The Extension of Air Pollution from Land over Ocean as Revealed in the Variation of Atmospheric Electric Conductivity

By M. Misaki* and T. Takeuti**

Abstract

The atmospheric electric conductivity and potential gradient were measured aboard the Icebreaker "Fuji", an antarctic observation ship, during her test cruise around the Japan Islands in October 1966.

The electric conductivity was found to vary with distance from the coastline, reflecting the effect of atmospheric pollution extending from land sources over the ocean by diffusion. Analysis of the data obtained shows that the conductivity was determined almost uniquely as a function of distance from the coastline when the weather was clear.

1. Introduction

After the observation by the Carnegie from 1915 to 1929, little has been reported on the measurement of atmospheric electric elements over the ocean. Condensation nuclei were investigated over the Atlantic Ocean by Hess (1948), Moore and Mason (1952), Woodcock (1953). Most of them were exclusively concerned with salt nuclei.

Parkinson and Weller (1953) made atmospheric electric measurements over the North Atlantic Ocean. The arguments in their paper were concentrated on the combination coefficient between small ions and nuclei in mid-ocean.

Ruttenberg and Holzer (1955) made measurements of atmospheric electric field intensity and conductivity over the Pacific Ocean during the five-month cruise of the R/V Horizon. They found their results in striking agreement with those of the Carnegie.

Atmospheric pollution of land origin is one of the important factors which control the electrical properties of the atmosphere over the ocean. In his comprehensive work on atmospheric pollution, Ohta (1965) dealt with the horizontal distribution of air pollution in association with the air streamline.

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On the basis of the aircraft experiments over the Atlantic Ocean, Sagalyn (1958) discussed the modification of electrical properties of an air-mass due to the alteration of pollution particles when the air-mass, leaving the continent, travels out over the ocean.

In 1965, Mühleisen made measurements of electric field, small ion concentration and space charge density over the Atlantic Ocean during the expedition of the Research Vessel "Meteor", attempting to correlate the potential gradient at sea and the voltage between ionosphere and earth measured over land (Mühleisen, 1968).

Since atmospheric electric phenomena over the ocean are rather simple because of less local disturbances than over land, discussions have been concerned primarily with large-scale phenomena or the global aspects.

In October 1966, measurements of atmospheric electric field intensity and conductivity were made aboard the antarctic observation ship "Fuji" during her test cruise around the Japan Islands. The discussions described in the present paper are based on the results of two series of measurements made on the Pacific Ocean and on the Sea of Japan.

Since the course of the cruise was taken close to land, atmospheric electric parameters were affected more or less by pollutions of land origin. The present discussion is therefore focussed on the local effects rather than the global aspects.

2. Instrumentation

The Gerdien apparatus used for measurements of electric conductivity has the following dimensions: the diameters of the outer and inner electrodes are 95.6 mm and 50.0 mm respectively, the length of the electrode is 600 mm. Thus the apparatus has the critical mobility of 2.15×10^{-4} m^2/V. sec, at a considerably low driving voltage, 6 V, and a sufficiently large air flow rate, 450 liter/min.

The apparatus was placed on the flag deck immediately behind the navigation bridge and about 14 m above the sea surface, with the opening of the chamber facing the ship's side. Positive and negative polar conductivities were recorded alternately, with the aid of a vibrating reed electrometer and a recorder, by switching the sign of voltage applied to the chamber every five minutes. The zero level was checked every three hours by automatically stopping the air flow through the chamber.

A portable field-mill developed at Kyoto University was placed on a pole of 150 cm length at a corner of the highest deck (the roof of the navigation bridge) which was about 2 m higher than the flag deck.

The observation spots were well apart from the main drafts or the stacks in the bow direction, so that the measurements were free from the pollution from the ship itself throughout the cruise.

3. Results of the electric conductivity measurements

Fig. 1 shows the course of the cruise, with the wind data obtained every hour. The first half of the cruise lay northward on the Pacific Ocean along the coastline of Honshu. It began from Yokosuka at 14 h, October 5, 1966, passed through the Tsugaru Straight on the morning of October 7, and ended at Otaru early on the

morning of October 8. Two days later, the latter half of the cruise started from Otaru. Its course lay over the Sea of Japan, and ended at Maizuru at noon of October 12.

The electric conductivity measured in the first half of the cruise is shown in Fig. 2 a. Before leaving the port, the conductivity was extremely low as was to be expected, because Yokosuka and its vicinity is a heavily industrialized area. As soon as the ship went out of Tokyo Bay, the conductivity began to increase markedly, and reached up to the value of 1.2×10^{-14} mho/m at 21 h 30 m of the same day. After that, the conductivity remained fairly stable, ranging between 1.0×10^{-14} and 1.4×10^{-14} mho/m till 02 h 30 m,
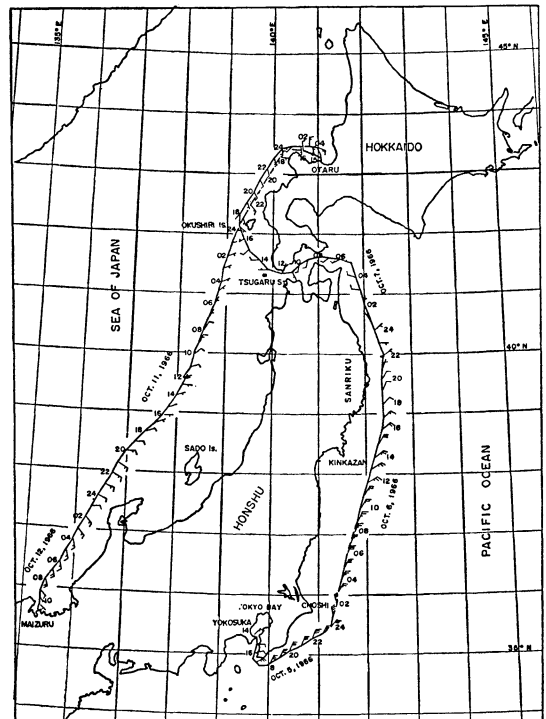
Fig. 1 The cruising course of the FUJI during the period from October 5th to 12th, 1966.
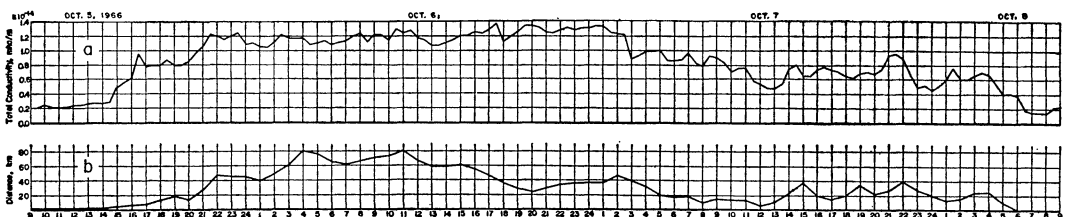
Fig. 2 Variation of electric conductivity (a), variation of distance from the coastline (b), during the first half of the cruise (over the Pacific Ocean).

October 7, and then decreased until entering the port at Otaru.

As the ship approached or departed from the coastline as seen in Fig. 1, the conductivity decreased or increased correspondingly. A careful examination of Figs. 1 and 2a will reveal a close relation between conductivity and distance from the coastline. For instance, after the first maximum of conductivity appeared at 21 h 30 m, October 5, it decreased slightly as the ship approached to Cape Choshi. The same situation was found at the point close to Cape kinkazan (13 h 30 m, Oct. 6). During the passage through the Tsugaru Straight (07 h-13 h, Oct. 7), the conductivity fell down to less than 0.9×10^{-14}mho/m. The minimum occurred between 12 h and 13 h when the ship was going through the narrow passage between a cape and a small island at the exit of the straight. The only exception to this was found at the approach to the coastline of Sanriku when the conductivity did not decrease but remained at a high value.

The variation of distance with time between the ship and the coastline is plotted in Fig. 2b for the sake of comparison with the variation in conductivity. "Distance" at a given point on the course was determined simply by the distance from the ship to the nearest coast, disregarding the direction of the distance-measuring line, as illustrated in Fig. 3.

Since the conductivity is in inverse proportion to the concentration of aerosol particles in the atmosphere, its variation reflects the extent of atmospheric pollution. As we go away to the mid-ocean, the air will be clean, and the conductivity will reach its maximum value, only the aerosol particles such as salt nuclei, inherent in marine air, working against it. The closer we approach the land, the more significantly the air will be affected by pollutions of land origin, resulting in a decrease in conductivity.

When we assume a simple model for the distribution of air pollution over the ocean which decreases exponentially in its concentration with increasing distance from the coast, then the concentration of aerosol particles, N, over the ocean takes the following form:

$$N = N_0 + N_c e^{-\alpha D} \qquad (1)$$

where N_0 is the concentration of aerosol particles inherent in marine air, N_c is that of pollution
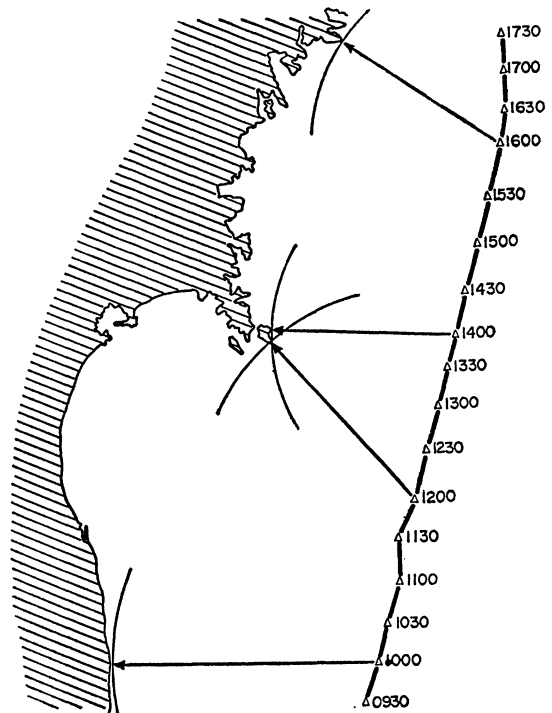

Fig. 3 Determination of "distance" from the coastline.

particles over land, α is the decaying factor, and D is distance from the coastline.

Consequently the conductivity can be expressed as a function of the distance D as

$$\lambda = \text{const.} \times (N_0 + N_c e^{-\alpha D})^{-1}$$

$$\doteqdot \text{const.} \times \frac{1}{N_0} \left(1 - \frac{N_c}{N_0} e^{-\alpha D} \right)$$

$$= \text{const.} \times \frac{1}{N_0} (1 - e^{C-\alpha D}) \qquad (2)$$

The approximation in Eq. (2) holds valid for D that makes $\dfrac{N_c}{N_0} e^{-\alpha D} < 1$. When D is large enough, the constant C can be ignored, and we get the simplest formula relating conductivity with distance as

$$\lambda = \lambda_\infty (1 - e^{-\alpha D}) \qquad (3)$$

After some trial calculations were made so as to get the best agreement with the observed values of conductivity, λ_∞ and α were determined as 1.35×10^{-14}mho/m and 0.06/km respectively when D is expressed in km.
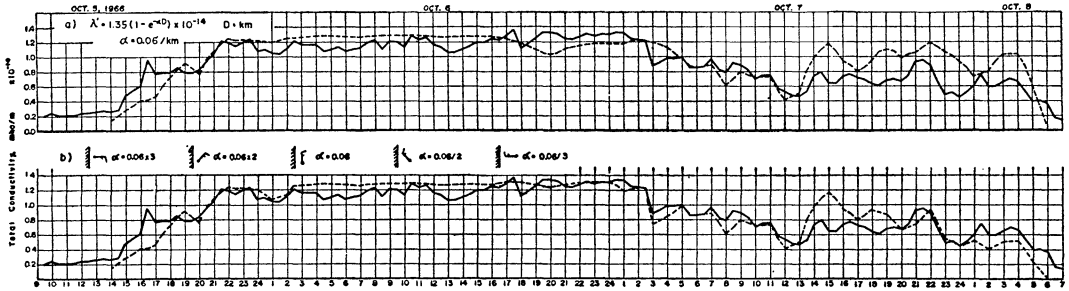
Fig. 4 (a): Comparison of the observed (the solid line) and the estimated conductivity (the broken line)
by Eq. (3).

(b): The broken line shows the estimated conductivity with α adjusted according to wind direction.
The solid line is the same as in (a).

Fig. 4a shows a comparison between the two values : the solid line indicating the observed conductivity and the broken line the estimated one according to Eq. (3). Fairly good agreement can be seen in this figure, except for the final stage after 13 h, October 7.

Looking back on Fig. 1, an abrupt change in the wind direction is found between 02 h and 03 h, October 7, which is closely associated with a rapid decrease in conductivity. It will be reasonable to suppose that when the wind blows landward, the extension of air pollution over the sea is restricted near the coast, and that faster increase with distance should occur in conductivity. Therefore, adjustments were made on the value of α depending on wind directions. In the first place, wind directions are classified into the following five cases:

Case 1 Wind direction perpendicular to the coastline from sea to land,

Case 2 Wind direction oblique to the coastline from sea to land,

Case 3 Wind direction parallel to the coastline,

Case 4 Wind direction oblique to the coastline from land to sea,

Case 5 Wind direction perpendicular to the coastline from land to sea.

For each case from 1 to 5, α was multiplied by the factors 3, 2, 1, 1/2, and 1/3, respectively. The recalculated curve with thus determined αs is shown in Fig. 4b by a broken line in the same way as in Fig. 4a. Agreement with the observed curve becomes better as seen in this figure.

The observational results obtained during the latter half of the cruise are shown in Fig. 5a, in which the conductivities observed and estimated are given by solid and broken lines respectively. The variation of distance from the coastline is given in (b) in the same way as in Fig. 4.

The observed conductivity curve is again in good agreement with the estimated one until 03 h, October 11. After that time, however, it gradually
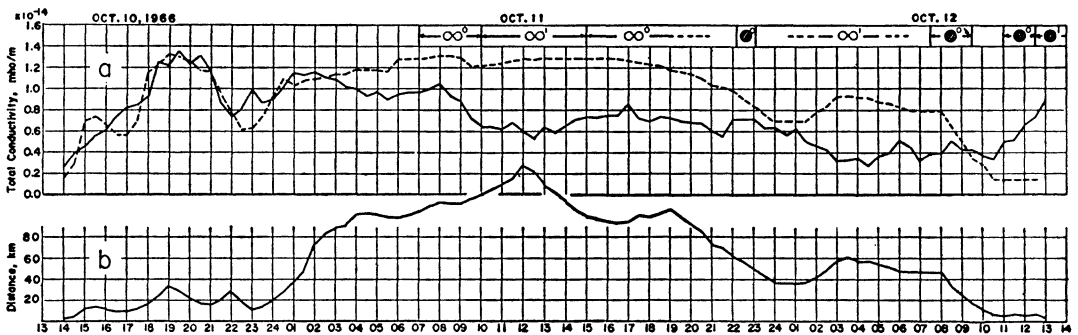

Fig. 5 Variation of the observed (the solid line) and the estimated conductivity (the broken line) by Eq. (3) with adjusted α (a), and the variation of distance from the coastline (b), during the latter half of the cruise (over the Sea of Japan).

falls down far from the expected values. The variation in conductivity after 10 h, October 11, does not seem to have correlation with distance from the coast any more.

The disagreement between the observed and the estimated curves can be reduced to difference in weather conditions. Throughout the period of the first series of measurements the weather was absolutely clear, but during the cruise on the Sea of Japan it kept getting worse: cloudy on October 10, cloudy and hazy with temporary rain on October 11, and rainy on October 12.

So long as good agreement was found at least for the first period of this series (14 h, Oct. 10—03 h, Oct. 11), it may be considered that the relation expressed by Eq. (3) still holds in this case between conductivity, distance from land, and wind direction, provided the weather is free from haze. Gradual departure of the conductivity from the expected values may be attributed to the haze which was noted from 07 h, October 11. Disturbances in the conductivity that occurred on the morning of October 12 were obviously caused by rain.

4. Results of the electric field measurements

The variation of the atmospheric electric field intensity obtained by the use of a field-mill is shown in Fig. 6 (the solid line), together with that of the air-earth current density (the broken line) derived as the product of the field intensity and the conductivity. For comparison, the mean diurnal variation of air-earth current density for the cruise of the R/V Horizon (Ruttenberg and Holzer, 1955) is also shown by a dotted line. in the same figure. The magnitudes of the field and the current intensity for our measurements are given in an arbitrary scale because the reduction factor for the field apparatus was not determined.

Although the cruise took a course near the land rather than in mid-ocean, a tendency somewhat resembling to the global variation can be seen especially in the air-earth current graph. Not much, however, can be drawn from those limited data. Fig. 6 is given just for the sake of reference.

5. Discussion

In the preceding section we described the very close relation between conductivity on the ocean and distance from the coastline. In the first series of measurement from October 5th to 8th, even an approach to a small, almost uninhabited island introduced a significant effect on the magnitude of conductivity. Such a close relation is well expressed by Eq. (3); it is based on the concept that the atmospheric pollution originating on the land and extending over the sea by diffusion reduces the small ion concentration and consequently the electric conductivity. Therefore, the rate of increase in electric conductivity with distance from land is to be considered to represent the rate of decrease in atmospheric pollution.

According to Eq. (3), λ tends to 1.35×10^{-14} mho/m with increasing D. This value is considerably low as compared with the values found by other authors over the mid-ocean (Ruttenberg and Holzer, 1955, Sagalyn, 1958). Throughout the period of our experiment, however, the conductivity never exceeded 1.4×10^{-14} mho/m.

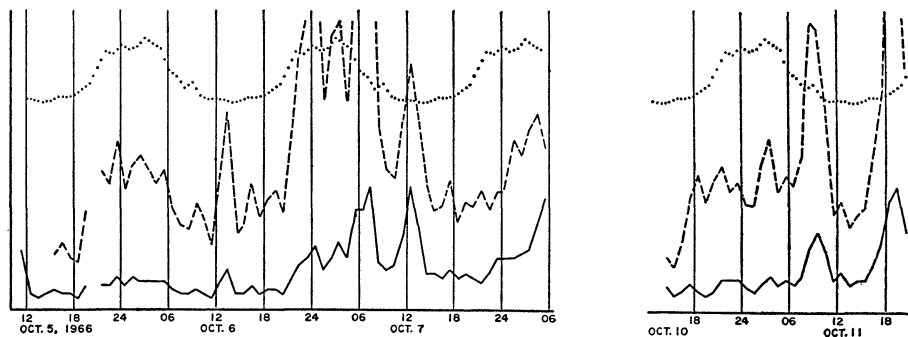It is interesting to refer at this point the recent

Fig. 6 Variation of the electric field intensity (the solid line) and the air-earth current density (the broken line) during the cruise. The dotted line shows mean diurnal variation of the air-earth current density obtained by Ruttenberg and Holzer, 1955. Scales are arbitrary.

work made by Mühleisen (1968). During the Atlantic expedition of the research vessel "Meteor", he found the average concentration of small ions on the ocean was smaller than values of other authors by a factor of 2 or 3, being 310 cm^{-3} for positive and 220 cm^{-3} for negative ions. His result gives the value of 1.03×10^{-14} mho/m as the average conductivity over the ocean when we apply the values 1.16×10^{-4} and 1.30×10^{-4} m^2/V.sec (Misaki and Kanazawa, 1969) for the effective mobility of positive and negative small ions respectively. Mühleisen's result agrees fairly well with ours.

Eq. (3) is written in the simplest form involving only a few parameters, and so obviously has some limitations to be considered.

(1) Eq. (3) can not be applied within a certain distance, say, 10 km, as was described in its derivation. Within such a short distance from the coast, the electrical properties of the atmosphere must be complicated. In the first place, a considerable increase in the ion production rate must be found when we approach the land, as a result of the diffusion of radioactive substances from land to ocean. The variation of ion production rate as a function of distance from the coastline is an important parameter to be determined.

The extension of the radioactive substances over the ocean may be confined closer to land as compared with that of atmospheric pollution because of their limited life time. However, so long as Eq. (3) is considered to reflect the distribution of air pollution, a uniform distribution of the ion production rate is tacitly assumed over the ocean. Eq. (3) can not be valid in areas very close to land in this respect, either.

The electrical characteristics in transition from land to ocean is a significant problem. Sagalyn (1958) found in her aircraft experiments that the conductivity in the exchange layer over the ocean is almost the same with that over the continent, being 2.4×10^{-14} mho/m and 2.2×10^{-14} mho/m respectively at an altitude of 2000 ft. She explained it by comparing the parameters over land with those over the ocean: ion production rate, concentration of pollution particles, and combination coefficient between particles and small ions.

It still seems rather curious that all of these parameters, which take entirely different values in magnitude as between over ocean and over land

should work together to give the same magnitude of conductivity in the two cases. The question now arises how the conductivity changes in the transitional area between land and ocean in association with the change in the ion production rate and in the nucleous concentration. The problem will not be solved until we get full information on the distribution of those parameters near the coastline.

(2) Though the wind direction was taken into consideration, either the wind velocity or the trajectory of the air stream was disregarded.

(3) A uniform origin of atmospheric pollution was assumed over the land, disregarding the irregular distribution of industrial population.

Referring to (2) and (3), we may proceed with some further analysis, but it would not be realistic to make more complicated assumtions for the present limited data. Provided the weather is in a favorable condition, as in the case of the first series of measurements, we get a remarkable agreement between the observed conductivity and the estimated value according to distance from land. Thus, it can be concluded that the assumptions we made are not far from the actual condition.

6. Conclusions

Atmospheric electric conductivity over the ocean was found to vary with distance from land: Eq. (3) expressed in terms of the distance was proved to give the value in sufficient agreement with the observed value. The conductivity remained almost constant over the sea which is a certain distance away from the land, being 1.35×10^{-14} mho/m. When we approach within about 40 km of the coast, the conductivity decreases with decreasing distance.

Since no diurnal variation in conductivity has been found on the ocean, and also the ion production rate is believed to be constant everywhere over the ocean exept in areas very close to land, the variation appearing in electric conductivity should be attributed entirelv to the effect of atmospheric pollution.

Accordingly, it is concluded that the atmospheric pollution originated on land extends over the ocean and decays with distance exponentially, just as revealed in the variation in conductivity. The determined rate of increasing cnoductivity with

distance from land can be regarded as the rate of decreasing air pollution extending from the land source to the ocean.

Acknowledgements:

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大気電気伝導率変化に現われた大気汚染の陸上より海上への張り出し

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1966年9月，南極観測船"ふじ"の日本周航の機会に，大気電気伝導率と大気電場の観測を船上で行った．この結果，大気電気伝導率は船と陸地との距離の増減にしたがって変動することがわかった．観測された大気電気伝導率は距離に対し関係式（3）で極めて良く表わされる．

海上ではイオン生成率が一定であり，電気伝導率には日変化もないから，畑霧等がない限り，電気伝導率の変動は大気汚染の程度をそのまま反映するものである．したがって，陸地起源の汚染粒子は海上に可成りの距離まで張り出し，その濃度は距離とともに指数関数的に減少し，$N_c e^{-\alpha D}$（式（1））で表わされることが類推される．

大気電気伝導率と陸地よりの距離についての上記の関係式は極めて粗い近似であり，陸岸より極めて近いところでは適用されないし，また 100 km 以上については保証されない．しかし今回の観測結果だけをもとにして，これ以上の推定を進めることは無意味であり，むしろこの程度の粗さの近似でもよく観測結果と一致したことに留意すべきであろう．