Atmospheric electric conductivity measurements over the Indian Ocean during the Indian Antarctic Expedition in 1996–1997

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The atmospheric electric conductivity measurements made over the Indian Ocean with a Gerdien’s apparatus mounted aboard MV Polarbird during the XVI Indian Scientific Expedition in 1996–1997 are reported. Simultaneous three-hourly measurements of aerosol concentrations of 13–1000 nm size and some meteorological parameters are also reported. Latitudinal variation of conductivity along the cruise route shows a minimum at ~28°S. Further, the variations in conductivity in the 10°N–20°S and 60°–70°S latitudinal belts show opposite trends on the outward and return cruises, which fall near to the onset and withdrawal phases of the northeast monsoon season, respectively. The results are explained on the basis of the well-known northward shift of the subsidence leg of the southern Hadley cell and of the position of the Intertropical Convergence Zone during the months of March–April in this region and the observations of the cyclonic systems near the continent of Antarctica during the period of outward cruise.

INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; KEYWORDS: atmospheric conductivity, latitudinal variation of conductivity, Indian Antarctic Expedition, electric conductivity over the Indian Ocean


1. Introduction

The atmospheric electric conductivity measurements made over open oceans are important as these are free from the presence of anthropogenic aerosols and the radioactivity of the ground. It is widely recognized that the atmospheric electric conductivity over open ocean acts as an index of the background air pollution. Cobb and Wells [1970] report a secular decrease in conductivity in the North Atlantic as compared to its value measured in the Carnegie cruises during 1909–1930, and they attribute it to a possible increase in the background aerosol pollution suspended in the atmosphere of the Northern Hemisphere. Several other oceanic measurements of atmospheric electric conductivity have been used to estimate the extension of air pollution from land to ocean [e.g., Misaki and Takeuti, 1970; Morita, 1971; Morita et al., 1973; Morita and Ishikawa, 1977; Kamra and Deshpande, 1995]. Recent measurements of Kamra et al. [2001] conducted over the Indian Ocean in three consecutive northeast monsoon seasons during the Indian Ocean Experiment show that the conductivity values over the Southern Hemisphere are, in general, 2 to 3 times higher than that over the northern Indian Ocean. Further, the north-to-south gradients of conductivity extend from the western coastline of India to the Intertropical Convergence Zone and have large interseasonal and intraseasonal variations. Takagi and Kanada [1972] observe a latitudinal decrease in the electric field and explain it on the basis of the increase in conductivity with latitude which they attribute to the change in the cosmic ray intensity and the consequent change in the rate of ionization with latitude. The value of electric conductivity over oceans can also be influenced by some meteorological conditions such as fog, cloud and strong winds causing wave-breaking on the sea surface.

The wind-flow pattern over the Indian Ocean is persistent throughout the year. There are two meteorological features of this region, which are very much relevant in interpreting the measurements presented in this paper. (1) The low-level wind-flow of the atmospheric circulation is persistently in the north-south direction during the northeast monsoon season (January to April). (2) The Intertropical Convergence Zone (ITCZ) shifts during this season to the Southern Hemisphere at about 10°S. As a result, the continental aerosols from the South Asian continent are transported over the Indian Ocean in this season and these are expected to change the region’s electric conductivity. Observations made during the Indian Ocean Experiment (INDOEX) conducted during 1997–1999 showed high pollution levels over the entire northern Indian Ocean during the northeast monsoon season [Lelieveld et al., 2001; Murugavel et al., 2001]. Latitudinal variations of aerosol concentrations computed from the conductivity measurements made by Kamra et al. [2001] during the INDOEX show positive gradients from the Indian coastline...
to the ITCZ. The aerosol concentrations attain their pristine level only at $15^\circ-20^\circ S$ in the northeast monsoon seasons. 

In this paper, we report our measurements of atmospheric electric conductivity along cruise track from $15^\circ N$ to $70^\circ S$. Also reported are simultaneous measurements of the submicron aerosol particle concentration and other meteorological parameters along the cruise track. A long-range transport process has been suggested to explain the latitudinal variation of conductivity.

2. Cruise and Weather

Figure 1 shows the route followed by the MV Polarbird during the XVI Indian Antarctic Expedition. The dates marked along the cruise route show the position of the ship at 1200 UT each day. After starting on 12 December 1996 from Goa ($15^\circ 24^\prime N$, $73^\circ 48^\prime E$), the ship berthed at Mauritius from 20 to 22 December 1996, for helicopter loading and bunkering. After crossing the zone of midlatitude westerlies and the Antarctic circle at $66^\circ$ latitude, the ship encountered the pack-ice. After the ice cutting/breaking operations, the ship reached the Antarctica coast ($69^\circ 40^\prime S$, $11^\circ 55^\prime E$) on 4 January 1997. The return journey started on 9 March 1997. After being berthed at Durban, South Africa on 20 March 1997 and at Mauritius on 27 March 1997, the ship reached Goa on 5 April 1997.

Figure 2 shows the three-hourly values of meteorological parameters during the outward and return cruises.
Among the prominent features are the sharp falls in dry bulb and sea surface temperatures below 10°C southward of 45°S, the sharp fall in atmospheric pressure at 50°–55°S, high winds of about 25–30 knots at 40°–50°S accompanied with the sea-state of 5–6, and the total cloud coverage of 6–8 octa below 45°S. The wind directions observed along the cruise track mostly follow the normal wind circulation pattern typical of these tropical and midlatitude regions during these months. Existence of two low pressure areas of a type which generally form a ‘wall of storms’ around the continent of Antarctica is evident from the meteorological measurements made during the outward cruise. The changes observed in the meteorological parameters during the outward and return journeys are typical of this season.

3. Instrumentation and Recording of Data

The electric conductivity of both polarities is measured with a Gerdien’s apparatus described in detail by Deshpande and Kamra [2001]. It consists of two identical cylindrical condensers of stainless steel joined with a U-tube and has a common fan to suck the air through the two tubes. The critical mobility of each condenser is adjusted at $3.60 \times 10^{-4}$ m$^2$ V$^{-1}$ s$^{-1}$. The signal from each condenser is amplified separately with an amplifier 311K of Analog Devices. The Gerdien’s apparatus is vertically installed on the port side deck of the ship such that its inlets are 24 cm above the platform of the deck. The height of this deck is about 10 m above sea level. The position of the Gerdien’s apparatus on the ship is so selected that the exhaust of the ship chimney does not pollute the conductivity measurements. The wind directions are generally across the cruise path except for close to the Indian and Antarctic coastlines. So the chances of the exhaust polluting the instrument site on open oceans are less. Moreover, the conductivity values did not show any significant correlation with the wind direction in the areas south of the ITCZ and away from the coastlines which are free from the pollutants carried from the continents. The amplifier boxes are fitted near to the sensors and the air suction fan is covered with a conical cap to avoid accumulation of snowfall or rain on it. The signals from Gerdien’s apparatus are fed to a PC-based data acquisition system which is kept inside a living cabin. The system has a capacity to sample $10^5$ samples s$^{-1}$ and to store and average the data at different time intervals. The conductivity data is sampled every second and stored in 1-min-average and 30-min-average modes during the entire period of measurements. Maintenance of the Gerdien’s apparatus, especially cleaning of its insulators, is done at least daily. The zero-shift is checked every 3 hours. No appreciable zero shift is found.

Figure 2. The three-hourly meteorological data of dry bulb temperature (D.B. Temp.), sea surface temperature (S. S. T.), relative humidity (R. H.), wind speed (W. S.) wind direction (W. D.), pressure (press.) and cloud coverage (N octas of cloud) taken on the ship during the outward and return cruises.
The aerosol measurements are made with a TSI 3030 Electrical Aerosol Analyzer (EAA) system. Since the accuracy of measurements from the lowest two channels (3 and 7 nm diameter ranges) in this system is not sufficient, their contributions are not considered in this analysis. The EAA system is operated after every 3 hours to collect 5 size-distribution samples and the data is stored in a PC. The total aerosol concentration in the size range of 13 to 1000 nm is obtained by adding and averaging the particle concentrations in 8 different channels for all the 5 samples. The air intake for the EAA system is through a grounded 1-cm diameter stainless steel tube of 1 m length. Inlet is projected outward from a cabin and is positioned 12 m above mean sea level. The EAA system is installed inside the cabin.

4. Observations

4.1. Electrical Conductivity Along Cruise Track

The aerosol measurements are made with a TSI 3030 Electrical Aerosol Analyzer (EAA) system. Since the accuracy of measurements from the lowest two channels (3 and 7 nm diameter ranges) in this system is not sufficient, their contributions are not considered in this analysis. The EAA system is operated after every 3 hours to collect 5 size-distribution samples and the data is stored in a PC. The total aerosol concentration in the size range of 13 to 1000 nm is obtained by adding and averaging the particle concentrations in 8 different channels for all the 5 samples. The air intake for the EAA system is through a grounded 1-cm diameter stainless steel tube of 1 m length. Inlet is projected outward from a cabin and is positioned 12 m above mean sea level. The EAA system is installed inside the cabin.

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Figure 3. The three-hourly averaged values of the total electric conductivity along the cruise tracks. A value of conductivity is plotted by taking its value as zero at the cruise track. Although dotted lines show the continued axis of conductivity, due care needs to be exercised for reading the conductivity absolute values whenever the cruise track changes its direction. The arrows show the three-hourly values of the wind speed and direction measured on the ship.
During the return cruise, the total conductivity is $2.5 - 3.5 \times 10^{-14} \text{ S m}^{-1}$ in $70^\circ - 40^\circ S$ belt. These high values of conductivity are perhaps typical of pristine air at those latitudes. Somewhat lower values of conductivity observed in this region on the outward cruise are most likely because of the passage of two low pressure systems during that period. Such systems are known to encircle the continent of Antarctica and are generally associated with enhanced aerosol concentrations [e.g., Voskresenskii, 1968; Gras and Adriaansen, 1985]. The conductivity values then decrease to $\sim 1 \times 10^{-14} \text{ S m}^{-1}$ while approaching Durban. This decrease is sharper but extends over shorter distances from the African coastline as compared to the one observed south of the Indian coastline. The difference can be ascribed to the difference in wind directions at the two locations.

While leaving Durban, the conductivity values are higher and remain between 1.5 and $2.5 \times 10^{-14} \text{ S m}^{-1}$ to 16'S. Apparently there is no appreciable land-to-ocean transport of aerosols in this region because of the surface winds being into the continent. The low value of conductivity ($\sim 1.0 \times 10^{-14} \text{ S m}^{-1}$) at 17'S and its slow northward increase up to 5'S is perhaps associated with the long-range transport of aerosols which, as mentioned earlier, will be discussed later. The conductivity value then fluctuates between 1 and $\sim 2 \times 10^{-14} \text{ S m}^{-1}$ between 6'S and the Indian coastline with some dominant peaks in the equatorial region.

The relative humidity at the sea surface varies from 45 to 97% during the cruise period. The size of aerosol particles sharply increases when the relative humidity exceeds $\sim 75\%$ [Pruppacher and Klett, 1997]. Therefore, the electric conductivity which is a function of the size and concentration of aerosol particles, should vary with the relative humidity. Kamra et al. [1997] have demonstrated the validity of this correlation from their observations in the Arabian Sea and the Indian Ocean. Figure 4 shows a plot of the half-hourly averaged values of the total conductivity vs instantaneous values observed at an interval of 3-hours from our cruise data for the days when there is no precipitation in the vicinity of the ship and winds are less than 20 m s$^{-1}$, so that there is no charge generation by the splashing of raindrops or by the wave breaking on sea surface. In spite of a large scatter in the diagram, a decrease in conductivity with increasing values of relative humidity is noticed when the relative humidity is higher than $\sim 70\%$. Large scatter in the diagram may be because of the vastly different aerosol concentrations or other local meteorological conditions at different locations.

Figure 5 shows the diurnal variation of polar conductivities averaged for eight fair-weather days during the cruise period. Also shown in Figure 4 are the curves for the ratio of polar conductivities and the relative humidity averaged for these eight fair-weather days. A fair-weather day is defined as a day when there is no precipitation at site and the total clouds are less than 3 octa throughout the day. Further, the distance of the ship from coastline has to be more than 200 kms on these days. The polar conductivity shows comparatively lower values during 0000 to 1200 UT. This is in agreement with our earlier observations over oceans [Kamra and Deshpande, 1995]. Further, Figure 5 shows that the conductivity values are large when the relative humidity is small. The average value of the total conductivity is $1.52 \times 10^{-14} \text{ S m}^{-1}$ during the cruise. This value is higher than that observed by Kamra and Deshpande [1995] whose observations have generally been made closer to the coastlines and are confined to the equatorial Indian Ocean, the Arabian Sea or the Bay of Bengal which are comparatively more polluted in this season. Such a result is expected in view of the fact that 7 out of 8 fair-weather days in the present cruise fall in the Southern Hemisphere. However, surprisingly, this value is roughly half of that measured by Cobb and Wells [1970] in 1967 and in Carnegie measurements during 1907–1920, in their control area in the south Pacific and also during 1911–1930 in the equatorial Indian Ocean. Such a decrease in conductivity is most likely typical of these longitudes in this season when the southward transport of aerosols is strong and persistent. Also, as observed by Kamra et al. [1970].
[2001], the conductivity and aerosol concentrations in this area show large intraseasonal and interseasonal variations during the northeast monsoon season. The cosmic ray ionization may also be modulated by the solar changes and the solar cycle. However, the changes in ionization due to this modulation may not be significant at ground level in low and midlatitudes. However, any change in the clean environment of the Southern Hemisphere, whatsoever small it is, needs to be checked thoroughly with more measurements.

4.2. Latitudinal Variation in the Electrical Conductivity

Figure 6 shows the latitudinal variations of the total conductivity and aerosol concentrations (13 to 1000 nm) during the outward and return cruises. The curves for the conductivity and aerosol concentrations when averaged over long distances roughly show an inverse correlation. For example, large aerosol concentrations observed north of the ITCZ and close to continents are accompanied with comparatively smaller values of conductivity. On the other hand, small values of aerosol concentration observed south of ITCZ are accompanied with larger values of conductivity. This inverse correlation also holds good over short distances in some regions, e.g., during most of the peaks observed on open ocean in the Southern Hemisphere. A detailed analysis of the validity or otherwise of this inverse correlation at different locations in terms of the local meteorological and other conditions will be reported elsewhere.

[14] The daily averaged total conductivity values for eight fair-weather days is plotted against the midday latitude of the ship in Figure 7a. The vertical bars show the standard deviation of the total conductivity from its average values. The total conductivity value shows a minimum at about 28°S and keeps increasing south of this latitude up to the Antarctica coast. The conductivity also increases north of 28° S except for showing a small decrease near the Equator. Takagi and Kanada [1972] explain the latitudinal decrease in the electric field observed in their measurements over the Pacific as a consequence of the increase in conductivity with latitude. Morita [1971], however, does not observe any latitudinal dependence of electric field and discussed his observations in terms of the effect of local influences only.

[15] To increase the number of days for the purpose of data analysis, we make the fair-weather conditions less stringent. Figure 7b shows the daily average of total conductivity against the midday latitude of the ship for all cruise days except the days with rain or with high winds causing wave-breaking at sea surface separately for the outward and return journeys. In other words, it also includes the days with 3-octa or more of non-raining clouds. However, such days did not experience any cloud with strong electrification. So, the conductivity values on these days are not expected to be much different from the values on the fair-weather days. Once again, the minimum in conductivity occurs at about 28°S. Noteworthy features are, however, the opposite trends in the latitudinal variations of conductivity.

Figure 5. Diurnal variations of the polar conductivities ($\lambda_+$, ---, $\lambda_-$ ....), ratio of the polar conductivities ($\lambda_+ / \lambda_-$, line with triangles), and the relative humidity (RH.) averaged for eight fair-weather days during the cruise. Dashes and open circles show the standard deviations of the positive and negative conductivity, respectively from their mean values.
in the 10°N–20°S and 60° and 70°S belts between the outward and return cruises. These features in our measurements and their possible explanations are further discussed in the next section.

5. Discussion

[16] In the absence of any local source of ionization, cosmic rays are the only major source of ionization over the open ocean. The rate of ion production at the surface, therefore, does not show any significant variation up to at least 40° of latitude. The small ions generated in the atmosphere, get attached to the aerosol particles and thus reduce their mobility because of the larger mass of the charged aerosol particle. Consequently, a decrease in the electric conductivity observed over open oceans is considered as an increase in the aerosol concentration and vice versa. Any change in ionization due to the change in the cosmic ray intensity, e.g., during Forbush decreases, is mostly confined to the upper atmosphere and its effect on ionization at the ground surface, especially at low latitudes, is negligible.

[17] The atmospheric circulation during the northeast monsoon season (i.e., January to April) has a typical role in the Indian Ocean region. The aerosols of different types such as the mineral dust of natural and anthropogenic origin, nitrates from agricultural and traffic related activities, sulphate particles, organic aerosols due to oxidation, biomass burning etc produced over South Asian continent are transported to the Indian Ocean in the South with the predominant low-level flow from the northeast. Also, this low-level air mass is uplifted over oceans to stratocumulus level and finally it forms the deep convective cumulus cloud systems of Intertropical Convergence Zone (ITCZ) which is mostly located in this season between the Equator and 10°S in the Indian Ocean. ITCZ is located at 5°S and 7°S during the periods of the outward and return cruises, respectively. The region south of the ITCZ is free from the continental pollutants as the region is mostly unhabited. The outward and return cruises fall close to the onset and withdrawal phases, respectively, of the northeast monsoon season. The difference in the latitudinal variation of conductivity observed between the outward and return cruises in our measurements can be interpreted in terms of the local meteorological conditions and general circulation in the area. We propose that the minimum at ~28° S is a consequence of the downward transport of fine particles generated by the gas-to-particle conversion process in the

![Figure 6. Variations of the total conductivity and aerosol concentrations with latitude for the outward and return cruises.](image-url)
upper troposphere, in the subsidence leg of the Hadley cell of the Southern Hemisphere which is located at this latitude during this part of the year. The opposite trends in the conductivity variation with latitude in the 10°N–20°S belt observed during the outward and return journeys in our measurements can be explained on the basis of latitudinal broadening of the width of the southern Hadley cell and the consequent northward shift of its subsidence leg during the period of return journey in March–April [Newell et al., 1972]. During the outward journey, the northern Hadley cell is intense and large in extent, extending from 28° N to 10°S. At that time, the southern Hadley cell extends from 10°S to 30°S. Transport of fine aerosols from the free troposphere in the subsidence leg of the southern Hadley cell shall cause the conductivity to decrease at about ~28°S. The northward transport of these aerosols at lower altitudes and their eventual lift-up in the upward leg of the southern Hadley cell will cause the aerosol concentration to decrease and consequently the conductivity to increase from 28° to 10°S. North of 10°S the aerosol concentration will increase due to the transport of continental aerosols with northeast low-level flow in the northern Hadley cell. This will cause the decrease in conductivity observed near the Equator. During the period of the return journey, two Hadley cells are of comparable intensities and there is a latitudinal broadening of the width of the Southern Hemisphere cell resulting in a northward shift of its subsidence leg. The features in the latitudinal variation of conductivity such as the diffused minimum between 30° and 20° S, the systematic increase from 20°S to the Equator and the decrease north of Equator support the hypothesis proposed above.

[18] From his measurements in the free troposphere of the equatorial Pacific, Clarke [1993] showed that nucleation in the upper troposphere and subsequent growth by coagulation and vapor diffusion could be a major source of new particles in that region. These measurements support the conclusions of a large-scale model of aerosol nucleation and dynamics in the free troposphere and marine boundary layer, developed by Raes [1995] which suggests that injection by mixing with the free troposphere is a major source of new submicron particles in the marine boundary layer. For interpreting their mid-Pacific observations, Covert et al. [1996] suggest a model in which the new particle formation occurs in outflow regions of the frontal or convective clouds in the free troposphere where conditions of new particle formation are met [Raes et al., 1993]. These newly formed particles grow by coagulation and condensation in the large-scale Hadley and Walker circulations. Transport of aerosols from the free troposphere to the marine boundary layer occurs by convective mixing in the vertical and general circulation in the horizontal. These particles grow by vapor deposition and therefore the growth is faster in the tropical marine boundary layer where gaseous precursor concentrations are large.

[19] Tending to support the distribution of marine aerosols as proposed in the above model are the results of Heintzenberg et al. [2000] who compiled data from different sources on a global scale, including the data from the INDOEX and other previous cruises in the Indian Ocean. Their analysis shows large maxima for the Aitken mode particle number concentration in 30–45°S belt and a general minimum in equatorial regions on a coarse grid of 15° × 15°. These maxima were observed in the mid and tropical North Atlantic and Indian Oceans downwind of continental sources. Maxima in accumulation mode is comparatively much weaker and is shifted equatorward. These features of
aerosol distribution indicate to some source of Aitken mode particles and their equatorward transport from 30°S. Since Aitken mode shows another minimum towards pole and there is no local source at 30°S the vertical transport of the particles in this mode is more likely.

[29] The opposite trends of the conductivity variation on the outward and return journeys in the 60°–70°S belt are because of the low pressure systems circulating around Antarctica on the outward journey during 1–3 January 1997. As shown in Figure 2, the surface atmospheric pressure at the ship experiences steep falls of 14 and 20 mb at 0300 hours on 2 January 1997 and at 0300 hours on 3 January 1997 respectively.

[31] Most of our cruise route lies in the Southern Hemisphere. The average value of the total conductivity along the cruise track is $1.52 \times 10^{-14} \text{ S m}^{-1}$. From their measurements in the northern Indian Ocean, the Arabian Sea and the Bay of Bengal, Kamra and Deshpande [1995] report an average value of conductivity equal to $1.15 \times 10^{-14} \text{ S m}^{-1}$ for those regions. Such a difference is well expected because of the larger loading of the northern hemispheric atmosphere with aerosol particles. However, surprisingly, the present values of total conductivity in the Southern Hemisphere are less than half of those observed by Cobb and Wells [1970] in the control area in the southern Pacific Ocean ($10°$ to $50°$ S) in 1967 and those observed during Carnegie cruises during 1911–1930 in the equatorial Indian Ocean. The question of whether such a difference is peculiar of these longitudes or season or it indicates a general increase in the aerosol loading of the atmosphere in the Southern Hemisphere, needs to be examined with more measurements.

[22] Our measurements of the atmospheric electric conductivity along the cruise track during the months of December and March do indicate a secular decrease in the conductivity which is most likely a consequence of an increase in the background air pollution. The extent and source of such an increase, of course, needs to be better understood from more measurements of the atmospheric electrical parameters along with those of aerosol and meteorological parameters in other seasons of the year as well.

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References
