

tion would probably result in a larger increase of insolation in summer than in winter everywhere but near the equator.

**2. First model**

If the varied state is represented by primes, the condition for the first model may be written

$$Q' = Q + H \cos \theta, \tag{7}$$

where  $H$  is the change of  $Q$  at the poles. The varied temperature-range distribution represented by (7) is obtained by superimposing on the observed temperature-range distribution a zonally symmetric wave of amplitude  $H$  with one node at the equator. The harmonic coefficients corresponding to (7) are therefore given by

$$\begin{aligned} a_1^{q'} &= a_1^q + H, \\ a_n^{m'} &= a_n^m \quad (\text{for } m > 0; n \neq 1), \\ b_n^{m'} &= b_n^m. \end{aligned} \tag{8}$$

Upon substitution of (8) in (3),

$$p_s' = p_s + Hh_0^{-1}(K_1^0 - 1) \cos \theta, \tag{9}$$

since  $K_n^m$  does not depend on the temperature.

The varied pressure-range was computed for  $H$  equal to  $2.00 \times 10^{10}$  dynes  $\text{cm}^{-1}$ , which corresponds to an increase of about 20C in the annual surface temperature range at the poles. The result is shown in fig. 1 and may be compared with the pressure-range field computed from the observed temperature ranges (fig. 2).

The mean horizontal pressure-gradients in summer, at least in the Northern Hemisphere, are quite small compared with those of the winter season, except in low latitudes. Figs. 1 and 2 may therefore be considered representative of the winter pressure distribution. From this point of view, the primary effects of increased solar radiation are intensification of the continental anticyclones and weakening of the Icelandic

and Aleutian lows. The geostrophic circulation is altered very little.

**3. Second model**

It is probably more realistic to assume that the effect of increased solar output on the annual temperature range will be greater over the continents than over the oceans. Since the variation of  $Q$  with longitude is largely a function of continentality, the condition that the effect of increased solar radiation be greater over continents than over oceans may be satisfied by assuming

$$Q' = GQ, \tag{10}$$

where  $G$  is a constant greater than one and the prime again denotes the varied condition.

From (5) and (6),

$$\left. \begin{matrix} a_n^{m'} \\ b_n^{m'} \end{matrix} \right\} = G \left\{ \begin{matrix} a_n^m \\ b_n^m \end{matrix} \right\}. \tag{11}$$

Upon combination of (11) and (3)

$$p_s' = Gp_s. \tag{12}$$

Thus, if the annual temperature range increases everywhere by an amount proportional to the observed temperature range, the magnitude of the annual pressure range increases by the same factor. In terms of the winter pressure distribution, this means that the continental highs and the Aleutian and Icelandic lows all increase in intensity, with resulting increase in geostrophic circulation. However, the positions of the pressure centers, as well as the isobaric configurations, are unchanged.

REFERENCES

1. Spar, J., 1950: On the theory of annual pressure variations. *J. Meteor.*, **7**, 167-180.
2. Chapman, S. and J. Bartels, 1940: *Geomagnetism*. (Vol. II), Oxford, Clarendon Press, 1049 pp.

SEA SALT IN A TROPICAL STORM

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Air-borne sea salt in a tropical storm was sampled from near the top of Hillsboro Lighthouse, Pompano, Florida, during September 1948. The samples taken were few in number, due to the interference of almost continuous rain, but they give a useful indication of the weight of the sea salt in the air as well as the size distribution among the individual sea-salt nuclei. The weight and number of nuclei present during storm

winds were compared to these quantities sampled during moderate winds in the same area. The quantities of hygroscopic salt in the storm winds were large enough to suggest that, in small parcels of air, significant amounts of latent heat may be released at relative humidities below 100 per cent.

Fig. 1 shows a diagram of the sampling position C in relation to the windward shore and surf. There immediately arises a question about the effects of local surf upon air-salt samples taken at C.

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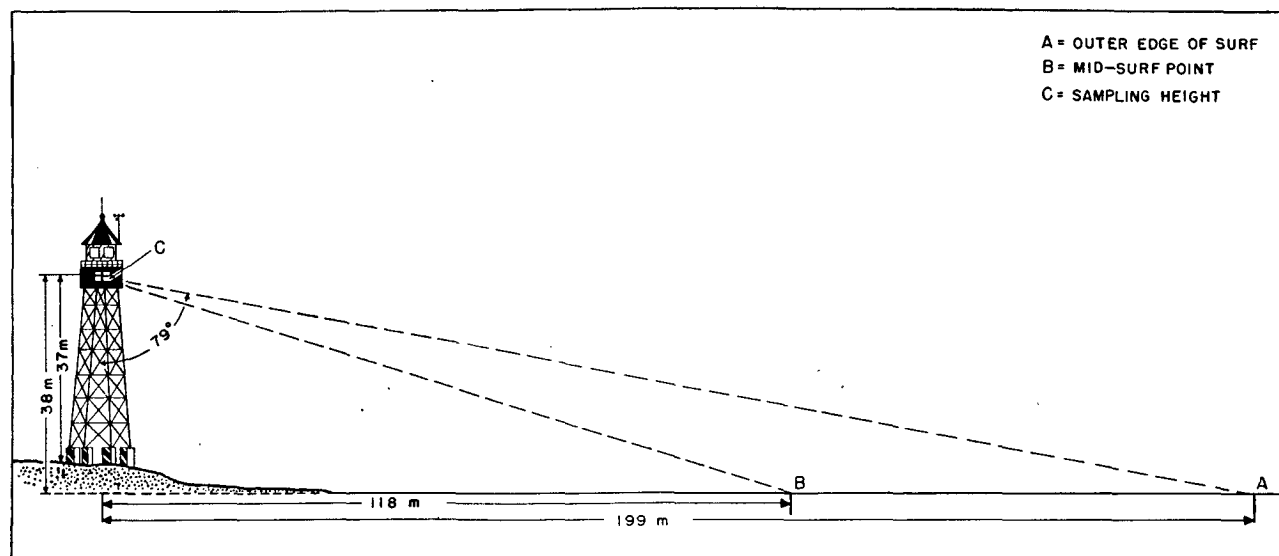


FIG. 1. Diagram showing height of sampling position C at Hillsboro Lighthouse and distance from windward surf. See table 1 for further information.

At the high average wind-speeds obtaining during the sampling periods (*i.e.*, 27 to 30 m sec<sup>-1</sup>), a vertical motion of about 6 m sec<sup>-1</sup> would be required to lift spray from the outer surf line A to the sampling level C. From the mid-surf point B, a rise of about 9 m sec<sup>-1</sup> is required. The breaking of waves and the effervescence of the water over the whole sea surface during the storm winds appeared almost as great as in the surf along the shore. Consequently the production of spray drops was probably very great over the entire sea surface. For the above reasons, it seems probable that atmospheric sea-salt samples taken at point C were very nearly representative of sea-salt concentrations which existed at that height in the free air over the sea. However, there remains the question of the possible effects of the local surf upon the samples taken. Hence a portion of the following results may be strictly regarded as applying only to the vicinity of the coast during onshore storm winds.

Twenty (1-mm square) silver rods were exposed twice for about 100 sec, one of the surfaces of each rod being held normal to the air stream by the wind

vane. During each exposure, these rods caught about 2 mg of salt. The rods were then removed, washed in 10 ml of distilled water, and the dissolved chlorides were titrated with a silver-nitrate solution which was measured with a micro-burette. The results of these titrations were then expressed in terms of total sea-salt cm<sup>-3</sup> of air. A Casella anemometer was used to measure the air flow at the sampling position.

Two samples were also taken, in 10-sec exposures, with 1-mm wide glass strips. These strips were made hydrophobic with Dri-film. Measurements were made of the sea-salt nuclei which impinged upon them, using the isopiestic method with which the weight of sea salt in each nucleus may be determined. The results of the latter measurements, expressed as total sea-salt cm<sup>-3</sup> of air, can then be compared to this quantity as obtained by direct titration of chlorides in nuclei impinged upon the silver rods. A detailed description of the methods used to sample atmospheric sea-salt in marine air has already been published (Woodcock and Gifford, 1949).

Using the isopiestic method, drop A (on fig. 2, upper

TABLE 1. Data relative to air-borne sea-salt samples taken in a tropical storm at Hillsboro Light, Pompano, Florida (26°16'N, 80°05'W), 22-23 September 1948. Wind direction ESE; sampling height 38 m.

	Time (EST)			
	2235	2350	2330	0045
1. Wind speed (m sec <sup>-1</sup> )	30	28	27.4	29.2
2. Exposure length (m)	300	280	2740	2630
3. Dry-bulb temp. (deg. C)	27.2	26.9	—	25.7
4. Wet-bulb temp. (deg. C)	25.0	24.5	—	24.6
5. Vapor pressure (mb)	30.15	29.0	—	30.2
6. Relative humidity (%)	84	82	—	91
7. Pressure (mb)	997	—	996	995
8. Sea-salt weight (g cm <sup>-3</sup> of air)	440 × 10 <sup>-12</sup>	952 × 10 <sup>-12</sup>	402 × 10 <sup>-12</sup>	592 × 10 <sup>-12</sup>
9. Nuclei cm <sup>-3</sup> of air	3.2	4.0	—	—
10. Covering fraction (%)	0.049	0.079	—	—
11. No. of nuclei measured	972	961	—	—
12. Method used	isopiestic	isopiestic	titration	titration

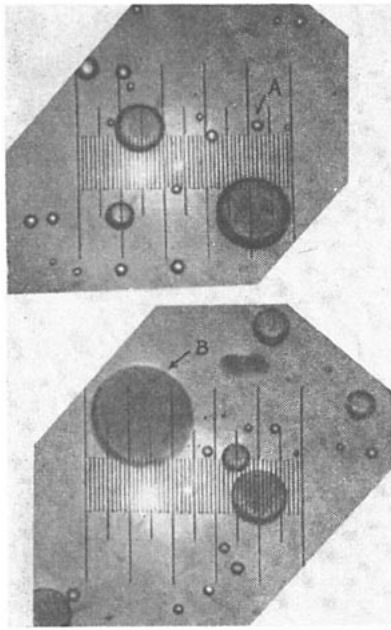


FIG. 2. Photomicrograph of sea-salt nuclei on glass slides which were exposed to air stream for 10 sec during passage of tropical storm. When photomicrograph was made, the air over the slides had temperature of 25C and relative humidity of 91 per cent. On scale, one division equals 2.2 $\mu$ .

picture) is found to contain about  $3.4 \times 10^{-12}$  g of sea salt and drop B about  $6200 \times 10^{-12}$  g. About 950 of these nuclei were measured over a known area of each slide and the sums of their weights were expressed in grams per cm<sup>3</sup> of air. In table 1 it can be seen in line 8 that the atmospheric sea-salt determinations made by the isopiestic method (first two observations) are very similar in magnitude to those made by direct titration (last two observations). The indicated variations are of the same range as those commonly found by the writer at different positions within an air stream at constant height over the sea. Other pertinent data are also shown in this table. The "covering fraction" (line 10) is low enough to avoid a serious amount of coalescence of the nuclei (Langmuir, 1944). It should be noted, in line 2, that from about 300 to 2700 m of air flowed by the sampling surfaces during the exposure periods.

Fig. 3 (solid dots) shows the distribution of the number and weight of 1933 nuclei found on the two slides. The weight distribution in the hurricane (dots) is rather similar to that found in the same area during moderate winds, as shown by the crosses. The latter

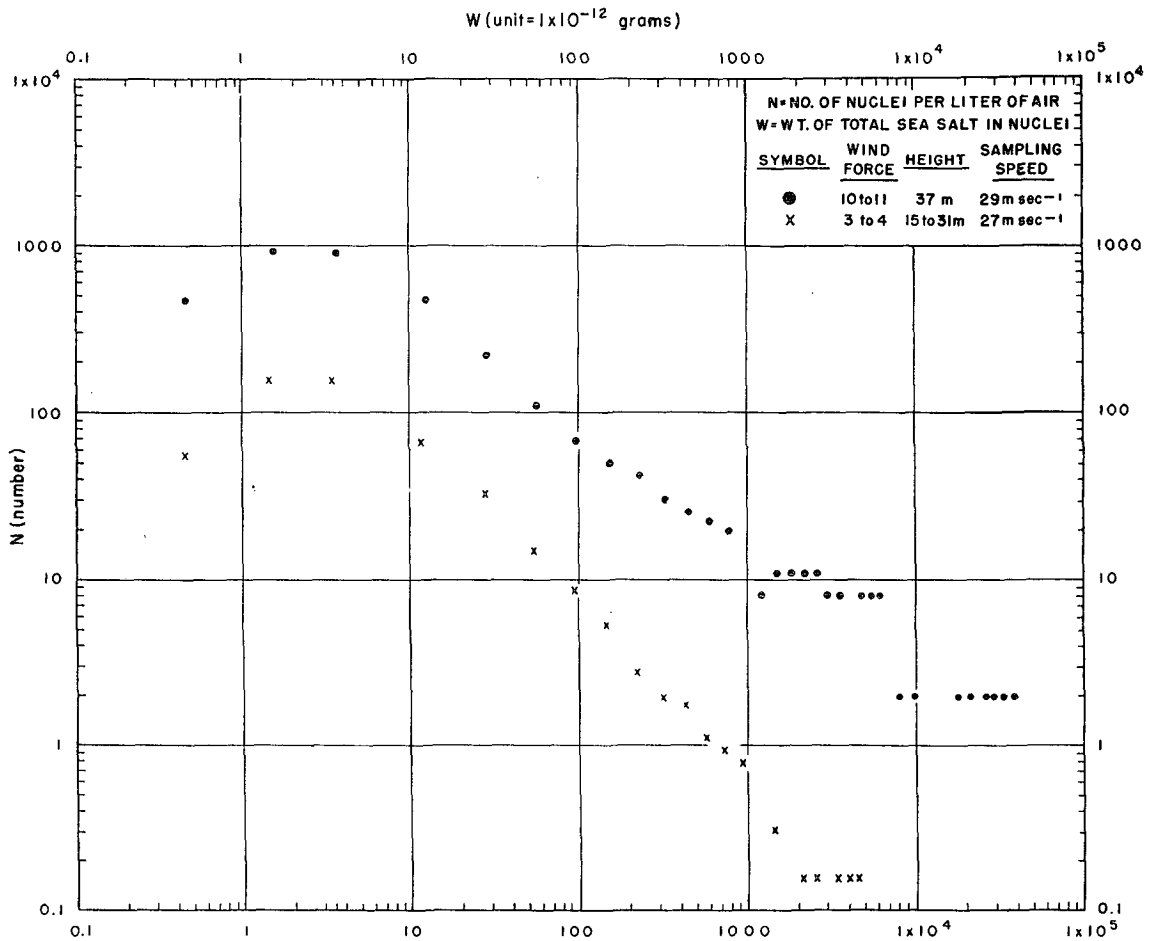


FIG. 3. Distribution of weight and number of sea-salt nuclei which impinged upon slides exposed during passage of tropical storm (upper symbols) and during moderate winds (lower symbols). Samples were taken at top of Hillsboro Lighthouse, Pompano, Florida, during storm and from aircraft over sea in same area during moderate winds. Winds were easterly at each sampling period. Average atmospheric sea-salt during storm =  $600 \times 10^{-12}$  g cm<sup>-3</sup>, during moderate winds =  $8 \times 10^{-12}$  g cm<sup>-3</sup>.

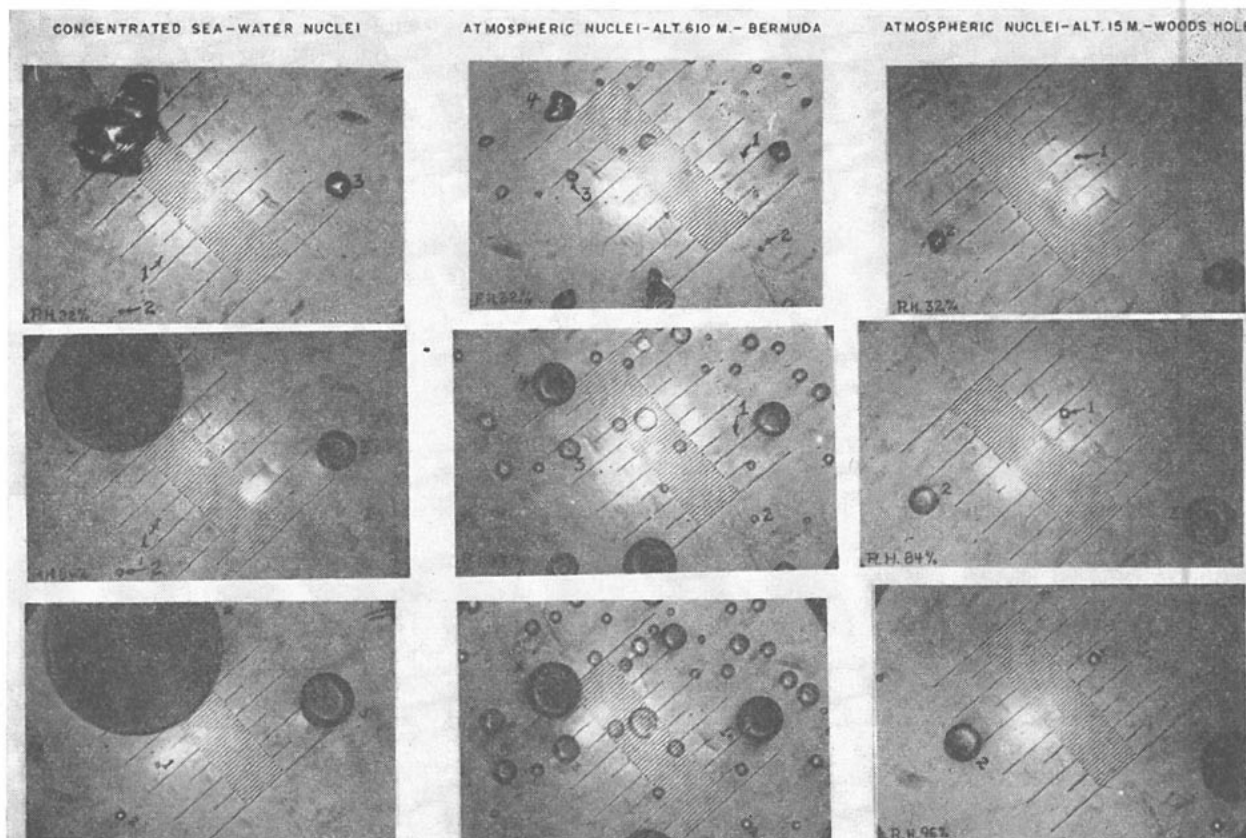


FIG. 4. Photomicrographs showing changes in appearance of nuclei on slides as relative humidity is increased. Nuclei at left were sprayed on slide. Scale: one division =  $2.2\mu$ .

samples were taken at a later date over the sea from an airplane, and the observed points represent measurements of 1743 drops on sampling slides. It can be seen, however, that there are present in the storm winds a greatly increased number of nuclei of the various sizes, and that there are larger nuclei present under storm conditions.

The maximum weight of sea salt  $\text{cm}^{-3}$  of air measured by random sampling in the hurricane (*i.e.*,  $9.5 \times 10^{-10} \text{ g cm}^{-3}$ ) is about 80 times greater than the average found during moderate winds in the same area and at the same height (Woodcock, 1950). It is interesting to note that this maximum value is near the maximum quantity found at La Jolla, California, by Jacobs (1938), who used an air-filtering sampling method. There seems little reason to suppose that this increase in quantity under storm conditions might not be 5 or 10 times greater in some smaller parcels of the lower air over the sea.

It may be supposed that these large quantities of salt aerosols might tend to remain in the lower air, due to settling of the particles. During lighter winds, however, samples taken in this region at a height of 30 m and near the base of the clouds have shown little difference in the quantities of salt present at the two levels (Woodcock, 1950). What effect will large quantities of sea salt in the air have on the release of latent

heat, if this air rises and the relative humidity increases towards saturation?

Sea salt is hygroscopic, the condensation of water vapor upon it beginning at a relative humidity near 70 per cent (Owens, 1926). As the humidity is increased, condensation increases and sea-salt nuclei increase in size. On fig. 4, photomicrographs of nuclei show crystalline masses at low relative humidity values. At higher relative humidities the crystals become liquid hemispheres. The increase in nuclei diameter or volume with increasing relative humidity is about the same as that which may be computed from the known relationships between vapor pressure, temperature and the amount of salt in concentrated sea water. As the relative humidity is increased from 40 to about 98 per cent, the nuclei on the glass slides grow rapidly, the larger ones establishing equilibrium in about 3 min and the smaller ones in about 40 sec.

Thus, if the amount of sea salt in the air is known, it is possible to calculate the amount of water which will be rapidly condensed with a given increase in vapor pressure. It is necessary to assume, of course, that condensation on the nuclei in the free air, in response to relative humidity changes, is similar to that on nuclei on the microscope stage.

During the hurricane, the maximum quantity of sea salt found was  $0.837 \times 10^{-6} \text{ g g}^{-1}$  of air, the air density

TABLE 2. Quantity of water condensed and quantity of heat released in one gram of air containing varying amounts of sea salt and in which the relative humidity is increased.

		Weight of sea salt in g g <sup>-1</sup> of air		
		0.837 × 10 <sup>-6</sup> **	4.37 × 10 <sup>-6</sup>	24.4 × 10 <sup>-6</sup> **
R.H. 82%	Condensed water (g g <sup>-1</sup> )	2.36 × 10 <sup>-6</sup>	11.7 × 10 <sup>-6</sup>	65.6 × 10 <sup>-6</sup>
	Latent heat (cal g <sup>-1</sup> )	0.0014	0.0069	0.0383
	Air temp. increase (deg C)	0.006	0.028	0.156
R.H. 90%	Condensed water (g g <sup>-1</sup> )	4.63 × 10 <sup>-6</sup>	24.2 × 10 <sup>-6</sup>	134.8 × 10 <sup>-6</sup>
	Latent heat (cal g <sup>-1</sup> )	0.0027	0.0142	0.0789
	Air temp. increase (deg C)	0.011	0.058	0.321
R.H. 95%	Condensed water (g g <sup>-1</sup> )	10.9 × 10 <sup>-6</sup>	56.1 × 10 <sup>-6</sup>	313.9 × 10 <sup>-6</sup>
	Latent heat (cal g <sup>-1</sup> )	0.0064	0.0328	0.1835
	Air temp. increase (deg C)	0.026	0.124	0.746
R.H. 98%	Condensed water (g g <sup>-1</sup> )	23.2 × 10 <sup>-6</sup>	120.4 × 10 <sup>-6</sup>	672.6 × 10 <sup>-6</sup>
	Latent heat (cal g <sup>-1</sup> )	0.0135	0.0705	0.3930
	Air temp. increase (deg C)	0.055	0.287	1.610

\* Maximum of random air-salt samples taken in the tropical storm.

\*\* Maximum air-salt reported in the literature (Gautier, 1899).

being 1.145 g liter<sup>-1</sup>. At this time the temperature was 26.9°C, the humidity 82 per cent, and the pressure about 1000 mb. The weight of water present under these conditions was obtained by use of the simple equation

$$W_w = W_s(C^{-1} - 1),$$

where  $W_w$  is the weight of the water present (g),  $W_s$  is the weight of sea salt present (g), and  $C$  is the concentration of sea salt by weight fraction.

The increases in air temperature resulting from condensation were then derived as follows:

$$\Delta T = W_w L c_p,$$

where  $\Delta T$  is air temperature increase (deg C),  $W_w$  is water condensed (g g<sup>-1</sup>),  $L$  is heat of vaporization of water (585 cal g<sup>-1</sup>), and  $c_p$  is specific heat of moist air (0.245 cal g<sup>-1</sup>).

In table 2, the amount of water condensed on the salt as the humidity of the ambient air is increased is shown for air containing the weights of salt<sup>2</sup> given at the tops of the three columns. The condensed water, latent heat and air temperature increases are shown at increasing relative humidities. The values given for latent heat are derived from the total water present on the sea salt at the humidity shown. For example, at a humidity of 98 per cent the latent heat of 0.0135 cal represents the heat of vaporization of all of the water condensed upon  $0.837 \times 10^{-6}$  g of salt and not simply the amount condensed as the humidity was increased from 95 to 98 per cent.

The first column of table 2 shows that the maximum of the four random air-salt samples taken in the Atlantic hurricane was near the lower limit of quantities which may be regarded as releasing significant amounts of latent heat below 100 per cent relative humidity. Note that about five-hundredths of a degree

<sup>2</sup> The heat of solution of sea salts is probably too low to be of meteorological significance since NaCl, the major constituent, has a heat of solution of only  $-21.9$  cal g<sup>-1</sup>.

heating has occurred at a relative humidity of 98 per cent. As shown in the last column of this table, the heat released becomes rather large if the quantity of air-borne salt measured at a lighthouse on the French coast by Gautier (1899) is used.

As previously stated, the four samples from the storm at Hillsboro Lighthouse were taken at random and represent the average concentrations of salt on rather long air-paths of 300 to 2700 m. It is the writer's opinion that selective sampling over the sea along shorter air-paths in this storm (perhaps 30 to 50 m in length) would have revealed much higher concentrations, perhaps as great as the value shown at the top of the middle column of table 2.

The writer wishes to suggest that certain smaller parcels of the lower air in wind storms along shore lines, and probably over the open sea as well, may contain so much sea salt that the increasing humidities associated with ascent of the air would cause the release of significant amounts of latent heat above a relative humidity of about 90 per cent. In these smaller parcels of air the quantity of sea salt would thus become an additional stability criterion.

#### REFERENCES

- Gautier, A., 1899: Quantité maximum de chlorures contenus dans l'air de la mer. *Bull. Soc. chim. Paris*, **21**, 391-392.
- Jacobs, W. C., 1936: A preliminary report on a study of atmospheric chlorides. *Bull. Amer. meteor. Soc.*, **17**, 301-303.
- Langmuir, I., 1944: Super-cooled water droplets in rising currents of cold saturated air. *Gen. Elec. Res. Lab. Rep.*, A.T.S.C. Contract N-33-106-sc-65, *precipitation static studies*, pp. 1-91.
- Owens, J. S., 1926: Condensation of water from the air upon hygroscopic crystals. *Proc. roy. Soc. London*, **A**, **110**, 738-752.
- Woodcock, A. H., 1950: Condensation nuclei and precipitation. *J. Meteor.*, **7**, 161-162.
- Woodcock, A. H., and M. M. Gifford, 1949: Sampling atmospheric sea-salt nuclei over the ocean. *J. marine Res.*, **8**, 177-197.