Oceanic Aerosol Levels Deduced from Measurements of the Electrical Conductivity of the Atmosphere

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ABSTRACT

The electrical conductivity of the atmosphere, monitored at sites remote from sources of anthropogenic aerosols, may be used to provide an index of the level of suspended particulates for the area representative of the sampling site. Conductivity measurements taken at Mauna Loa, Hawaii, and from ocean research vessels, indicate that most of the oceanic regions of the world are maintaining a natural aerosol level unchanged by the activities of mankind. Significant exceptions are the paths of aerosol pollution extending eastward from the United States in the North Atlantic, from Japan in the North Pacific, and southward from Asia in the Northern Indian Ocean. These regions are discussed with respect to the lifetime of the suspended particulates and the influence of large-scale atmospheric circulation. Anthropogenic aerosols are largely produced from the burning of fossil fuels such as coal and oil. The present trend is toward control of these particulate emissions and an inevitable switch to other forms of energy production. It is concluded that the anthropogenic aerosols now detectable in some oceanic regions will begin to decline by the end of the century and that any global climatic changes due to the current increase will be insignificant.

1. Introduction

It has become important to the well-being of mankind on this planet to assess the consequences of the particulate material which is produced and injected into the atmosphere through the activities of an expanding human population. The task is to document aerosol levels in the past; to establish environmental benchmarks of the present state of the atmosphere; and to predict, if possible, future trends and effects.

It is well known that the electrical conductivity of the atmosphere, monitored at sites remote from sources of pollution, will yield data interpretable as an index of the amount of particulate matter suspended in the atmosphere. The conductivity is a particularly important parameter because new measurements may be compared to those taken on the scientific cruises of the sailing vessel Carnegie.

Wait (1946) was probably the first to attempt on a global scale to correlate aerosol levels with the atmospheric conductivity. He reported an alarming decrease in oceanic conductivity and attributed it to an increase in anthropogenic aerosols. Gunn (1964) found Wait’s conclusions to be in error due to an instrumental air-sampling problem which existed during Cruise VII of the Carnegie. Gunn, nevertheless, reported a measurable increase in air pollution over the mid-Atlantic between 1928 and 1962. Cobb and Wells (1970) measured the conductivity during the global voyage of the Oceanographer in 1967. They reported that the aerosol concentration in the North Atlantic had approximately doubled in the preceding 60 years but found no significant change in the South Pacific.

This report presents new conductivity data from the Mauna Loa high altitude observatory in Hawaii and discusses recent oceanic measurements made in the western North Pacific (Misaki and Takeuti, 1970; Morita, 1971).

2. The electrical conductivity of the atmosphere

The atmosphere is a poor electrical conductor. This fact is easily demonstrated by observing that an electrically charged and highly insulated conductor placed in the atmosphere will systematically lose its charge in the surrounding air. The conductivity is due to the presence of highly mobile ions produced in the atmosphere by cosmic rays and local radioactive sources. Over the oceans, ionizing radiations produce about 2 ion pairs cm^{-3} sec^{-1} and a resulting small ion density and conductivity, near sea level, of roughly 1000 ions cm^{-3} and 2.5×10^{-14} Ω^{-1} m^{-1}, respectively. A balance is maintained since the small ions are being removed from the atmosphere at the same rate that they are being produced. They are removed by recombination with oppositely charged small ions, thus neutralizing the charge, and by attachment to much larger aerosols, both charged and uncharged. These recombination and attachment processes thus determine the lifetimes of small ions in the atmosphere and the existing conductivity and small ion population. Ionic lifetimes near the earth’s surface vary from ~20 sec in highly polluted
air to ~300 sec in very clean air. The particulates which have appreciable atmospheric suspension times are largely sub-micron sized; however, they are much larger than the molecular sized small ions. Their role is mainly a passive one, that of providing relatively immobile surfaces for the diffusional attachment of small ions thus leading to a subsequent reduction in the electrical conductivity.

3. Aerosols: Natural and anthropogenic

The fine-particle aerosol content of the atmosphere is largely composed of condensation nuclei. While the size distribution of these nuclei is very large, the majority have radii of less than 10^{-6} cm. The relative abundance or scarcity of condensation nuclei can be of great importance to the physics of precipitation since nearly each cloud droplet requires a grain of particulate matter at its birth. Of equal or greater importance is the effect of the total particulate suspension on the global heat balance.

The distribution of particulate matter in the atmosphere results from the dynamic balance of processes which continuously cleanse and replenish the air with nuclei. Sources are both natural and anthropogenic. Nuclei are produced from the oceans and the continents, and from forest fires, volcanoes, dust storms, etc. They are also produced through the activities of mankind, particularly from the burning of fossil fuels. Thus, a continuing flux of material from the earth's surface is borne aloft by the mechanisms of convection, diffusion and large-scale circulation.

Within the troposphere, where most of our global weather occurs, washout by precipitation and other aerosol removal processes tend to reduce the amount of material in suspension. The average atmospheric residence times of these fine-particle aerosols is of the order of days to a few weeks. Aerosols, which in some manner are transported to above the tropopause, may remain suspended for months, even years, drifting with the prevailing winds, until the processes of coagulation and gravitational settling slowly bring the particles down into the region of clouds and storms to become moisture laden and eventually precipitated to earth.

The atmospheric mechanisms of particle injection, transport, and eventual deposition have maintained a balanced aerosol level presumably for centuries, with the exception of periods of up to a few years following great volcanic eruptions. Within this century particulates produced by human activities have become a factor to be considered.

It has been estimated (Squires, 1966; Selezneva, 1966; Hide and Brock, 1970; Robinson and Robbins, 1970) that the anthropogenic component of the global particulate burden of the atmosphere amounts to 5-12%; not, it would seem a very alarming figure. The ratio of natural to anthropogenic aerosols, however, varies greatly. The author recently measured the Aitken nucleus concentration at the Amundsen-Scott South Pole station and found less than 200 nuclei cm^{-3}, probably all of natural origin. The same instrumentation, in Boulder, Colo., a typical urban non-industrial community, measured from 50,000 to 300,000 nuclei cm^{-3} of which more than 90% were considered to be anthropogenic. Weickmann (1971) has considered, on a global basis, areas of industrialization and population density and concluded that nearly all of the man-made aerosol pollution is produced from only 2.5% of the earth's surface. Particulates injected from this relatively small area, however, may be transported over long distances. Smoke from forest fires in North America, for example, is sometimes observed over Europe. Volcanic ash has been known to circle the globe for several years. Libby and Palmer (1960) have shown that radioactive debris can remain suspended for many months, accumulating at high levels over the poles during the winter season and descending toward mid-latitude troposphere in the following spring. Harmattan dust has been traced across the equatorial Atlantic from North Africa to Barbados (Prospero and Carlson, 1972). Thus, there is no doubt that suspended particulates, whether natural or anthropogenic, may be transported great distances and remain aloft for extended periods.

An unknown fraction of the total particulate suspension of the atmosphere results from the transformation of pollutant gases. Such aerosols may also be natural or anthropogenic, resulting, for example, from gases produced from the biological decay of vegetation; from volcanic gases; or in the case of human activity, from gases produced from the burning of fossil fuels.

4. Atmospheric conductivity measurements at Mauna Loa: Comparison of 1960 and 1968 data

The Geradian-type conductivity sensors used in 1960 and in 1968 have been previously described (Cobb and Phillips, 1962). An important change was made in the air intake system prior to the 1968 measurements. As suggested by Cobb (1968a), the intake ahead of the Geradian chamber was reduced to a short length (50 cm) of straight flow pipe. The air transit time from the intake entrance to the Geradian chamber was thus reduced from 0.5 to 0.1 sec. It was experimentally determined that the earlier intake system used at Mauna Loa resulted in a 3% loss in conductivity and small-ion density from the free-air values, the loss being primarily due to the diffusion of ions to the walls of the intake system. The 1960 data in Fig. 1 have been adjusted accordingly.

The data in Fig. 1 consist of mean hourly values of the electrical conductivity measured in fair weather during the respective 1-year measurement periods. A "fair weather" day, more restrictive than that originally used, is defined as follows: 24 hr of record with no clouds above the Observatory level other than the possible existence of cirrus; no restrictions to visibility such as
smoke from brush fires or a local volcanic eruption; and no upslope wind. Fifty-six such fair-weather days occurred during the initial measurement period, 1 September 1960–1 September 1961, and 72 days in the latter period, 1 June 1968–1 June 1969. The fair-weather restrictions were imposed to make the sampled atmosphere representative of as large an area as possible. Cobb (1968b) has described the Observatory environment during downslope wind conditions, as typical of the free atmosphere over the mid-Pacific at 3–5 km.

The only conclusion to be drawn from the data in Fig. 1 is that there is no measurable difference in the electrical conductivity, and thus of the aerosol level, between that found in 1960 and again in 1968. The double oscillation which occurs diurnally, is a persistent feature of the conductivity measurement at Mauna Loa entirely due to the mountain’s presence. The mean diurnal variations are small, however, amounting to ±5% from the mean conductivity of $7.3 	imes 10^{-14} \ \Omega^{-1} \ \text{m}^{-1}$ in 1960 and $7.25 	imes 10^{-14} \ \Omega^{-1} \ \text{m}^{-1}$ in 1968. The early morning conductivity minimum is associated with the electrode effect (Cobb, 1968b) which becomes progressively stronger during the night and reduces the negative and total conductivity. The mid-afternoon minimum occurs at the time of greatest heating of the mountain’s lava surface and a subsequent increase in particulates raised from the surface by thermal convective processes. It may be deduced, then, that the free-air conductivity at the Observatory’s elevation would, in the absence of the mountain effects described above, approach a constant level equivalent to the maximum values shown in Fig. 1.

5. The oceanic distribution of anthropogenic aerosols

Depicted on the world map in Fig. 2 are ocean areas where measurements of the atmospheric electrical conductivity indicate a secular increase in aerosol pollution. Conductivity values are shown which also indicate areas where the natural aerosol level remains unaffected by human activity. The size and intensity of the three regions of aerosol pollution must remain in doubt since oceanic measurements are not frequently made. Nevertheless, there is sufficient evidence to state that the three areas do indeed exist, and that they are extensions of anthropogenic aerosol concentrations produced in populated land areas.

The secular decrease in atmospheric conductivity over the North Atlantic is based on the report of Cobb and Wells (1970). No new data have been reported although some overlooked measurements of Anderson and Trent (1962) made in 1960 agree with the downward trend of atmospheric conductivity in the region.

Recent investigations in the Pacific indicate an aerosol increase east of the Asian continent and the islands of Japan similar to that found in the North Atlantic. Misaki and Takeuti (1970) measured the electrical conductivity around the Japanese Islands on the research vessel Fuji and found a mean conductivity of $1.35 	imes 10^{-14} \ \Omega^{-1} \ \text{m}^{-1}$. While the conductivity increased with the distance from land, the vessel was never more than 150 km at sea and the measurements are probably more representative of the land than of the ocean. Morita (1971) made atmospheric electric measurements in the western North Pacific aboard the research vessel Hakuko-Maru and reported a mean conductivity, in fair weather and more than 1000 km from shore, of $2.2 \times 10^{-14} \ \Omega^{-1} \ \text{m}^{-1}$. This is 20–25% less than the conductivity measured by the Carnegie on cruises IV and VII in the area from 10–50N and 140–180E in 1915 and 1929 (Ault and Mauchly, 1925; Torreson et al., 1946).

The increased aerosol pollution reported by Cobb and Wells in the northern Indian Ocean is considered to be a special case. Drought conditions over the past decade in India have helped produce large areas of barren soil and dust particles which may be borne aloft and transported by the monsoon circulation. Thus, the aerosol pollution found at sea is probably seasonal and not as extensive as the areas in the North Pacific and North Atlantic.

It should be noted that some regions have always had a relatively high natural aerosol level. The conductivity measured, for example, in the Red Sea in 1911 (Angenheister, 1914), is the same as that found by the Oceanographer in 1967. This is an arid region which has always had a high level of haze and dust particles and a lack of rainfall to remove them.

6. Summary and conclusions

Conductivity measurements made at Mauna Loa and from ocean research vessels indicate that most of the global ocean environment, within the planetary boundary layer at least, has maintained a natural aerosol level unchanged by the activities of mankind. Significant exceptions are the paths of aerosol pollution extending eastward from the United States in the North Atlantic, from Asia and Japan in the North Pacific, and southward from Asia in the northern Indian Ocean. These regions comprise less than 10% of the earth’s ocean...
area. It is likely that the polar regions should be included with the clean-air ocean environment even though measurements are lacking.

It was indicated by Cobb and Wells (1970) that the unchanged aerosol level in the vast South Pacific trade wind region was partly due to the enhanced processes of aerosol removal. In this report conductivity measurements at Mauna Loa indicate that a similar trendless aerosol condition exists in the Northern Hemisphere trade wind region, at least between 1960 and 1969. It should be noted that measurements at Mauna Loa, on days with no clouds or upslope wind, are representative of the free atmosphere of the mid-Pacific at 3.4 km, well above the trade wind inversion. Ellis and Pueschel (1971), in a report based on solar radiation data at Mauna Loa for the period 1958-70, conclude that human activities have not affected the atmospheric turbidity on a global scale. They also conclude that the 1963 eruption of Mount Agung, a natural phenomena, produced stratospheric aerosols which persisted for 7 years.

The lack of continuous data in the oceanic areas of pollution, shown in Fig. 2, makes it difficult to detect variations of the size and intensity of the regions. It is reasonable to assume, however, that seasonal changes are quite large. In North America, for example, aerosols are more likely to be transported into the stratosphere during the thunderstorm season and as explained earlier, such aerosols will have a much longer atmospheric residence time. Aerosols in the lower troposphere, on the other hand, are largely removed by rainfall, especially the non-shower type precipitation more likely to occur over the western North Atlantic during the winter and spring. Assuming that the production of anthropogenic aerosols in North America is relatively constant throughout the year, the above forces of particle injection and removal suggest that the area of man-made pollution extending over the North Atlantic would be more persistent during the summer and less so in the winter and spring.

Seasonal variations of the oceanic aerosol regions shown in Fig. 2 remain to be proved by observation. The most practical method at this time would appear to lie in the long-term analysis of satellite photography such as the figure shown in a recent paper by Lovelock (1971).

Anthropogenic aerosols are largely produced from the burning of fossil fuels such as coal and oil. The present trend within the world's industrialized urban complexes is toward control of these particulate emissions and an inevitable change to other forms of energy production. Machta (1972) reports that the present growth rate of fossil fuel consumption of 4% per year is expected to fall to 3.5% between 1980 and 2000 as nuclear power comes into wider use. Perhaps it is not too farsighted to predict that the anthropogenic aerosols now detectable in some oceanic regions will begin to decline by the end of the century and that any global climatic changes due to the current increase will be insignificant. Such a prediction is based on the logical assumption that the major sources of anthropogenic aerosols will be reduced and thus the oceanic regions in Fig. 2, which are extensions of the source areas, will also be reduced.

Improved emission control technology, and the change in domestic fuel from coal to oil and gas, have already reduced particulate pollution in major urban areas of the United States as documented by Ludwig et al. (1970) of the National Air Pollution Control Administration. Spirats and Levin (1971) have also documented a mean decrease in particulate levels at 58 U. S. urban centers. Visibility statistics have been analyzed by several investigators, most indicating a decrease in suspended particulates at urban centers (Beebe, 1967; Holzworth, 1962; Freeman, 1968) but with some single-station studies for downtown Los Angeles and New York indicating a secular increase in air pollution (Keith, 1970; McNulty 1968).

This author does not wish to imply that areas of anthropogenic aerosols over the ocean can be ignored. Certainly it is important to monitor the global environment at every opportunity and particularly at sites remote from sources of atmospheric pollution. So long as man continues to produce aerosol pollutants at a rate measured in millions of tons per year, the potential exists for initiating global climatic change. Environmental benchmarks at locations such as Mauna Loa, ocean vessels, the South Pole, and the new geophysical monitoring sites being established by the National Atmospheric and Oceanic Administration at Samoa in the South Pacific and Point Barrow, Alaska, provide the most logical way of detecting secular changes within our global atmosphere.

The reader is reminded that all the measurements of atmospheric electrical conductivity discussed in this paper were made at the surface and are probably not applicable to aerosol conditions in the stratosphere. As discussed in Section 3, aerosols which are carried to the stratosphere have much greater residence times. There may be storage regions over the poles or within the "Junge layer." The existence of aerosol concentrations within the stratosphere, whether natural or anthropogenic, is probably more potentially significant with respect to global climatic change than aerosols in the lower atmosphere.

Aerosol measurements in the stratosphere are scarce and it is hoped that the methods of atmospheric electric measurements used at the surface can be used to detect aerosol levels within the lower stratosphere, either using balloons or high flying aircraft.

REFERENCES


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