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Observations of the Distribution of Giant Sea-Salt Particles in the Sea-Surface Boundary Layer

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Abstract

Number concentrations of sea-salt particles at three heights above the sea surface were observed on board the Kagoshima Maru, Kagoshima University, during the cruise of the International Indian Ocean Expedition (IIOE) in the period of December 1963 through January 1964. Wind dependency of the number concentration, the salt-mass distribution, and the vertical distribution were studied.

The particle number concentration, in an average, increased with increasing wind speed. The large amount of sea-salt particles was often found at the area where squalls or rains were frequently observed. The relation between the mean particle number concentration and wind speed may be approximately expressed by an exponential function. The wind factor is slightly larger for larger salt masses than for smaller ones. The mean salt-mass distribution of each class interval of from log m=0.5 to log m=2.5 is presented for various wind forces. The vertical distribution of the mean particle number concentration is approximately distributed by a straight line on the logarithmic diagram of log θ-log z, as theoretically expected. The observed vertical gradients are nearly in agreement with the theoretical ones for the class of small salt mass in wind forces 0-1 and 2, though the observed gradients are slightly stronger than the theoretical ones for three classes of salt mass in wind forces 3, 4 and 5.

1. Introduction

It is a well-known fact in the air-sea system that the transfer of energy and materials through the sea surface takes place in many different phenomena, such as the development of the wind waves and the surface current by wind, the exchange of heat energy between the atmosphere and the ocean, the water exchange related to the evaporation and precipitation, and also the exchange of materials, for example, sea salt and carbon dioxide, in relation to the air bubbles and sea-water droplets produced by the breaking of wind waves. These particular phenomena occurring at the sea surface are closely correlated to each other, and they constitute a branch of study of the air-sea boundary processes as a unit process of the air-sea system (e.g., Toba, 1970).

Now, we take up a problem of the sea-water droplets, among various problems concerning the air-sea boundary processes. Sea-water droplets are produced on the sea surface, when the wind becomes strong and exceeds a certain critical wind speed, the breaking of wind waves occur, and the air bubbles entrained into water burst at the sea surface. If the amount and the distribution of sea-water droplets above the sea surface are made clear, it is expected that it

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will afford some basic data for the study of the effect of sea-water droplets on the evaporation from the sea surface, as well as of the overall degree of breaking of wind waves, in relation to the problem of the exchange of momentum and other physical properties through the sea surface.

In the past years, observations of sea-salt particles in the sea-surface bounbary layer were carried out by Moore (1952) and Moore and Mason (1954) in the Atlantic Ocean. Recently, Kikuchi and Yaura (1970) observed sea-salt particles on board the ice breaker "Fuji" from Tokyo to Antarctica. The former observed the salt-mass distribution of sea-salt particles at a certain height above the sea surface, and the latter discussed the geographical distribution of sea-salt particles by comparing the data with Toba's (1966) estimated distribution. These articles do not afford the basic data for the study of the production rate of sea-salt particles on the sea surface, because they are not concerned with the vertical distribution of sea-salt particles in the sea-surface boundary layer.

The vertical distribution of sea-salt particles in the sea-surface boundary layer was theoretically predicted in Toba's study (1965a), but the actual distribution above the sea surface is still unknown.

In this report, the results of observetions of sea-salt particles, on board the Kagoshima Maru in the cruise of the International Indian Ocean Expedition (IIOE) are presented, and especially the distribution of sea-salt particles in the sea-surface boundary layer are discussed.

2. Procedure of the observation of sea-salt particles

In order to observe the sea-salt particles, a hand operated impactor and a halide ion-sensitive film, described by Toba and Tanaka (1967), was used. At each run of the observation, six different volumes of air were sampled by the impactor to obtain six spots on the film. We selected one spot in which sea-salt particles distributed in a most suitable number among the six spots, by use of the microscopic photograph, and counted the number of particles for each class of mass of salt. For the selected spots, the volume of air impacted varied from 100cc to 1000cc, mostly around 400cc. In the impaction of air by the jet impactor, there is a possibility that particles once collected on the sampling surface may be blown off again by the air jet. Therefore, the number concentration of sea-salt particles (particle number per unit volume) should be corrected by the retention factor as a function of the volume of air impacted as described by Toba and Tanaka (1967). In this report, the data are all normalized as in the case where 100 cc of air is impacted, the retention factor being 0.92 for 100 cc of air impacted. According to Toba and Tanaka (1968), it is significant for the determination of the amount and the distribution of sea-salt particles that the counted particle number is larger than several tens. In this observation, there were some spots in which particle number was smaller than several tens. Consequently, it may not be fully significant to discuss the amount and the distribution of sea-salt particle for individual runs. However, it is considered that the data are sufficient to discuss the mean aspects of the amount and distribution of sea-salt particles in the sea-surface boundary layer, by the use of all the data of observation.

The observations of sea-salt particles in this study were carried out along the observation line of the Kagoshima Maru (1038.4 ton), Kagoshima University, in her cruise of the International Indian Ocean Expedition (IIOE), in the period of Dec. 1963 through Jan. 1964, as shown in Fig. 1. The black circles entered along the observation line indicate the point of observation and the number of observations. The sampling places on board are three heights : the main deck, the boat deck and the flying bridge deck as shown in Fig. 2, the heights being about 2 m, 4 m and 9 m above the sea surface, respectively. The sampling of sea-salt particles were carried out every two or three hours in stations during the drifting of the vessel. The total number of observations were 196, including 21 which is lacking in data at a height. Throughout the cruise, the routine observations of surface meteorological elements, i.e., the wind direction, the wind speed, the air temperature, the humidity, the amount of cloud, the visibility and the sea-surface temperature, were carried out every two hours. Also, the photographs of the sea surface were taken at the observation time during the day time. Several examples of wind and humidity profiles obtained during this cruise were discussed by Takahashi (1965).

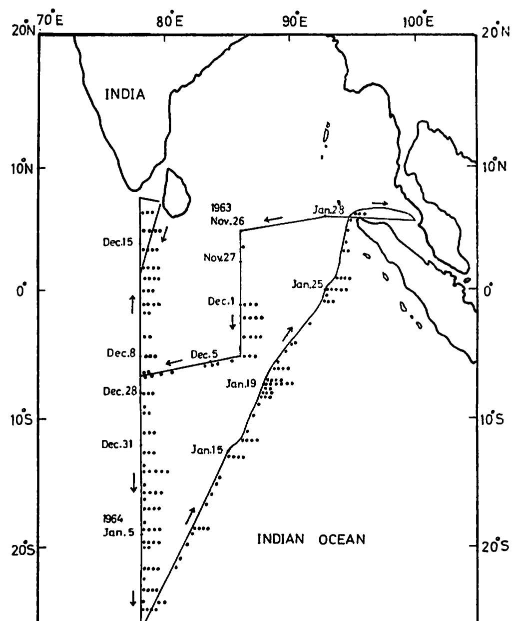


Fig. 1. Map showing the observation stations. Black circles indicate the location and the number of observations of sea-salt particles.

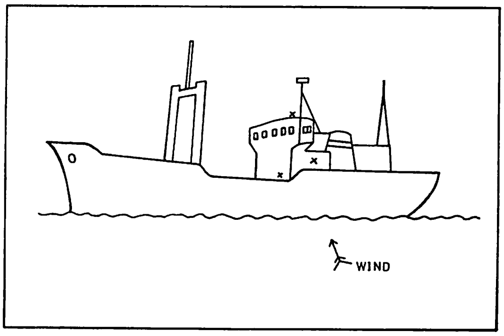


Fig. 2. Sampling places (cross marks) on board the Kagoshima Maru.

3. Results of the observations of sea-salt particles and the general meteorological conditions along the observation line

In Fig, 3 are shown the number concentrations of sea-salt particles larger than 1.9×10^{-11} gm in mass of salt ($\log m = 0.5, m:$ 10^{-12} gm unit). The values are normarized as in the case where 100cc of air is impacted, as described in the previous section. The local mean time is adopted as the observation time. In this figure, the wind speed interpolated to 10 m level above the sea surface by the logarithmic law is shown, as one of the maritime meteorological elements at the time of sampling. Passages of the squall and rain on the observation line are indicated by the letters "S" and "R", respectively. By eye observation, it was difficult to distinguish between squall and rain, with the exception of a typical squall. The rain caused by the passage of fronts is also indicated by the letter "R". As the other meteorological elements, the air temperature, the sea-surface temperature and the relative humidity observed along the meridian of 78°E are shown in Fig. 4, and their diurnal variations in the region from 5°S

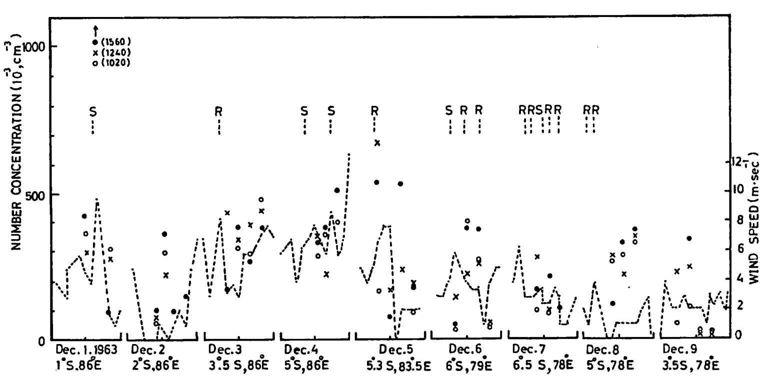


Fig. 3. Number concentration of sea-salt particles of log m>0.5 and wind speed (doted line) along the observation line of IIOE. Capital letters "S" and "R" represent squall and rain, respectively.
Height above the sea surface: black circles, 2m ; crosses, 4m ; circles, 9m.

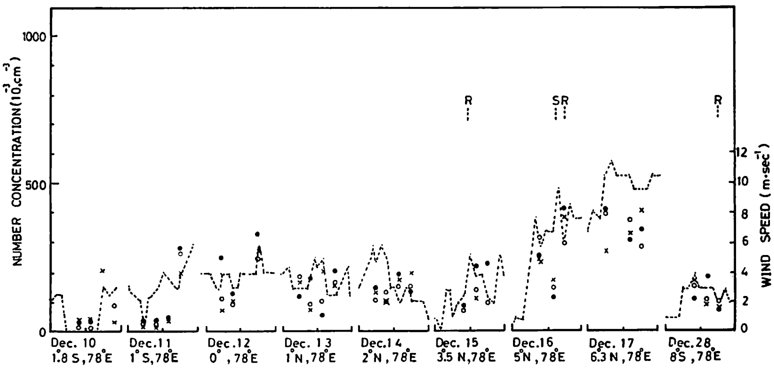
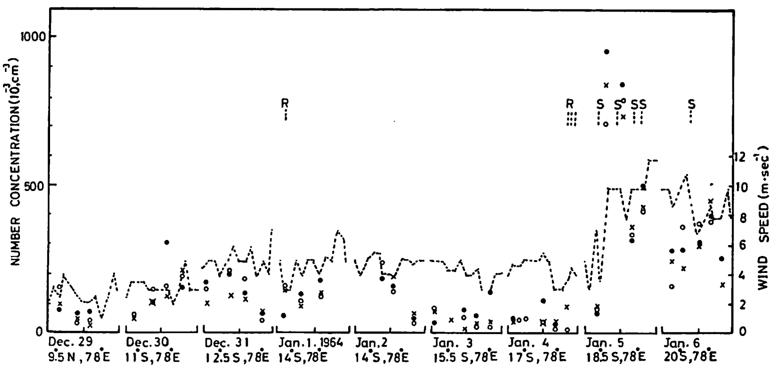


Fig. 3. (continued)



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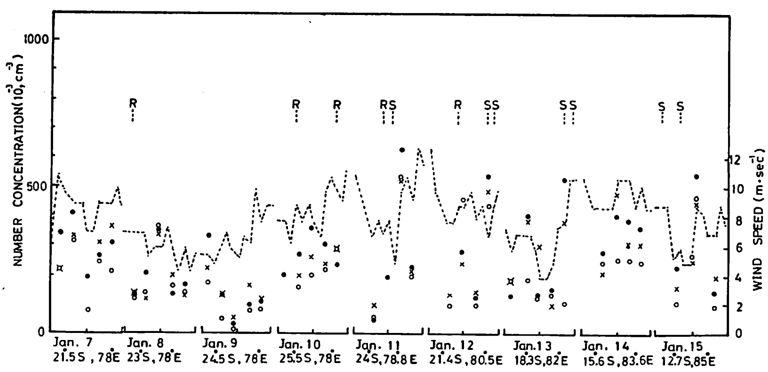
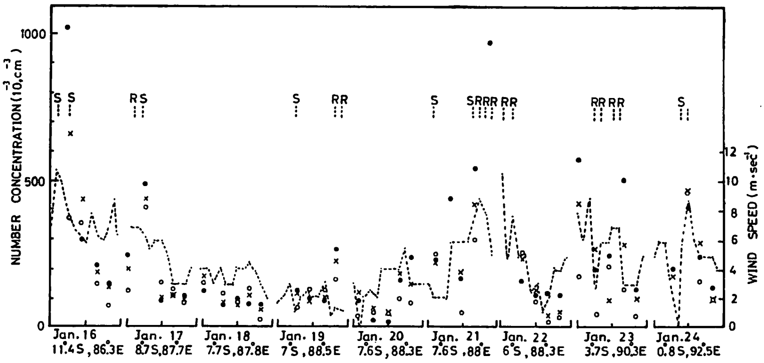


Fig. 3. (continued)

to 3°N along the same meridian, on Dec. 8 through 16, are shown in Fig. 5, where the weather was partly cloudy.

In the period of this observation, the wind ranged from calm to 12 m/sec in speed, and the strong breeze often occurred during the passage of squall or rain, as shown in Fig. 3. The air temperature and the sea-surface temperature along the meridian of 78°E showed that the former was about 0.5–1.0°C lower than the



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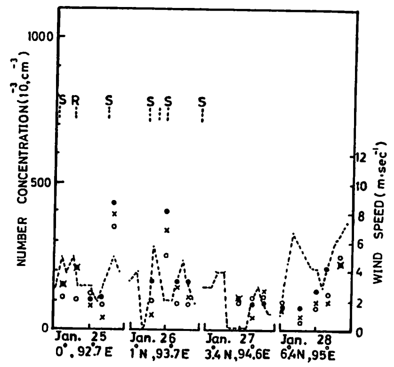

Fig. 3. (continued)

latter. Almost all values of the relative humidity along the same meridian was between 90% and 70%. The air temperature and the sea-surface temperature under the partly cloudy conditions showed that the diurnal variations both had a maximum at around 14 : 00 and a minimum at around 04 : 00, and their diurnal ranges were about 2°C in air temperature and about 1°C in sea-surface temperature. The relative humidity under the same condition showed the diurnal variation with a maximum at 22 : 00–00 : 00 and a minimum at 14 :00–16 : 00, and the diurnal range was about 10% in average.

The amount of the number concentration of sea-salt particles on the observation line seemed to follow the wind speed at the time of sampling. High values of the particle number concentration occurred at the area where the wind was strong, and where squalls often passed, on the other hand low values were found at the area where the wind was weak and the sea surface was smooth. These facts will be discussed in following sections.

4. Number concentration of sea-salt particles and its dependency on wind speed

In Fig. 6 are plotted the particle number concentrations against the wind speed at the time of sampling for all observation: (a) log $m>0.5$, (b) $0.5<\log m<$

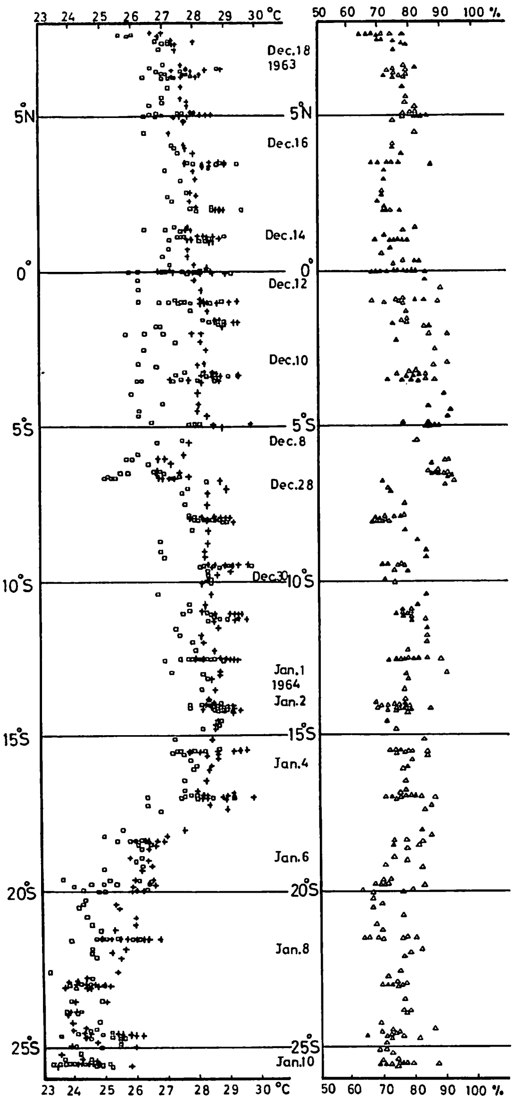

Fig. 4. Air temperature, sea-surface temperature and relative humidity observed every two hours along the meridian of 78°E. Symbols : squares, air temperature (°C) ; crosses, sea-surfaec temperature (°C) ; triangles, relative humidity (%).

1.5 and (c) log $m>1.5$. Points of particle number concentration scatter largely, but there is a tendency that the particle number concentration increases with wind speed. Though the particle number concentration does not increase with wind speed of lower than 3-4 m/sec, it begins to increase when the wind speed exceeds about 5 m/sec. The particle number concentrations in the case where squall or rain was observed within an hour before the sampling, showed high values as shown in Fig. 7. This seems to indicate that many sea-salt particles

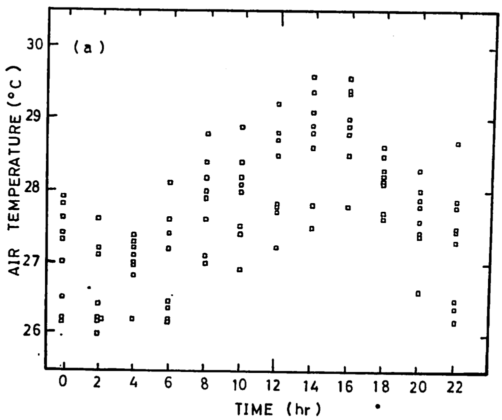

Fig. 5. Diurnal variations of air temperature (a), sea-surface temperature (b) and relative humidity (c) observed from 5°S to 3°N along the meridian of 78°E.

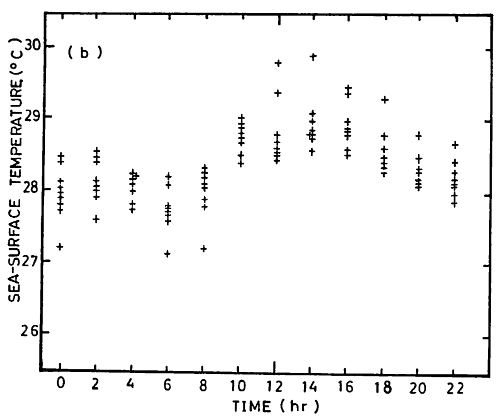

Fig. 5. (b)

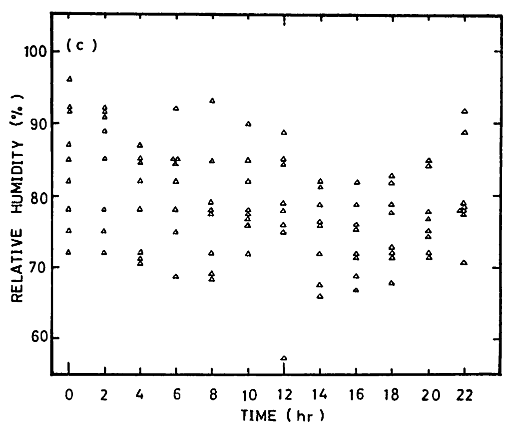

Fig. 5. (c)

are produced or concentrated in number by the temporary disturbance of the sea surface caused during the approach and the passage of squalls or fronts, although in general the value of the number concentration of sea-salt particles decreased due to the washout by precipitation. In Fig. 8 are plotted the particle number concentrations against the wind speed at the time of sampling, in the case where there was no precipitation, and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling. Values are entered only for the case that the counted particle number was larger than about 40 and that there was no lack of observation at a height among the three heights. As shown in the figure, the scattering of the points of particle number concentrations is relatively small compared with the case that squall or rain was observed within an hour before the sampling. The particle number concentration increases wind speed.

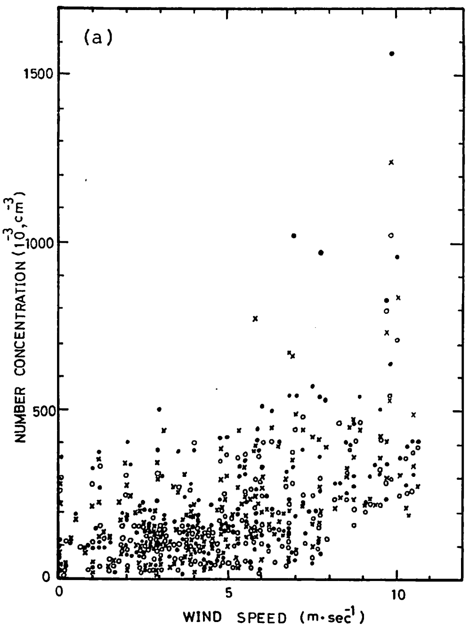

Fig. 6. Relation between number concentration of sea-salt particles and wind speed. (a) log $m > 0.5$, (b) $0.5 <$ log $m < 1.5$ (c) log $m > 1.5$.
Height above the sea surface: black circles, 2m; crosses, 4m ; circles, 9m.

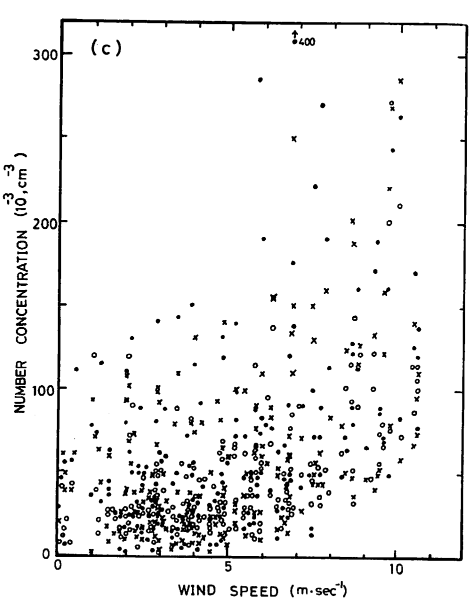

Fig. 6. (c)

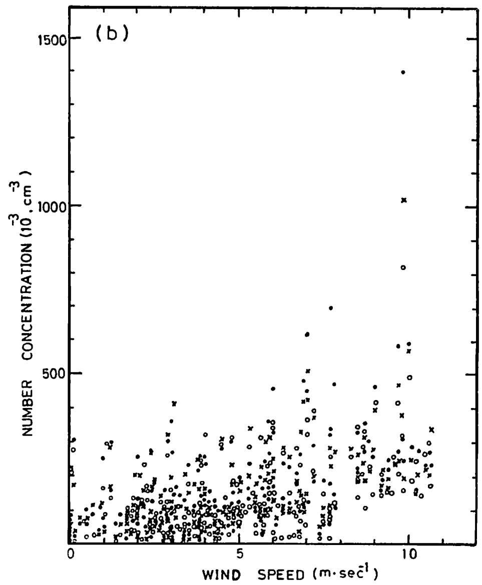

Fig. 6. (b)

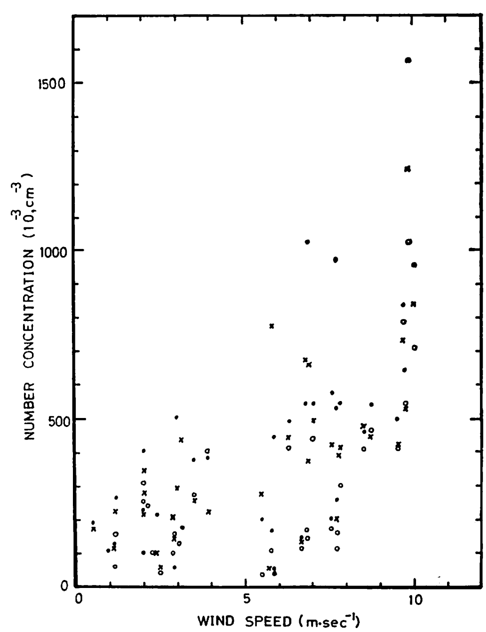

Fig. 7. Relation between number concentration of sea-salt particles (log $m >$ 0.5) and wind speed, in the case where squall or rain was observed within an hour before the sampling.
Height above the sea surface : black circles, 2m ; crosses, 4m ; circles, 9m.

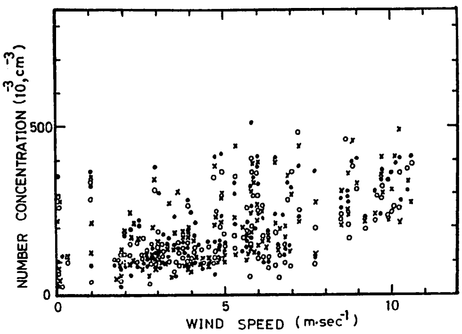

Fig. 8. Relation between number concentration of sea-salt particles (log m>0.5) and wind speed, in the case where there was no precipitation and no wind speed variation beyond a range of 4m/sec within two hours before the sampling. Height above the sea surface: black circles, 2m; crosses, 4m; circles, 9 m.

In order to obtain the relation between the particle number concentration and wind speed, mean values for every sampling height and for every wind force are calculated and then these values are discussed. The mean values for each class of log $m = 0.25$ are listed in Table 1. The number of observations are 11, 29, 30, 32 and 20 for wind forces 0-1, 2, 3, 4 and 5, respectively. The relation between the mean particle number concentration and wind force is shown in Fig. 9, for every salt-mass class of log m=0.5: (a) 0.75 <log m <1.25, (b) 1.25<log m<1.75 and (c) 1.75<log m <2.25 for three heights. The wind force is indicated on the abscissa by the median wind speed. In Fig. 9 (a) and (b), the value of the mean particle number concentration for wind force 0-1 is higher than that

Table 1. Mean number concentration of sea-salt particles (10^{-3}, cm^{-3}), in the case where there was no precipitation, and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling. Values of number concentration are normalized as in the case where 100cc of air is impacted, and where the retention factor is about 0.92.

Wind Force	No. of obs.	Height (m)	log m							
				1				2		
0-1	11	9	36.18	29.65	22.10	20.91	12.18	7.74	3.59	2.92
		4	31.33	32.54	21.63	21.64	17.12	7.45	5.00	3.37
		2	33.33	31.09	27.45	21.09	16.15	8.35	4.88	2.50
2	29	9	30.54	26.85	20.98	15.04	11.87	6.25	4.63	2.29
		4	32.61	23.42	25.93	16.41	13.78	7.86	4.60	3.47
		2	35.33	25.53	23.52	20.27	14.40	9.05	5.75	3.92
3	30	9	38.72	31.47	22.66	21.08	14.70	9.25	6.01	4.30
		4	40.62	31.06	25.68	21.25	17.12	10.71	7.02	5.30
		2	42.10	37.72	28.80	24.59	17.89	10.63	7.42	5.80
4	32	9	53.61	39.00	35.29	28.60	19.55	13.25	9.22	5.00
		4	59.64	43.08	39.09	32.40	21.90	14.83	10.36	4.90
		2	51.98	49.54	38.09	32.56	25.53	16.56	11.75	5.89
5	20	9	64.33	56.12	42.16	39.50	29.86	18.97	15.55	9.32
		4	67.54	60.05	53.81	35.51	32.12	21.24	17.61	11.73
		2	71.21	62.30	51.03	46.53	34.13	23.42	16.45	10.02

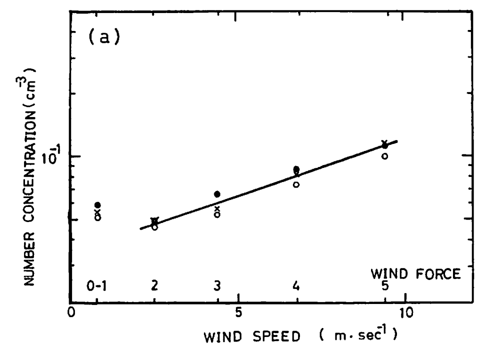

Fig. 9. Wind dependency of number concentration of sea-salt particles, in the case where there was no precipitation and no wind speed variation beyond a range of 4m/sec within two hours before the sampling. Values are entered for the ranges of log m=0.5 : (a) 0.75<log m<1.25, (b) 1.25<log m<1.75,(c) 1.75<log m<2.25. Height above the sea surface : black circles, 2m ; crosses, 4m ; circles, 9 m.

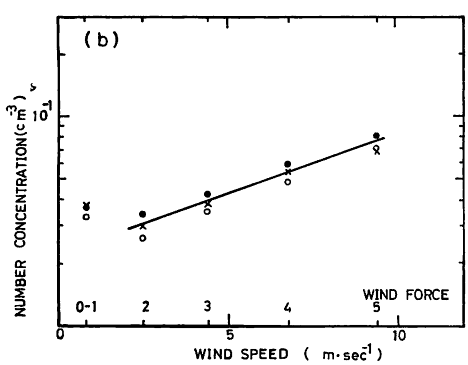

Fig. 9. (b)

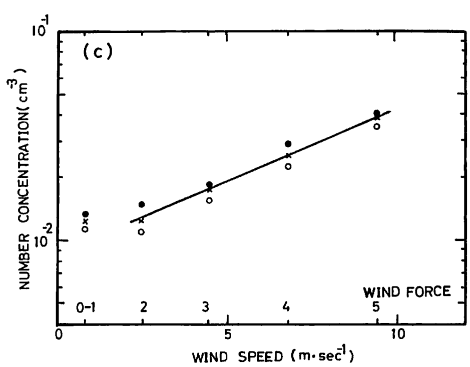

Fig. 9. (c)

for wind force 2. However, it is not reasonable to consider that there is a significant difference between the values for wind forces 0-1 and 2, since the number of observations for wind force 0-1 are small. The particle number concentration begins to increase from wind force 3. For wind forces stronger than 2, the relation between the particle number concentration and wind force (the median wind speed (m/sec) for each wind force) are obtained by the method of least squares. The dependency of the mean particle number concentration θ on wind speed u (the median wind speed (m/sec) for each wind force) for the average value of three heights are as follows :

$$\theta=35.3\,e^{0.12u} \qquad (0.75<\log m<1.25)$$
$$\theta=22.1e^{0.13u} \qquad (1.25<\log m<1.75)$$
$$\theta=8.4e^{0.16u} \qquad (1.75<\log m<2.25)$$

The value of wind factor increases with increasing salt mass. This seems to

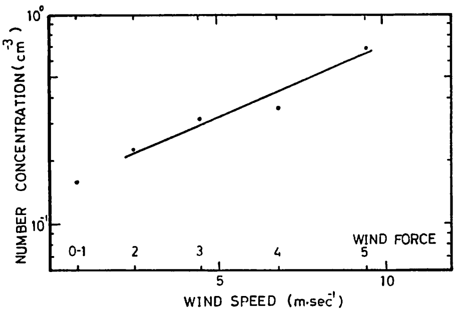

Fig. 10. Wind dependency of number concentration of sea-salt particles of log $m>0.5$, in the case where squall or rain was observed within an hour before the sampling.

indicate that the smaller the salt mass, the more it retains the effect of wind before the sampling.

In the case where squall or rain was observed within an hour before the sampling, the relation between the particle number concentration and wind force is shown in Fig. 10. In this figure, the particle number concentrations for log $m>0.5$ for three heights are all averaged, since the number of observations are small. For wind forces stronger than 2, the relation is as follows:

$$\theta=150\ e^{0.16u} \qquad (\log m>0.5)$$

The wind factor is the same as that of the third class of salt mass ($1.75<\log m<2.25$) in the case where there was no precipitation, and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling. Toba (1961) expressed the dependency of the rate of droplet production on wind speed (m/sec at 10 m level) approximately exp(0.40 u) in the range of the wind speed between 15 m/sec and 23 m/sec, using the results of the wind flume experiments. The wind factor is larger than that of our observation. However, both the results may not be compared directly with each other, since our results were obtained when the wind speed was smaller than 12 m/sec.

5. Mean salt-mass distribution of sea-salt particles for various wind forces

In Fig. 11 are shown the mean salt-mass distributions of sea-salt particles for three heights and wind forces, in the case where there was no precipitation and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling. The values are also listed in Table 1. In each wind force, the particle number concentration decreases with increasing salt mass, from log $m = 0.5$ to log $m = 2.5$. Concerning the shape of the curve of the salt-mass distributions, it is noted that the values for larger salt masses become relatively higher with increasing wind force. The mean salt-mass distributions for three heights for various wind forces are shown in Fig. 12, in which values are entered for the ranges of salt mass of log $m = 0.5$. In this figure, the mean salt-mass distribution for wind force 5 in the case where squall or rain was observed within an hour before the sampling is also shown. The values for wind 0-1 and 2 are nearly the same. With increasing wind force, the variation of the shape of the salt-mass distribution stated above is found. The shape of salt-mass distribution for wind force 5, in the case where squall or rain was observed within an hour before the sampling, indicates a relatively high value at around log $m = 2.0$-2.5. The salt-mass distribution for each wind force is com-

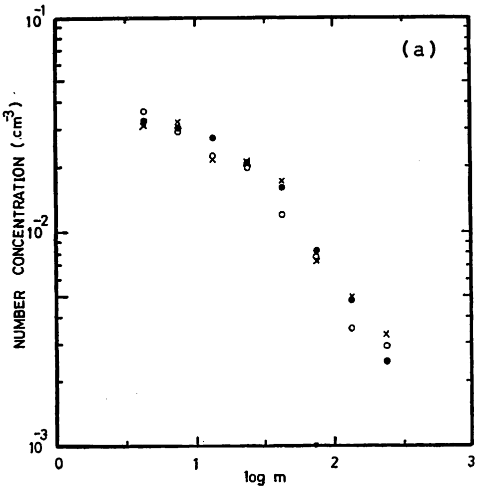

Fig. 11. Mean salt-mass distribution of sea-salt particles, in the case where there was no precipitation and no wind speed variation beyond a range of 4m/sec within two hours before the sampling. (a) W.F. O-1,(b) W.F. 2, (c) W.F. 3, (d) W.F. 4, (e) W.F. 5. Values are entered for the range of log *m*=0.25. Height above the sea surface: black circles, 2m; crosses, 4m; circles, 9m.

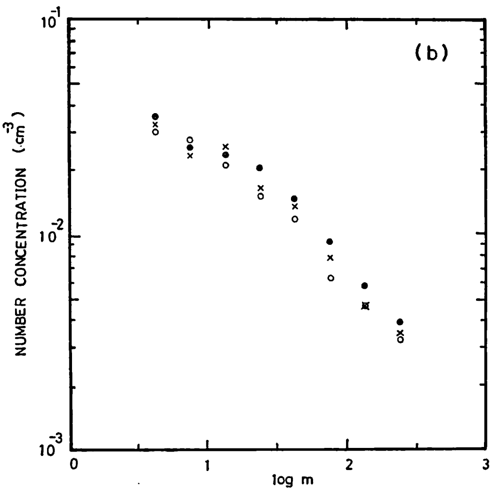

Fig. 11. (b)

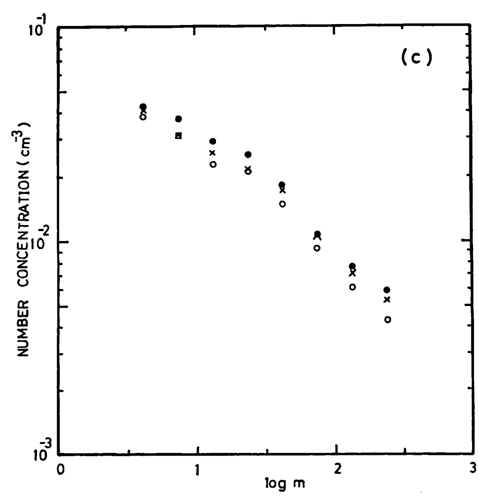

Fig. 11. (c)

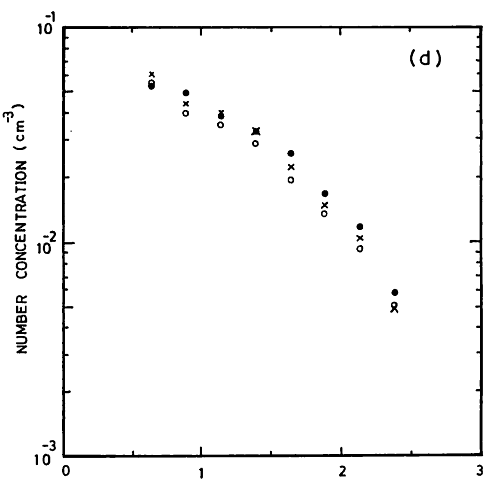

Fig. 11. (d)

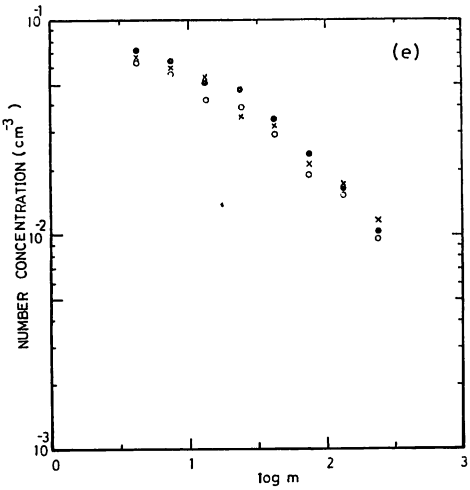

Fig. 11. (e)

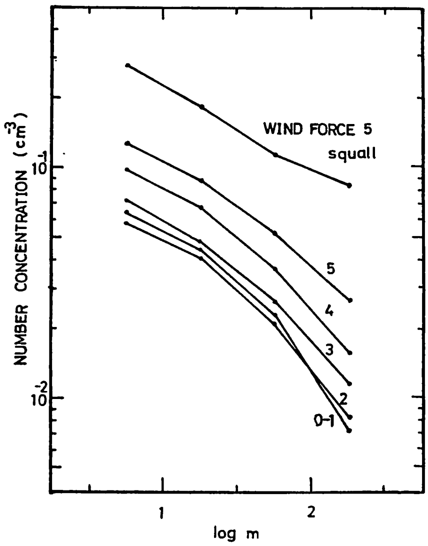

Fig. 12. Mean salt-mass distribution of sea-salt particles in the sea-surface boundary layer. Values are entered for the range of log m=0.5.

pared with that of the 10 m layer above the sea surface, derived from the cloud base level data of Woodcock by means of the theory concerning the vertical distribution of sea-salt particles in the atmosphere (Toba, 1965). The amount of the former is about one half of that of the latter. The amount of particle number concentration in each salt-mass class for wind force 5, in the case where squall or rain was observed within an hour before the sampling, is about two times of that in the case where there was no precipitation and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling. Consequently, the values for wind force 5 in the case of squall or rain agree with the values derived by Toba (1965).

6. Mean vertical distribution of sea-salt particles for various wind forces

In Fig. 13 are shown the mean vertical distributions of sea-salt particles in the case where there was no precipitation, and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling (the values are listed in Table 1). They are shown by three classes of salt mass, i. e., $0.75 < \log m < 1.25$, $1.25 < \log m < 1.75$, $1.75 < \log m < 2.25$. Values are shown for each salt-mass class of the range of log m = 0.5. Inspecting Fig. 13, it is seen that the mean vertical distribution of sea-salt particles has a curve close to a straight line in a logarithmic diagram.

Concerning the vertical distribution of sea-salt particles in the sea-surface boundary layer, a relative humidity equilibrium theory is proposed by Toba (1965a). In this theory, it was assumed that the size of sea-salt particles is always in equilibrium with the relative humidity at the height under consideration. The vertical distribution of sea-salt particles predicted by this theory was expressed by

$$\log(\theta/\theta_0) = -m^{2/3} \cdot u_l^{-1} \cdot X(RH_l, \gamma_l, z),$$

where θ and θ_0 is the particle number concentration at the height z and at the sea surface, respectively, m the salt mass, u the wind speed, RH the relative

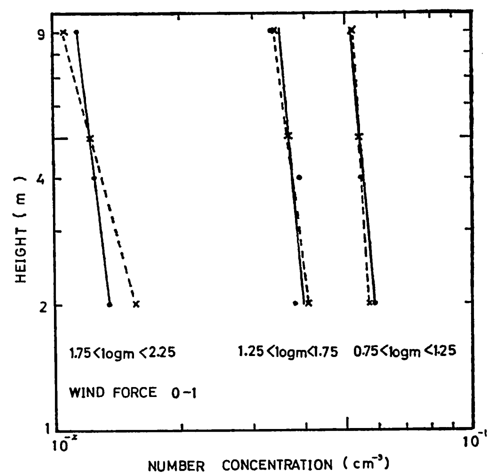

Fig. 13. Mean observed vertical distribution of sea-salt particles (solid line). (a) W. F. 0-1, (b) W. F. 2, (c) W. F. 3, (d) W. F. 4, (e) W. F. 5. Values are entered for the range of log m=0.5. Theoretical vertical distribution of sea-salt particles calculated by Toba's model are entered (dashed line).
In the calculation, RH_l=90 %, m=median value of the range of log m=0.5, u_l=median value of wind speed in each wind force are adopted.

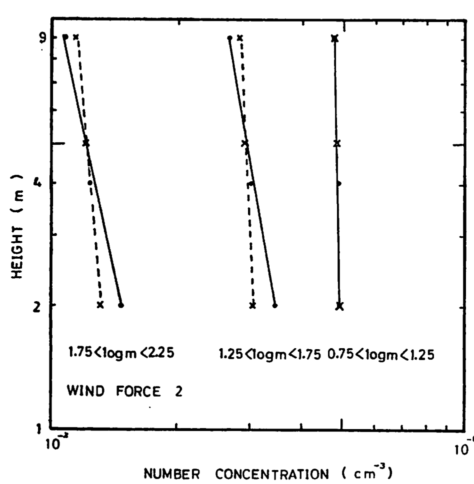

Fig. 13. (b)

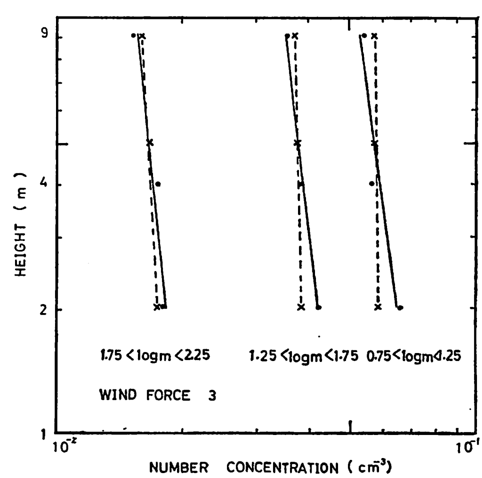

Fig. 13. (c)

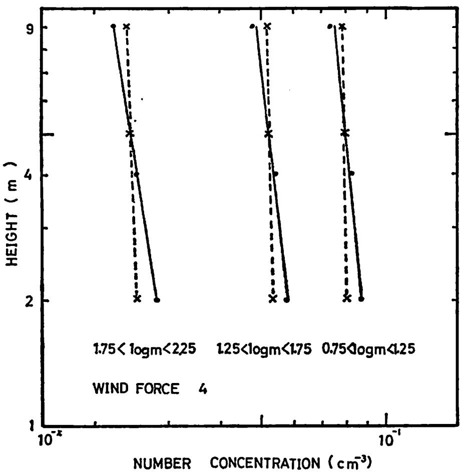

Fig. 13. (d)

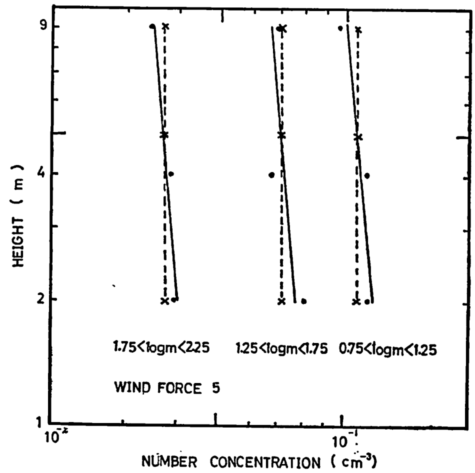

Fig. 13. (e)

humidity, γ_l^2 the drag coefficient, and the subscript l represents the 10 m level, and z the height above the sea surface. Though the variable, X, is a function of RH_l, γ_l and z, the value of γ_l is assumed constant under the condition of the wind speed from about 3 m/sec to 15 m/sec. Therefore, the value of X is a function only of RH_l for a given z. The vertical distribution of sea-salt particles in this theory is expressed as a function of m, u and RH_l. If we plot log θ against log z, it is approximately distributed by a straight line on a logarithmic diagram. According to this theory, the higher the relative humidity and the weaker the wind speed, the more the particle number concentration decreases with height. On the other hand, the lower the relative humidity and the stronger the wind speed, the more the particle number concentration is distributed nearly uniformly in the boundary layer.

In our observation, the mean vertical distributions of sea-salt particles for wind forces 0–1 and 2 have a weak gradient for the class of small salt mass ($0.75 < \log m < 1.25$) and a relatively strong gradient for the class of large salt mass ($1.75 < \log m < 2.25$). For wind forces 3, 4 and 5, the gradients of the three classes of salt mass are nearly the same. The theoretical vertical distribution is calculated by Toba's theory, where RH_l of the effective RH of 90 % in this observation (as shown in Fig. 4 and 5), u of the median of each wind force, and m of the median of each salt-mass class are used. The theoretical distribution is entered by dashed lines in Fig. 13, which cross the observed one at the height $z = 5$ m, because the abscissa is θ/θ_0 in the theoretical model. In comparison with the vertical gradient of observed distribution to the theoretical one, the good agreement between the two is found for smaller salt masses for lower wind speeds, and otherwise a tendency is seen that the observed gradient is a little stronger than that of the theoretical one.

7. Summary

In the cruise of the International Indian Ocean Expedition (IIOE), in the period from December 1963 to January 1964, the observatins of sea-salt particles were carried out at three heights above the sea surface on board the Kagoshima Maru, Kagoshima University. The mean salt mass and the vertical distributions of sea-salt particles in the sea-surface boundary layer have been mainly studied besed on the results of the observation.

The particle number concentrations of sea-salt particles had a large amount in the area where the wind speed was strong, and relatively small amount was found in the area where the wind speed was weak. Then, the large amount of sea-salt particles was often found at the area where squalls or rains were observed. The particle number concentration increases with wind speed, though the points plotted against the wind speed scattered largely. The relation between the mean particle number concentrations and wind speed may be approximately expressed by an exponential function. The wind factor in the case where there was no precipitation is a little large for the larger salt masses compared with that for smaller salt masses. The wind factor for log $m>0.5$ in the case where squall or rain was observed within an hour before the sampling is nearly the same with that for larger salt mass in the case stated above.

The mean salt-mass distributions for various wind forces are presented, the particle number concentration decreases with increasing salt mass from log $m=0.5$ to log $m = 2.5$. Concerning the shape of salt-mass distribution curves, values of the particle number concentration for larger salt masses becomes relatively high with increasing wind force. In wind force 5, the amount of particle numder concentration for each salt-mass class, in the case where squall or rain was observed within an hour before the sampling, is large compared with that in the case where there was no precipitation and no wind speed variation beyond a range of 4 m/sec within two hours before the sampling, by a factor of two.

The vertical distribution of the mean particle number concentration of three salt-mass classes is approximately distributed by a straight line on the logarithmic diagram of log θ- log z. The vertical gradient is weak for smaller salt masses, and strong for larger salt masses for wind forces 0-1 and 2, and is nearly in the same degree for each salt-mass class for wind force 3, 4 and 5. The theoretical vertical distribution is calculated by means of Toba's theory (1965a) under the condition of RH_t of 90 %. A comparison of observed vertical gradients with the theoretical ones shows a good agreement for the smaller salt masses for wind forces 0-1 and 2, and the observed gradients are a little stronger than the theoretical ones for wind forces 3, 4 and 5.

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