1. Introduction

The U.S. Coast and Geodetic Survey Ship Oceanographer, research vessel of the Environmental Science Services Administration, completed its initial scientific expedition in December 1967, after a globe-circling cruise of nearly 45,000 n mi. Among the many scientific objectives of the cruise was the measurement of the atmospheric electrical conductivity.

In the past decade this laboratory has initiated investigations of the conductivity and other atmospheric electrical parameters from sites on the earth's surface remotely isolated from sources of atmospheric pollution. These sites include polar regions (Kasemir, 1968), Mauna Loa Observatory in Hawaii (Cobb and Phillips, 1962), and now oceanic regions as reported here. The purpose of such investigations is the establishment of "benchmarks" of the atmospheric electric climate. It is well known that a large increase in the number of small particles suspended in the atmosphere will significantly modify the electrical conductivity; thus, the conductivity, measured at locations that ideally are representative of global conditions, will yield data interpretable as an index of the amount of particulate matter suspended in the atmosphere.

The suspended fine-particle pollution is largely composed of condensation nuclei ranging in size from $2 \times 10^{-8}$ to $10 \mu$ in radius. The small mass of such particles permits them to be easily transported by convective processes that often overcome gravitational forces. The total mass of these suspended particulates has presumably been maintained at a nearly constant level for centuries. Even such cataclysmic events as the Krakatoa eruption have not affected this balance for more than a few years. It is, however, the steadily increasing anthropogenic production of particulates with which the natural processes of aerosol removal may not be able to cope in the future.

2. The effect of condensation nuclei on the electrical conductivity

The following well-known equation describes the change of small ion density with time in terms of the production and disappearance of the small ions in the atmosphere. Considering positive small ions, we have

$$ \frac{dn}{dt} = q - c_1 n_2 - \eta_2 n_1 N_2 - \eta_1 n_1 N_0, $$

where $n_1$, $N_1$ and $n_2$, $N_2$ are the small and large positive and negative ion densities respectively; $N_0$ is the concentration of uncharged nuclei; $q$ is the ion pair production rate; $\alpha$, $\eta_1$, and $\eta_2$ are the respective coefficients of recombination between oppositely charged small ions, between positive small ions and negative large ions, and between positive small ions and uncharged nuclei. The relative importance of the recombination terms of Eq. (1) vary greatly. In exceptionally clean air the last two terms become insignificant; in highly polluted air they become predominate.

Sagay and Faucher (1956) have shown that Eq. (1) can be solved for the unipolar small ion density $n$, assuming the equilibrium conditions exist, i.e., $dn_1/dt = 0$;
also that \( n_1 = n_2 = n \) and \( N_1 = N_2 = N \). Thus,

\[
n = -\frac{\beta N \pm (\beta N^2 + 4\alpha q)^{\frac{1}{2}}}{2\alpha},
\]

(2)

where \( \beta = \eta_{13} + \eta_{19} / N \). Chalmers (1967) reports the values: \( \eta_{13} = 4.6 \times 10^{-6} \text{ cm}^3 \text{ sec}^{-1} \), \( \eta_{19} = 1.8 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1} \), and \( N_o / N = 3 \). By substitution then, \( \beta = 10^{-5} \text{ cm}^3 \text{ sec}^{-1} \).

The total nuclei population \( Z \) includes charged nuclei, or large ions, as well as uncharged nuclei. Thus, \( Z = N_1 + N_2 + N_0 \). Since \( N_0 = 3N \) and from the earlier assumption that \( N_1 = N_2 = N \), \( Z = 5N \). In other words, \( \frac{1}{5} \) of the total nuclei are large ions of one polarity. The values of \( \alpha \) and \( q \) for sea level and mid-ocean are given by Chalmers as \( \alpha = 1.6 \times 10^{-6} \text{ cm}^3 \text{ sec}^{-1} \) and \( q = 1.6 \text{ ion pairs cm}^{-2} \text{ sec}^{-1} \).

Substituting the above values in (2), we have an expression for the small ion density in terms of the total nuclei concentration, i.e.,

\[
n = -\frac{Z \times 10^{-3} + (Z^2 \times 10^{-6} + 2.56)^{\frac{1}{2}}}{1.6 \times 10^{-3}}.
\]

(3)

Eq. (3) is shown graphically in Fig. 1. Also shown in the shaded area are data derived from recent measurements at Mauna Loa Observatory in Hawaii. A brief volcanic eruption occurred in October 1968, and volcanic haze covered the island for several days. The condensation nuclei density in the usually clean air at the mountain observatory increased to 30 times its normal value. The sensitivity of the conductivity to changes in the nuclei density is clearly evident.

3. Importance of the Carnegie measurements

Much credit must go to the Carnegie Institution of Washington, whose scientists had the foresight 60 years ago to recognize the importance of monitoring the electrical properties of oceanic air. Their classic measurements (Kidson, 1910, 1911; Swann, 1915; Ault and Mauchly, 1925; Torrson and McCallum, 1946) made aboard the sailing vessel Carnegie and its predecessor Galilee (Dike, 1908) have established an invaluable atmospheric benchmark of an era preceding the atomic age and most of the great increase of atmospheric pollution sources.

On 18 November 1929, at the Island of Samoa, a tragic fire and explosion aboard the Carnegie resulted in the sinking of the ship and the death of her captain. One need only read the accounts of the Carnegie cruises to appreciate the remarkable achievements of these dedicated sailor-scientists. Their meticulous care in making observations, with instruments now considered crude, has set an example of dedication seldom equaled.

Fortunately, the basic conductivity sensor (Gerdien, 1905) has remained essentially unchanged, and although recording methods have improved, the Carnegie measurements have, for the most part, withstood advances in the state of the art. Modern measurements may be compared to the Carnegie data in order to detect secular changes in the conductivity of oceanic air.

4. Instrumentation and measurement procedures for the 1967 Oceanographer cruise

The polar conductivities were recorded simultaneously throughout the voyage. Gerdien-type sensors were used, as previously described (Cobb and Phillips, 1962).

It is imperative that conductivity measurements be made as absolute as possible when attempting to detect diminutive secular changes in the atmospheric conductivity. The aspiration method of measuring the collected ionic charge in a flowing air sample is one in which the existing free-air value is usually approached but not exceeded. The measured conductivity, for example, will be less than the free-air value, if part of the collected ionic current "leaks to ground" because of poor insulation of the collecting electrode. Also, the free-air ion population will be decreased by recombination and diffusion processes within the air intake system. A third problem may lead to the repelling of ions at the air intake entrance and is principally a result of the electrical charge induced on the exposed air intake in the presence of the atmospheric electric field.

These Gerdien sensor problems have been eliminated or reduced to insignificant factors. The collecting electrode, for example, is suspended from an amber insulator, which is kept absolutely clean, is never handled with fingers, and is heated to a temperature of 100°C to
ensure dryness and to repel spiders. Current leakage across the insulators was never a problem even in sustained rain or fog.

The reduction in the measured conductivity caused by diffusion of ions to the walls of the intake system was determined by comparison tests of the Oceanographer conductivity system with a "standard instrument," as suggested by Cobb (1968). It was found that the Oceanographer system suffered a 4% reduction from the "standard instrument" measured conductivity, due to a right angle fitting attached at the entrance to the air intake.

The undesired repelling of ions caused by an induced charge on the air intake was recognized by Swann (1914) and more recently investigated by Phillips (1963). The problem is most easily solved if the Gerdién intakes are exposed in an area where the atmospheric electric field has been greatly reduced. This was conveniently accomplished aboard ship by the overhead antennas and superstructure, which intercepted most of the field lines of force.

5. Definition of "fair-weather"

The data considered here are restricted to days having 24 hr of fair weather and are defined as days for which no hydrometeors or other restrictions to visibility were reported on the ship's weather log. Ideally, the "fair-weather day" should be defined as cloudless, and this definition is now used at the Mauna Loa High Altitude Observatory. Such a restriction is too severe for a maritime environment, however, and cloudiness did not disqualify a day's observations unless precipitation was visibly present.

In addition to the "fair-weather" restrictions, the data were not used when contamination caused by the ship's presence disturbed the conductivity record.

Two types of pollution, caused by the ship's presence, frequently affected the conductivity measurement. At times, the "apparent" wind speed and direction (i.e., the true wind speed and direction adjusted for the ship's speed and heading) allowed diesel exhaust to collect around the ship. Conversely, strong winds, even though a favorable direction to carry the exhaust smoke away, often created breaking waves over the bow and a resulting salt spray over the entire ship.

In many ways the pollution-free sailing vessel Carnegie provided a superior platform for the conductivity measurement to the diesel-burning vessels of today. In spite of considerable discarded data from the 1967 Oceanographer cruise, 75 days of conductivity data were obtained, an average of one day in three for the entire voyage.

6. Results and discussion

Fig. 2 shows average values of the total conductivity in fair weather along the route of the Oceanographer. Also shown are comparative values obtained by the Carnegie. Conductivity values are shown for the Mediterranean, the Red Sea, and Indonesian Islands and off the coast of Australia. These values cannot be considered typical of the open ocean because of nearby land masses.

A significant result of the voyage concerns the high atmospheric conductivity found during the Pacific Ocean crossing at 35S. The environment of this vast remote region appears to be at least as free of aerosols as it was during the Carnegie era of 1910–29. In two other open ocean areas traversed by the Oceanographer, the North Atlantic and the Indian Ocean, the conductivity was found to be from 10–40% less than comparative values reported by the Carnegie.

The apparent ability of tropospheric air above the remote South Pacific to maintain its low level of aerosol pollution over the last half century may be attributed to several factors. First, the vast oceanic regions and limited land masses of the Southern Hemisphere have not witnessed the enormous increase of man-made pollution sources created in the Northern Hemisphere. Second, the meteorological equator effectively inhibits the transport of tropospheric aerosols from the Northern Hemisphere. Finally, the mid-Pacific at 35S is a region where the mean vertical motion in the lower troposphere is always downward (Riehl, 1954). The persistent subsidence of these Hadley cells accelerates the gravitational settling of airborne particulates.

The conductivity measured in the Indian Ocean, even several hundred miles from land, appeared to be affected by airborne pollution from Southeast Asia. This was apparent from the low values and wide fluctuations of the recorded conductivity.

Large air masses regularly cross the equator in the Indian Ocean with the monsoon circulation (Junge, 1962). This is a major exception to the effectiveness of the equatorial barrier mentioned earlier and may explain the low conductivity values found in the Indian Ocean.

The conductivity in the mid-North Atlantic was found to be 40% less than at the same latitude of the South Pacific for the 1967 Oceanographer cruise, and at least 20% less than that measured in the mid-North Atlantic during the early Carnegie years, 1910–15.

The lower conductivity over the North Atlantic is an indication that the suspended balance of aerosols is increasing in this region, an increase that can be attributed to the far greater proportion of aerosol pollution produced in the Northern Hemisphere. These particulates have a tropospheric lifetime of about one month (Junge, 1962), and for the most part they are injected, transported and fall out in the same hemisphere. The effectiveness of the meteorological equator (except for the monsoon circulation) as a barrier to the interhemispheric transport of tropospheric particulates has been well demonstrated for radioactive particles by
Lockhart et al. (1960), and their results should apply equally well to non-radioactive aerosols.

7. The secular change in atmospheric conductivity over the North Atlantic and South Pacific Oceans

Two regions, designated "control areas," and outlined on the map in Fig. 2, have been investigated in an attempt to detect secular changes in the atmospheric conductivity of the areas. Boundaries for the regions are 20-50N and 20-60W in the Atlantic, and 10-50S and 80-180W in the Pacific.

Fig. 3 shows the average total conductivity found by various investigators in the two control areas from 1907-67. The data in this figure indicate, as discussed earlier, a stable secular trend of the conductivity above the remote South Pacific but a slow decrease over the North Atlantic.

It should be noted that the Cruise VII Carnegie data have been adjusted. A new air induction system was installed in 1928, which inadvertently reduced the free-air conductivity. A correction factor was obtained by Gunn (1964), who made comparative measurements with the original 1928 Carnegie intake system, and that correction factor has been applied to the 1928-29 value shown in Fig. 3.

The secular trends indicated in Fig. 3 are not entirely free of ambiguity. Although the Gerdien conductivity sensor has remained essentially unchanged, the oscillographic recorders and vibrating reed electrometers used today were nonexistent before 1930. The Carnegie measurements, however carefully made, were manual observations with considerable scatter. It is now common practice to record the polar conductivities continuously, to damp out momentary fluctuations, and to reduce data to average hourly values. Every effort has been made, in the preparation of Fig. 3, to obtain the true average values from the Carnegie records whenever the sailing vessel was within the control area boundaries. Some doubt will always exist as to the absolute value and comparability of measurements that span more than 50 years. However, even allowing for errors, the evidence is sufficiently reliable to state that the true secular trend to the atmospheric conductivity in the two control areas is reasonably close to that indicated in Fig. 3. Indeed, the serious implications of an aerosol increase in the North Atlantic are such that no evidence can be ignored.

8. Summary and conclusions

The atmospheric electrical conductivity was recorded during a nine-month global expedition of the research vessel Oceanographer. The conductivity has been interpreted as an index of the suspended fine-particle aerosol pollution. Results indicate that there has been a significant increase in aerosol pollution above the North Atlantic since the Carnegie measurements of 1910-29 but that there is a stable trend in the South Pacific.

The relatively high atmospheric conductivity found in the Pacific Ocean at 35S, sometimes higher than that
observed during the Carnegie era, has been attributed to 1) the remoteness of the region, 2) the enhanced aerosol fallout in a region of persistent atmospheric subsidence, and 3) the meteorological equator that effectively inhibits the tropospheric transport of aerosols from the more highly contaminated Northern Hemisphere.

The conductivity over the North Atlantic appears to have decreased by at least 20% in the past 60 years and by ~15% since the last Carnegie measurements in 1929. This would be equivalent to perhaps a doubling of the fine particle aerosol pollution in the area.

The detection of secular changes in the atmospheric conductivity has been further complicated since 1945 by the production of man-made radioactive aerosols. Nuclear atmospheric testing throughout the world has been greatly reduced, but not completely stopped, since 1963. The net effect of radioactive contamination is to make the atmosphere more conducting. The 1967 Oceanographer measurements did not reveal any abnormally high conductivities such as those that followed atmospheric nuclear explosions in the past (Schilling, 1964). It appears that radioactive contamination of the free atmosphere has returned to a reasonably normal level, which is not detectable as a secular increase in the electrical conductivity.

The consequences of an increasing global aerosol concentration are not well known or understood. There is, for example, a widely accepted hypothesis which claims that an increase in the number of condensation nuclei, the same particles forming the major part of the aerosols discussed in this report, will lead to an increase in nonprecipitating clouds and a probable decrease in rainfall (Gunn and Phillips, 1957; Warner and Twomey, 1967). Washout by precipitation is the major process of aerosol removal (Junge, 1958). Since these two processes complement each other, an increase in nuclei particles may decrease the total rainfall and, in turn, the major process of aerosol removal.

The “Atmospheric Electricity Ten Year Program” was initiated in 1969 by the Joint Committee on Atmospheric Electricity of the IUGG-IAMAP (Dolezalek, 1967). It is proposed, as a part of the Ten Year Program, that one of the Carnegie cruises be repeated. The knowledge to be gained would be invaluable and a fitting tribute to the last fateful voyage of the Carnegie.

REFERENCES


