KINZER (1949). The amounts of sea salt which are falling, are given in column 7, and are the product of the fall rate (column 6) and the quantity of salt in the size ranges concerned (column 9). The amounts of water falling are a product of the amounts of salt falling (column 7) and their concentration, expressed as grams per gram. (These rates of fall of salt and water represent fall relative to the air.) Finally, column 9, which indicates an increased amount of salt in the air, is a product of the initial amount of salt passing unit area per second and the quantity one over the rate of ascent of the air minus the rate of fall of the particles.

[1] The conditions assumed in deriving the droplet sizes given in Figure 6, are not strictly applicable to the present case. However the error, in computed particle size at cloud base, which results from these differences in conditions is not significant here.

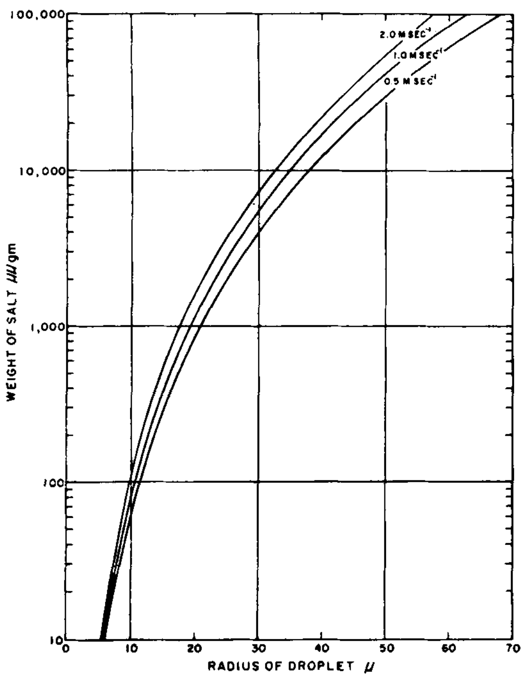

Fig. 6. Calculated radius of sea-salt droplets at cloud base (RH 100 per cent), as a function of nucleus mass and rate (taken from KEITH and ARONS, 1954).

More definitely expressed, this relationship becomes:

$$W = w' \frac{1}{v - u} \qquad (4)$$

where W = wt. of sea salt m^{-3} of air
w' = wt. of sea salt crossing each m^{-2} per second (μ gms)
v = rate of ascent of air (m sec^{-1}), and
u = rate of fall of the particles (m sec^{-1}).

In each case w' is fixed, in any column of air ascending at a steady rate, by the initial quantity of salt of each size range in the air as it rises from near the sea surface, by the fall rate of the particles and by the rate of rise of the air. This means that within an ascending column of air the weight of salt passing each square meter of horizontal surface, which is fixed in reference to the ground, is constant. It is assumed here that there is a horizontal homogeneity in the salt aerosol population.

Thus it seems, from the results in column 9, that the adiabatic ascent of moist air containing salt particles, will cause a concentration or a compression of the particle distribution. This compression is due to the condensational growth of the particles and to their consequent increased fall rate (in Table I, compare columns 2 and 3 to columns 5 and 6). It can be seen in equation (4) that the changing relationships between the rates of rise of the air and of the particles, alter the salt particle concentration.

An increase in the amount of salt with increasing altitude in the sub-cloud layer of the trade-wind atmosphere was first reported

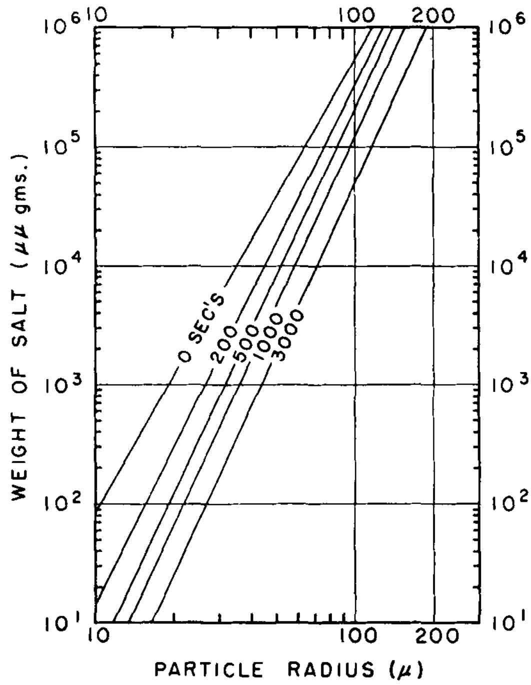

Fig. 7. Sizes of salt particles after given times in cloud:—including growth in coming to cloud base at 1 m/sec rise. (From Keith and Arons, 1954, see text).

by Lodge (1955) and has been subsequently occasionally observed by the author while making nuclei measurements for other purposes. These observations are not adequate to be used here as a test for the computed increase in salt with altitude. Such test measurements are planned in the future, using the recently developed airborne flame photometer (Woodcock, Spencer, 1957) in conjunction with the glass-slide sampling method (Woodcock, 1952).

(b) *Ascent of salt-laden air in cumuli.* In the trade-wind areas the cumulus clouds are the major mechanism bringing about the transport of surface air from near cloud base altitudes upwards into the cloud layer (Malkus, 1956) (Riehl et al., 1951). We now assume that the clouds serve a similar role in the lower air spiraling into hurricanes, and determine the change in salt particle size and concentration as the air rises in these clouds and into the inter-cloud regions.

Figure 7 shows the radii of the various weights of sea-salt particles as a function of time of exposure in cloud air, assuming a relative humidity in the cloud of 100 per cent. These growth rates were derived for the author by C. H. Kieth, and are based upon his experimental determination of the condensation on sea-salt nuclei (Kieth, Arons, 1954).

In Table 4, the droplet radii shown in column 2 are taken from the 1,000 second curve of Figure 7. At the rate of ascent assumed, this is about the time required for an air parcel to rise from cloud base to the top of a cloud of medium vertical development. Equation (4) is again applied to the different conditions in the cloud, in order to determine the additional "compression" of the particle distribution due to the changed relative motions. In this case, however, W is determined by the quantity of salt in the air at cloud base and by the increased values for particle fall rate and rate of rise of the air in the cloud. The sums of the quantities in column 6 of Table 4, show that the calculated amount of salt per unit volume of air has again been increased by ascent in the cloud, as it was in ascending in the sub-cloud layer. Comparison of columns 4 and 5 of this table to columns 4, 7 and 8 of Table I, show that there has also been a marked increase in the rates of fall of salt and water with reference to the ascending air.

(c) *Fall-out of salt particles from cloud into clear air.* As the large salt-containing droplets in the cloud (column 2, Table 4) fall or are mixed into the clear environmental air, evaporation occurs and the resulting alteration of particle settling rate again compresses the distribution. This compression is derived as follows:

$$W' = W_c \frac{U}{U'} \qquad (5)$$

where W' = wt. of sea salt in the clear air (μ gms m^{-3}) after evaporation to equilibrium has occurred

W_c = wt. of sea salt in cloud (column 6, Table 4) in μ gms m^{-3}

U = particle fall rate as droplet in cloud (column 3, Table 4), in cm sec^{-1}

U' = particle fall rate after evaporation to equilibrium in clear air, in cm sec^{-1}

TABLE 4

Alterations in the distribution of the salt particles represented by curve 12 figure 3, upon ascent in a cumulus cloud and upon falling out of the cloud into clear inter-cloud air.

Sea-salt nuclei as cloud droplets after 1000 seconds in cloud; R. H. 100 %; rise rate 4 m sec^{-1}						Droplets fall into clear air at cloud levels where R. H. < 74 % and evaporate to a crystal state		
Weight of sea-salt particles 10^{-12} g	Cloud droplet radius μ	Cloud droplet fall rate cm sec^{-1}	Amounts of salt and water falling μ gms. m^{-2} sec^{-1} salt	water	Wt. of salt in each size range μgms. m^{-3}	Salt particle radius μ	Particle fall rate cm. sec^{-1}	Wt. of salt in each size range μ gms. m^{-3}
1	2	3	4	5	6	7	8	9
50	19	4.4	2.7	1,545	61	1.8	0.084	2,980
600	32	11.6	7.3	1,663	63	4.0	0.42	1,710
1,750	40	17.5	11.4	1,739	65	5.8	0.86	1,320
3,200	45	22.0	14.7	1,775	67	7.0	1.27	1,130
4,800	50	25.5	17.4	1,823	68	8.9	1.63	1,075
7,100	54	29.5	20.5	1,869	70	9.2	2.15	925
9,900	58	33.0	23.2	1,887	71	10.2	2.72	863
13,100	62	36.5	26.5	1,983	72	11.2	3.25	825
16,700	65	39.5	29.2	1,981	74	12.2	3.85	770
21,800	68	42	31.5	1,868	75	13.3	4.50	685
28,000	72	46	35.4	1,935	77	14.5	5.5	656
36,000	76	50	39.5	1,980	79	15.7	6.4	618
44,000	80	54	44.2	2,106	82	16.8	7.3	600
54,000	83	57	47.9	2,077	84	18.0	8.4	577
68,000	88	61	53.0	2,177	87	19.4	9.7	546
88,000	92	65	58.5	2,111	90	21.2	11.6	508
114,000	98	70	68.8	1,921	93	23.1	13.8	465
152,000	104	76	74.5	2,225	98	25.4	16.7	440
223,000	113	84	87.4	2,273	104	29.0	22.0	398
410,000	128	97	117.3	2,403	121	35.4	33.0	362
			811	39,341*	1,602			17,453

* This fall rate, expressed in more familiar terms, is about 0.04 mm hr^{-1}, which is near the minimum measured within trade-wind orographic clouds (BLANCHARD, 1953).

Column 9 of Table 4 shows that a "compression" of salt concentration of about one order of magnitude would result if evaporation to a crystalline state in the clear air occurred with a continuous source of cloud particles allowing the establishment of a steady-state condition. The total rate of fall of salt in the clear air is the same as that in the cloud, for the product of the fall rate and the salt concentration, columns 8 and 9 of Table 4, can be seen to equal the values in column 4. In other words the conservation of mass principle is assumed to apply here, so that the number of particles falling into the top of a given column of air in a certain time interval must equal the number falling out at the bottom of this column in the same interval.

Thus the ascent of salt-laden air from near the sea surface to cloud base altitudes, its ascent in cumulus clouds and its final passage into the clear cloud-level air, tend in each case to increase the quantity of salt in the air.

As previously mentioned, an increase of salt with altitude is sometimes observed in the sub-cloud layer. Recent use of an airborne flame photometer in trade-wind clouds has indicated that the average salt (sodium) content of these clouds is sometimes higher than the average salt content of the air below cloud base (WOODCOCK, SPENCER, 1957). No data are available however on the nuclei present in the clear air at cloud levels at times or at places where an inter-cloud increase in salt might have been encountered. Observations aimed specifically at exploration of the salt nuclei gradients in the lower trade-wind atmosphere during storms are needed to test the above calculated gradients.

The computed and observed increase with altitude in the amount of salt particles in the air encourages some calculations concerning the possible effects of these particles in altering the distribution of water vapor and temperature as they fall, in undiluted concentration, from the higher levels towards the sea. For convenience in making the calculations of salt fall-out in inter-cloud air, it is assumed that the ascent of new masses or bubbles (SCORER, LUDLAM, 1953) of cloud materials is frequent enough to produce a relatively steady source of the larger salt particles, which supply the greatest amount of falling salt (see column 4, Table 4). With a markedly transient cloud source of the falling particles, the wide range of fall speeds present among these larger particles (see column 8, Table 4) would soon cause a diminishing concentration in the clear air as the larger particles fell away from the smaller.

Of course the droplet population of a significant volume of a cumulus cloud is not likely to have been exposed to saturated conditions for exactly 1,000 seconds as was assumed in Table 4. However, for the rate of rise assumed here, exposure times in ascending air parcels of about 500 to perhaps 1,500 seconds seems reasonable for the clouds concerned. On Figure 7 and Table 4 it can be seen that this range of exposure duration is not sufficient to cause droplet size differences, for any given particle weight, which would markedly alter the particle-concentration effects discussed here. The important requirements are that droplets of the approximate sizes given be present in the clouds and that they form on salt particles having weights approximating those given. No reference to measurements of the droplet size distribution of marine cumuli in tropical storms has been found in the literature. However, Squire's results in Australian and Hawaiian maritime clouds during moderate winds (SQUIRES, GILLESPIE, 1952) (SQUIRES, WARNER, 1957) are consistent with the computed drop size distributions given here. The effects of coalescence of droplets upon size distribution and in increasing rates of fall were not considered above. Introduction of these complicating effects would serve only to increase salt fall-out, which for present purposes is shown to be adequate.

The purpose of the above computations of the compression effects of ascent and growth upon salt particle concentration was to show, in the section to follow the local heating effects of fall-out of salt from areas of undiluted aerosol concentration. In estimating these effects in the sub-cloud layer as a whole, it will be remembered that, in section 5 above, a dilution of the cloud-borne salt by a factor of ten was assumed.

(d) *Altered vapor and temperature distribution in cloud layer.* When the particles fall from the cloud into the inter-cloud air having a relative humidity less than 74 %, evaporation to relative dryness will occur. The diminishing droplet size causes a sharp reduction in rate of fall of individual particles (see column 8, Table 4). However, the great increase in the salt concentration in the air, shown in column 9, will cause the total rate of fall of salt m^{-2} sec^{-1} in each weight range to remain the same as it was in the cloud - note for instance that the product of the fall rate and the weight of salt in each size range (columns 8 and 9 of Table 4) is equal to the quantities in column 4. The sum of these quantities can be seen to be 811 μ grams of sea salt falling per square meter per second.

If, in falling towards the sea, this mass of salt moves out of the dry air (RH $<$ 75 per cent) and into a layer where the RH is 90 per cent, condensation will occur on the particles, heat will be released and water will be carried downward. Upon subsequently falling out of the moist layer and into a dry

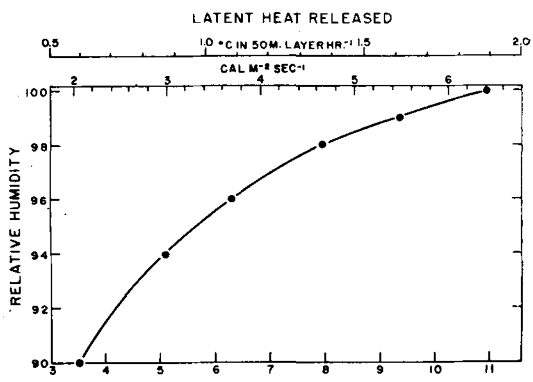

Fig. 8. Condensation and heating in moist layer of air of 50 m depth, during initial 100 seconds after entry into layer of salt particles falling from dry air. (See text for more information.)

TABLE 5

Amounts of water condensed on salt particles 100 seconds after they fall into saturated air from dry air (RH < 74 %).

Sea-salt particle weight 10^{-12} g	Total amounts of salt falling μ gms m^{-2} sec^{-1}	Particle radius after 100 seconds μ	Particle fall rates after 100 seconds cm sec^{-1}	Amount of water falling after 100 seconds μ gms m^{-2} sec^{-1}
50	2.7	12.5	2.1	440
600	7.3	21.5	6.0	492
1,750	11.4	26.5	9.0	491
3,200	14.7	30.0	11.5	503
4,800	17.4	33.0	13.5	526
7,100	20.5	36.0	15.8	542
9,900	23.2	38.5	17.8	539
13,100	26.5	41.0	20.0	569
16,700	29.2	42.5	21.3	539
21,800	31.5	45.0	23.8	517
28,000	35.4	47.0	25.5	521
36,000	39.5	50	28.7	541
44,000	44.2	52	31.0	559
54,000	47.9	55	33.7	572
68,000	53.0	58	36.4	585
88,000	58.5	61	39.0	579
114,000	68.8	64	42.0	596
152,000	74.5	69	47.0	592
223,000	87.4	75	53.5	598
410,000	117.3	86	64.0	641
	811			10,942

layer, evaporation will occur, the dry layer will be cooled and water vapor added. Thus the passage of salt-bearing particles down through the atmosphere will act to warm and dry the moist layers and to cool and moisten the dry layers. The heat released and the water transported by this process is estimated as follows.

The particles represented by column 4, Table 4, upon falling from dry air into saturated air, will cause condensation of about 11 mg of water m^{-2} sec^{-1} during the first one hundred seconds of their fall through the moist air. This quantity was derived as shown in Table 5, using the information given in Figure 5. Other quantities were obtained in this manner for unsaturated air layers. The results are given in Figure 8.

Since the condensation in the first one hundred seconds will occur in an air layer of about 50 meters of vertical thickness, or less (see fall rates, Table 5), we can estimate the average heating of this layer. Using equation (3), it is found that the condensation rates given on the lower scale of Figure 8 will heat 50 kg of air by the amounts given on the upper scale. This range of rates of release of latent heat is equivalent to the wet-adiabatic lifting of the lower air at 3 to 10 cm sec^{-1}.

Thus fall-out of undiluted aerosols can produce greater amounts of local heating than those estimated for the sub-cloud layer as a whole (Table 3). It is suggested that this heating may be an important factor in the production of instability, especially in those cases where moist parcels of air are trapped by overlying layers of stable air.

Thus a significant transport of water and release of heat can occur at relative humidities of 100 per cent and less as sea-salt aerosols fall through layers of air of different relative humidities. Of course the actual amount of water condensed would be somewhat less, due to the slow lowering of the relative humidity of a moist layer, of specific vertical extent, as water is removed and latent heat released. It is supposed that such lowering of the relative humidity is, in many cases, reduced or prevented by ascent due to the heating of the air.

It may be useful to point out a further effect of the fall-out of salt particles through the moist air of the cloud layer. Their tendency to establish vapor pressure equilibrium at each level should act to equalize the relative water vapor distribution. A trend towards constancy of relative humidity would result from the fact that in air over sea-salt solutions of constant salinity, the relative humidity changes very little with temperature. Note on Figure 2 for instance, that the relative humidity over a sea-salt solution, which is 80 ‰ chloride, is 91.3 % at ten degrees and 90.4 % at twenty-five degrees. Particles falling through air layers of differing relative humidity will add water to the relatively dry levels and subtract water from the relatively moist levels. The trend will always be towards a more constant droplet salinity and hence a more constant relative humidity. To what extent this effect is traceable in the trade-wind or tropical-storm atmosphere is as yet unknown.

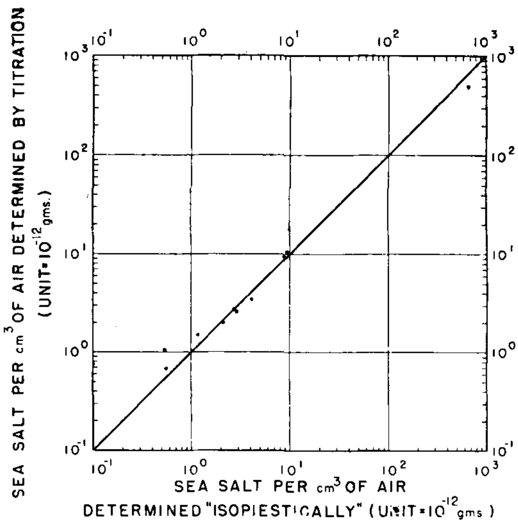

Fig. 9. The quantities of airborne salt collected by impingement on one mm wide strips and measured directly by precipitation with silver nitrate and indirectly by the equal pressure method.

7. Accuracy of measurement of salt particles

The isopiestic method (GLASSTONE, 1940) for measuring the weights of salts in solution in small droplets is considered sufficiently accurate as applied to the problems discussed here. Figure 9 shows several test comparisons of weights of chloride measured by titration, using a microburette to measure the silver nitrate solution, and by the isopiestic method (WOODCOCK, 1950) (WOODCOCK, GIFFORD, 1949). The error of the titration was less than plus or minus 10 per cent. TWOMEY (1954) has recently demonstrated the close correspondence of the individual salt particle sizes determined isopiestically and by the chemically sensitized film method of SEELY (1952). It should be noted that experimental application of the isopiestic method above a relative humidity of about 90 per cent apparently introduces an error which becomes increasingly significant as 100 per cent is approached (CROZIER, 1954).

8. Discussion

In evaluating and expanding upon the foregoing explanation for the relatively constant temperature of the surface air in hurricanes, consideration of the following questions seems useful at this time.

a) Will the fall speed of the salt particles in the inter-cloud air be sufficient to bring them down to the sub-cloud air before they are carried out of the storm area by radial winds?

The data on Table 1 show that the particles which contribute most to the salt fall-out, descend as crystalline nuclei (RH < 74 %) at rates of several hundreds to one thousand meters per hour. They will soon fall back from the inter-cloud to the sub-cloud layers, if they are not carried up into the regions of rapid out-flow at high levels. This conclusion is based upon RIEHL's evidence (1954, p. 303) that the radial wind speeds at intermediate altitudes are low, and vacillate between inflow and outflow. At the upper levels high outflow rates will probably carry the particles far out from their areas of origin. The question of the role of the fall-out of these dispersed particles in the release of heat in moist peripheral regions of storms, such as those in the lower atmosphere in advance of Edna and Ione (KESSLER, 1957), will be investigated in a later study.

b) Are observed rates of radial inflow of surface air adequate to replace the ascending air required to transport the salt up in clouds?

In section 2 of this paper it was simply assumed that cumulus clouds in a hurricane carry aloft sufficient surface air and aerosols to maintain a certain average or "steady state" salt fall through the inter-cloud area. This assumption seems questionable however, if it is supposed that there is no interchange of air between the cloud and sub-cloud layers, and that each mass of rising air in the clouds is replaced by an equal mass of converging sub-cloud air. This question is elaborated in the following discussion.

Converging sub-cloud air in tropical storms is thought to equal in mass the air which ascends in the cumuli and which eventually flows radially outwards at higher levels (RIEHL, 1954). Observations of radially converging lower air, which might be compared to the above estimates of the amounts of ascending air needed to carry the load of salt aerosols, are not available for individual storms. However, in Hughes' study (HUGHES, 1952) of the pattern of low level winds (at about 1,000 feet) in Pacific tropical cyclones, averaged radial inflow was derived for 28 storms. From this inflow averaged ascent over the whole storm area of from 1 to 12 cm sec^{-1} is derived, the greater and more rapid part of the ascent being in or near the central "rain area". In the present study of the role of salt particles in the release of latent heat, the best estimates of the range of rates of ascent of air required to carry a sufficient salt load lie between 10 and 100 cm sec^{-1}. This range of rates is computed, assuming that the salt load of the sub-cloud air varies from the average of my own measurements to a maximum which is about equal to the highest values reported in the literature (about 10 mg m^{-3}, RAU, 1956). Thus an overlap of the range of rates of ascent derived from Hughes' measurements, and the range of rates of ascent required to carry the salt load occurs, but a wide disparity in average magnitude exists.

It appears improbable from the above estimates that the radial inflow of the lower air is sufficient to carry the salt load required in the present study. A mass of ascending air several times that of the recorded average inflowing air is required. The question remains open however, for recent evidence indicates that the earlier observations of radial inflow are too low, and also that a considerable interchange of air between the cloud and sub-cloud layers occurs which is part of the normal growth mechanism of trade-wind cumulus clouds (MALKUS). This latter evidence shows that a part of the air ascending in cumuli can be regarded as "cyclic air", and that it is incorrect to assume that the amount of radially converging air necessarily equals the amount ascending in the cumuli.

c) Is it necessary to regard the amounts of salt observed in one hurricane as an upper limit of quantities to be expected in these storms? This problem is especially pertinent here, since the present study reveals somewhat marginal heating effects from salt amounts taken from available data.

The experience of sampling atmospheric salt particles under a wide range of conditions has convinced the author that the amount of salt represented by curve 12 of Figure 3 should not be considered an upper limiting quantity. The hurricane-aerosol data used here, which are the only available data, were obtained at a time when most of the storm was over land. The sampling position was the top of Hillsboro Lighthouse, on the Florida east coast, at Pompano. At the time of sampling, September 22, 1948, 2330, E.S.T. (WOODCOCK, 1950), the storm center or "eye" was over inland Florida, and the air from which the samples were taken had only recently passed from over land about 30 miles south of the station (see surface winds, Miami to Key West, N.W.R.C., Ashville, N.C.). Since the salt aerosol load of the air is a function of the fetch over the sea, as well as of wind force (WOODCOCK, 1954), this recent passage of the air from over land would result in a relatively low salt content when compared to this content if the entire cyclone had been over the sea. The author has little doubt that the salt load of the lower air in severe wind storms at sea commonly exceeds the amounts given here by a factor of ten or more. Such amounts would of course result in proportional increases in the heating of the sub-cloud air in the model proposed. However, the above hurricane sample serves the purpose here, which is to demonstrate that observed quantities of salt nuclei, upon ascent in clouds, will alter the distribution of water vapor and temperature as they fall back towards the sea. The magnitudes of these effects are certainly large enough to satisfy a first-approximation study.

It is perhaps not a coincidence that the weights of salt required to bring about the

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release of latent heat discussed here, add little to the air density. The maximum quantity of airborne sea salt considered (i.e. about 10 mg m^{-3}) will produce a density increase, at ordinary surface pressures, about equal to the increase caused by a temperature decrease of 0.01 C in the usual air temperature range.

9. Conclusions and Recommendations

A mature hurricane at sea is a gigantic salt-aerosol generating and distributing mechanism. Fall-out from the aerosols carried aloft in the storm clouds, may liberate significant amounts of latent heat in the moist lower layers of the atmosphere. Thus the vast self-generated salt cloud in the atmosphere of these storms should be seriously considered as one of the properties influencing their stability. In the model proposed a moist lower layer and a relatively dry inter-cloud layer of air is required.

It is recommended that many measurements of the size distribution of sea-salt particles be made in the relatively clear air in various parts of tropical (and extra-tropical) marine cyclones. If these measurements reveal a salt fall-out of several milligrams per square meter per second into the air converging upon a storm center, the effects of this salt in adding to the internal temperature gradient become apparent. Riehl shows for instance (RIEHL, 1954, p. 313—316) that the isothermal expansion of the converging sub-cloud air, results in temperature excesses of several degrees as this air ascends in the "rain area" of hurricanes.

Acknowledgments

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