JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D22, PAGES 28,643–28,651, NOVEMBER 27, 2001

Background aerosol concentration derived from the atmospheric electric conductivity measurements made over the Indian Ocean during INDOEX

A. K. Kamra, P. Murugavel, S. D. Pawar and V. Gopalakrishnan
Indian Institute of Tropical Meteorology, Pune, India

Abstract. Measurements of the atmospheric electric conductivity on board ORV Sagarkanya during her three cruises over the Indian Ocean (17°N to 20°S, 57°E to 79°E) during the periods of December to March 1996-1997, 1998, and 1999 are reported. The results show that the values of atmospheric conductivity over the southern hemisphere are 2 to 3 times of that over the northern Indian Ocean and the north-to-south gradients extend up to the Intertropical Convergence Zone (ITCZ) and have large interseasonal and intraseasonal variations. The values of electric conductivity have been used to calculate the aerosol concentrations. The latitudinal variations of the aerosol concentration have been observed to have positive gradients from the Indian coastline to the ITCZ, and the gradients are different during the three cruises. The aerosol concentrations attain their pristine level only at 15°–20°S in this season. Because of the large interseasonal variability of the aerosol concentration observed over the northern Indian Ocean, it is concluded that estimating any secular change in the background aerosol pollution may be a futile exercise in this area.

1. Introduction

The measurements of the atmospheric electric conductivity in the marine atmosphere are of special importance because these can be used as an indicator of the background aerosol pollution over the ocean. The major source for the ionization of the air over the ocean is cosmic rays, and the rate of ion production due to this source is almost constant in the lower latitudes. The mobility of small ions also does not show any significant variation. These ions recombine with each other and combine with the aerosol particles, and a state of electrical equilibrium is soon obtained. Under the state of electrical equilibrium, the electrical conductivity is inversely proportional to the aerosol concentration. Therefore the conductivity measurements made over oceans have often been used as an index of background air pollution. These measurements also serve to study the extent of the land-to-ocean transport of aerosol particles. Many observations of conductivity have been made since the Carnegie cruises during 1911-1920 over all major oceans [*Swann*, 1915; *Torreson et al.*, 1946; *Cobb and Wells*, 1970; *Misaki et al.*, 1972; *Morita et al.*, 1973]. These measurements are generally compared with those made during the Carnegie expeditions to find out the secular increase in the background aerosol pollution over the oceans. However, only a few such studies have been carried out over the southern Indian Ocean [*Kamra and Deshpande*, 1995; *Gopalakrishnan and Kamra*, 1999]. In this paper, we report the measurements of conductivity made on board the ORV *Sagarkanya* during its three INDOEX cruises over the Indian Ocean during 1997-1999. Some conclusions regarding the relative trends in latitudinal variations of conductivity and aerosol concentration observed in different years are drawn.

Paper number 2001JD900178.
0148-0227/01/2001JD900178$09.00

2. Instrumentation

The measurements of both polarities of conductivity are made with a Gerdiens apparatus having two identical cylindrical condensers connected with a U-tube. The air is sucked through the condensers with a common fan fixed in the U-tube. The details of the apparatus are given by *Dhanorkar and Kamra* [1992]. The critical mobility of the apparatus is adjusted at 3.6 X 10^{-4} m^2 V^{-1} s^{-1}. The signal from both the condensers is amplified with IC AD549/AD311. Measurements have been made continuously and sampled at an interval of 5 s and stored in a computer except during 1997 when the recording was done on a strip chart recorder. The instrument is placed vertically and is tied to the railing on the balloon deck of the ship at a height of about 9 m from the sea level except during 1997 when the instrument was positioned horizontally at the same level of 9 m. Care was taken to avoid contamination of the air by the exhaust of the ship. Since the level of the chimney is much higher than the balloon deck and the exhaust from the chimney is blown away from the ship, the chimney generally does not contaminate the air around the balloon deck. The condensers are cleaned every 4 hours by alcohol and dried to remove any sea salts deposited on these condensers. Cleaning of Teflon parts of the amplifiers is done whenever required. Further, the observations obtained whenever there is noise in the signal are excluded from analysis. Other steps taken to minimize the contamination by the exhaust of the ship or by other sources are discussed in detail by *Kamra et al.* [1994]. Observations of meteorological parameters such as the wet- and dry-bulb temperatures, wind speed, wind direction, atmospheric surface pressure, and cloud coverage were made after every 3 hours by the India Meteorological Department.

The size-distribution measurements of submicron particles also were made with an Electrical Aerosol Analyzer of TSI Inc., United States during the cruise of 1998 and the onward cruise of 1999. This instrument measures concentration of particles of diameter 3 to 1000 nm in 10 different size ranges. However,

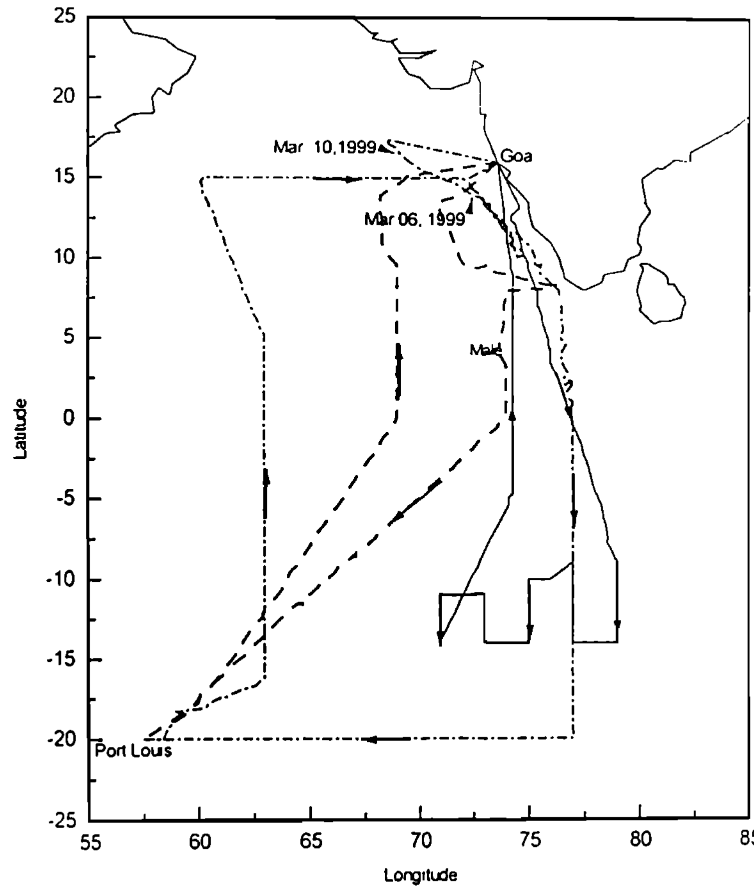

Figure 1. The cruise routes of ORV *Sagarkanya* during 1996-1997, 1998, and 1999 cruises.

because of the insufficient accuracy of the instrument in the lowest two ranges, particles >13 nm diameter only are included in our data. Although the details of these measurements are reported elsewhere (Kamra et al., 2000, JGR, communicated), the measured values of aerosol concentrations on a few days are included here for comparison with those derived from conductivity.

3. Cruises and Weather

Figure 1 shows the tracks of the three cruises of ORV *Sagarkanya* during December 27, 1996, to January 30, 1997, February 19 to March 26, 1998, and January 20 to March 12, 1999. All the three cruises are within the area 17°N–20°S and 59°–79°E and are within the period of December to March. During this period of winter monsoon the northeasterly surface winds flowing out of the subtropical high of the northern hemisphere meet the southwesterly trade winds of the southern hemisphere in the Intertropical Convergence Zone (ITCZ) which is marked with deep convection. The position of ITCZ keeps fluctuating mostly between 0° and 15°S during this period. Ranges of some meteorological parameters on the fair-weather days and the approximate positions of ITCZ when the ship sailed through this zone on the three cruises are given in Table 1.

4. Observations

In order to assume the state of electrical equilibrium the observations obtained only on the fair-weather days are considered. Further, to avoid the effect of any diurnal variations of conductivity, daily average values have been used in our analysis. A day is taken as the fair-weather day when the low-level clouds are less than 3 octas, winds are less than 10 m s^{-1}, and there is no precipitation on the ship. However, to increase the statistics, observations obtained when the above conditions are satisfied during most part of a day are also included. Observations for 20 days during the 1996-1997 cruise, 18 days during the 1998 cruise, and 19 days during 1999 cruise are included for discussion. The conductivity values are first averaged for every hour and then for a day. Figures 2, 3, and 4 are the plots of daily average of the positive and negative conductivity values during the cruises of 1996-1997, 1998, and 1999, respectively. The vertical bars show the standard deviations of the conductivity value on that day. The magnitudes of positive and negative conductivity are approximately the same for most of the days. Somewhat higher values of positive conductivity on some days are most probably because of the manifestation of the electrode effect. In general, the values of conductivity in the northern hemisphere are less than half of that measured in the southern hemisphere.

Table 1. Ranges of Some Meteorological Parameters During the Three Cruises

Feature	1996-1997	1998	1999
Number of fair-weather days	20	18	19
Range of atmospheric temperature, °C	25.8-28.2	24.8–28.8	25.0– 32.6
Range of relative humidity, %	73-92	53-92	63–90
Wind, m s^{-1}	1-8	1-6	1-8
Range of visibility, km	6-10	6-15	6-15
Position of ITCZ	10°–14°S	12°S on March 9 (onward) 4°-5°S on March 19/20 (return)	2°–3°S on Jan. 28/29 (onward) 7.5°S on Feb. 22 (return)

During the 1996-1997 cruise the values of conductivity increase as one moves away from coast on the onward journey and decrease as one approaches the coast on the return journey. The values of conductivity vary between 0.23 and 0.84 x 10^{-14} s m^{-1} in the northern hemisphere and from 0.99 to 2.48 x 10^{-14} s m^{-1} in the southern hemisphere.

During the 1998 cruise the ship either remains close to the Indian west coast or sails between some islands in the Indian Ocean up to March 1, 1998. Therefore, because of the closeness of land areas to the cruise route, the values of conductivity remain comparatively lower during this period. The conductivity rapidly increases after March 1 when the ship starts sailing farther southward from Male. It is noticeable that on the return journey when the cruise route is away from the coast and islands, the values of conductivity are comparatively much higher as compared to those observed on the same latitudes on the onward journey.

During the 1999 cruise the conductivity values are surprisingly low in the central Arabian Sea region 0°-15°N, 60° –72°E on the return journey. However, this is in conformity with the observation of the high values of optical depth observed by *Krishnamoorthy and Saha* [1999] in this region during the same cruise. They explain those relatively higher values of aerosol concentration in this region on the basis of some aerosols being transported from the east Asian deserts.

Morita et al. [1973] and *Kamra and Deshpande* [1995] have

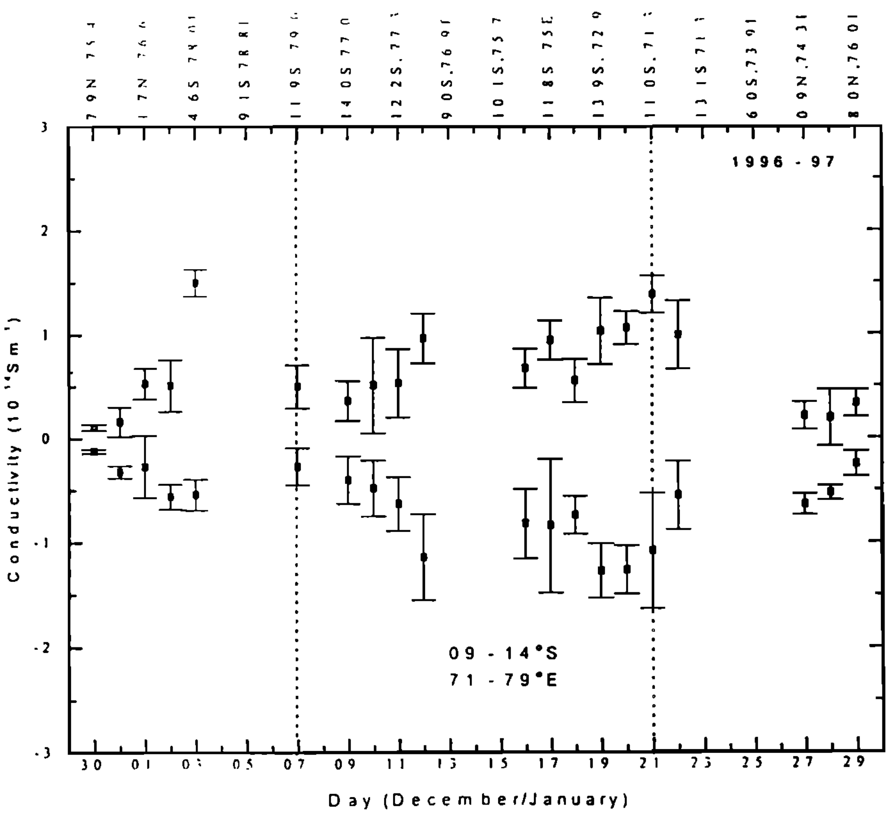

Figure 2. The daily average values of positive and negative conductivity for 1996-1997 cruise. The top axis denotes the latitude and longitude position of the ship at 0000 UT.

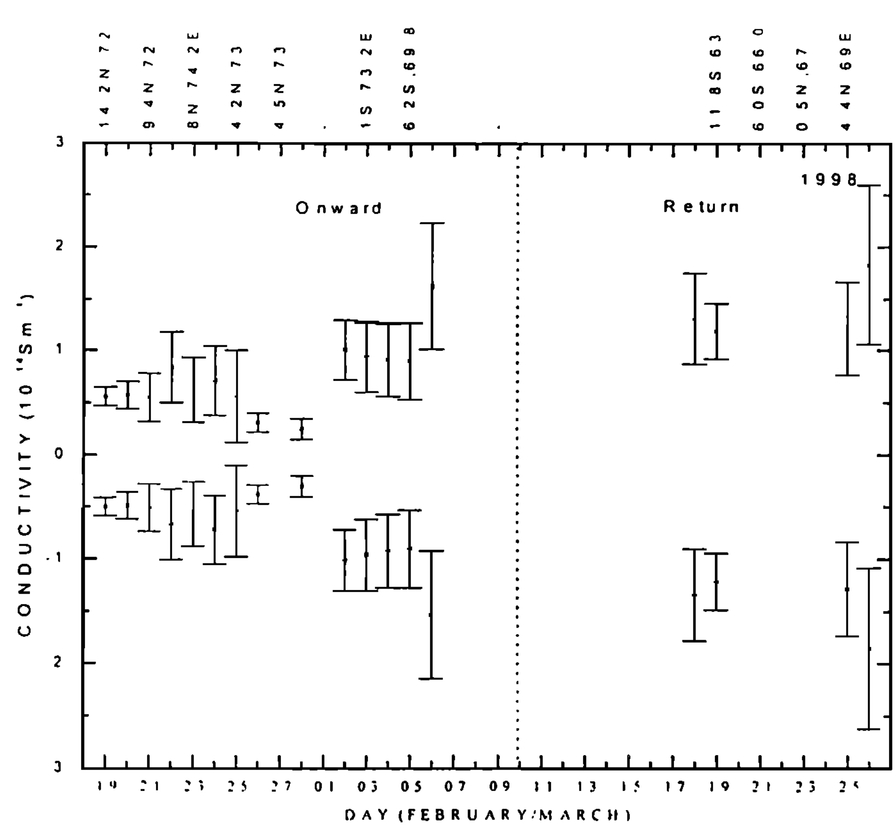

Figure 3. Same as Figure 2 but for 1998 cruise.

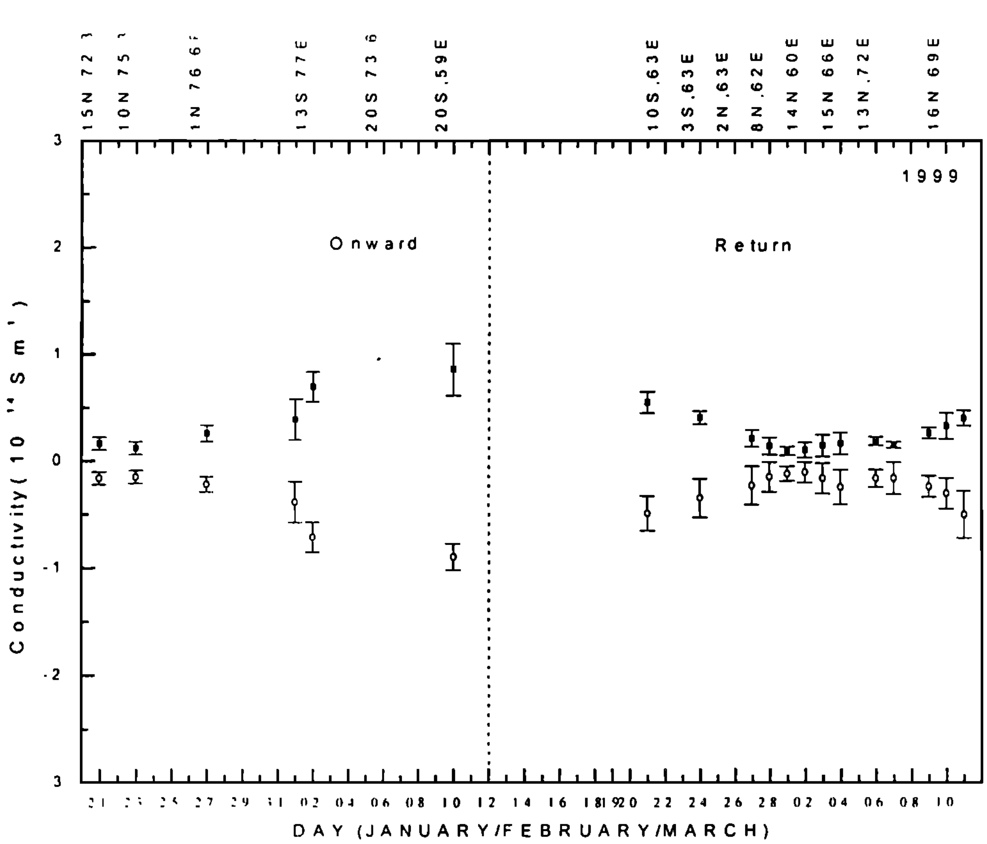

Figure 4. Same as Figure 2 but for 1999 cruise.

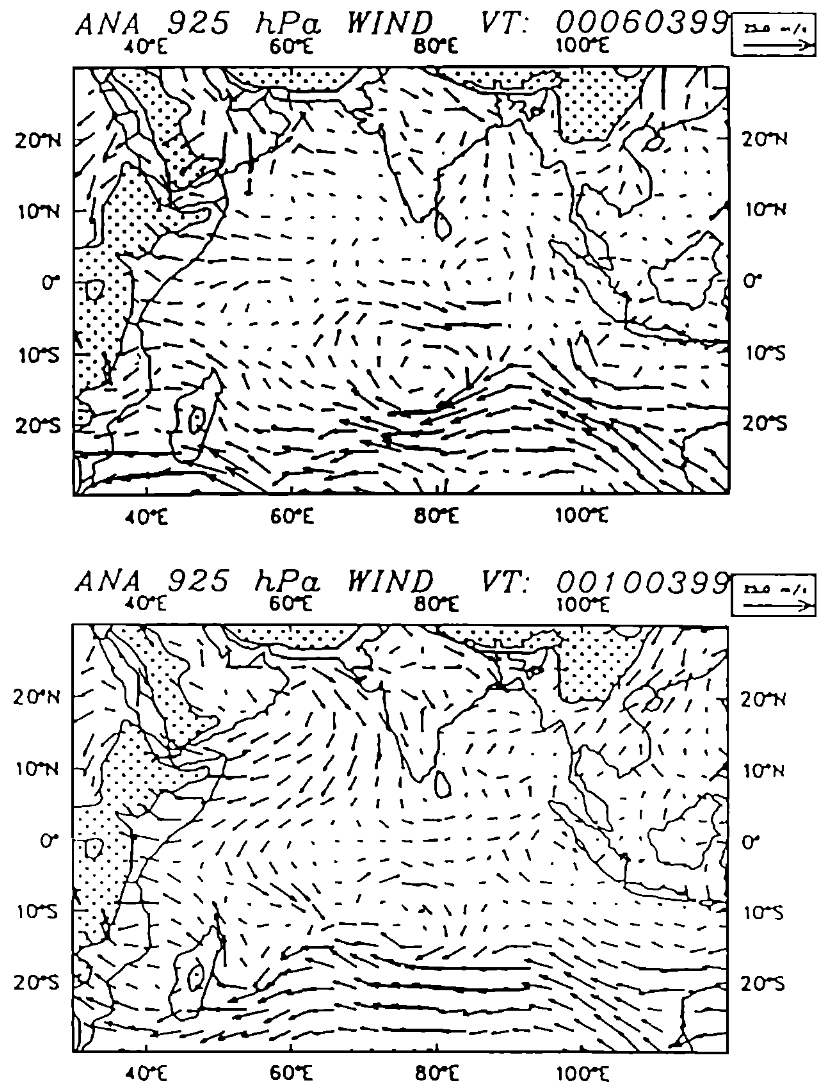

Figure 5. Wind plot at 925 mbar level on March 6 and March 10, 1999. (From Meteorological Analysis During INDOEX Intensive Field Phase – 1999 – Volume II: Wind Analysis and Trajectories, prepared by O.P. Madan, U. C. Mohanty, R. K. Paliwal, D. R. Sikka, S. R. Kalsi, Gopal Iyengar, Harendu Prakash, K. J. Ramesh, R. S. Pareek, K. S. Zalpuri, P.V. S. Raju, Asit Patra and Sumana Bhattacharya).

pointed out that the value of conductivity at a place on the ocean is determined by the age of air mass at that location. This fact is well documented in our observation of conductivity from February 28 to March 11, 1999, when the cruise has two legs along the Indian coastline. Figure 5 shows the 925 mbar winds on March 6 and March 10, 1999. On March 6, winds are weak and not well organized at 13^{0}N and 69^{0}E. So, any transportation of the aerosols to the site will be dominated by their diffusion from the Indian subcontinent. However, on March 10, 1999, the winds are northwesterly and approaching the ship from the west Asian deserts after a relatively long journey over the ocean. Accordingly, the values of conductivity increase from March 7 to March 10, 1999, as the ship sails northward from 13°N, 69°E to 17°N, 72°E. This increase in conductivity may also be partly attributed to the increase in the distance between the cruise route and the coastline.

To study the latitudinal variation of conductivity, we have averaged the total conductivity values for each 2° of latitude obtained on both the onward and return journeys for each cruise separately. Figure 6 shows that the value of conductivity in this region systematically increases in each cruise as one goes from north to south. However, the slope of this latitudinal variation of conductivity varies from cruise to cruise. The average value of conductivity at any particular latitude in any cruise is determined from its value in that year near to the Indian coastline. For example, in our observations the values of conductivity are higher at all latitudes during the 1998 cruise and lower during the 1999 cruise. Consequently, the values of conductivity continue to remain higher at all latitudes during the 1998 cruise than during the 1999 cruise. Similarly, the values of conductivity during the 1996–1997 cruise continue to remain in between 1998 and 1999 values on all latitudes.

5. Calculation of the Background Aerosol Pollution

If a state of electrical equilibrium is assumed over the marine atmosphere, the concentration of aerosol pollutants can be

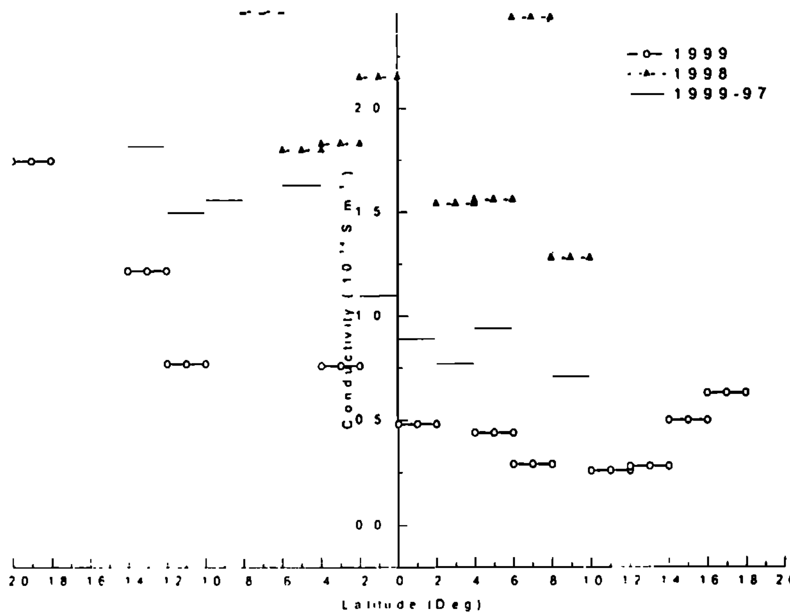

Figure 6. The variation of conductivity with latitude.

calculated from the values of conductivity by using the unipolar ion balance equation. Assuming that the unipolar large ion concentration N is 20% of the total aerosol concentration Z, then from the solution of ion-balance equation of *Sagalyn and Faucher* [1956], *Manes* [1977] derives that

$$Z = \frac{5}{\beta}\left[\frac{qek}{\lambda} - \frac{\alpha\lambda}{ek}\right] \quad (1)$$

where α is the coefficient of recombination of the oppositely charged small ions, β is the attachment coefficient, q is the ion production rate over marine atmosphere, k is the mobility of small ions, e is the elementary charge, and λ is the atmospheric polar conductivity of the air. In our calculations we take $\alpha = 1.6 \times 10^{-12} m^3 s^{-1}$, $\beta = 10^{-11-3} s^{-1}$, $q = 1.6 \times 10^6$ ion pairs $m^{-3} s^{-1}$, $k = 1.14 \ m^2 V^{-1} s^{-1}$, $e = 1.6 \times 10^{-19}C$, and λ as the positive conductivity of the atmosphere.

In computing the aerosol concentrations from (1), the values of β, Z/N, and k are assumed to be constant. However, the values of these constants vary with the size of aerosols. For example, *Hoppel* [1985] shows that the value of β decreases from 10^{-5} $cm^{-3} s^{-1}$ to 10^{-6} $cm^{-3} s^{-1}$ as the particle size decreases from 1000 to 1 nm. Similarly, the average value of ratio Z/N varies between 0.1 and 0.22 as the particle size of a monodisperse aerosol decreases from 1000 to 10 nm and then sharply drops to 0.01 as the particle size decreases to 1 nm. Further, the value of k varies with not only the size of ion but also with the ambient meteorological conditions such as the atmospheric temperature, pressure, and humidity. Moreover, the solution of ion-aerosol balance equation involves certain assumptions. For example, it is assumed that a state of electrical equilibrium exists and the number concentrations of positive and negative small ions are equal. These assumptions may not be always correct under different conditions, and the constant values assumed for different parameters in (1) may not be always justified.. Consequently, the values of aerosol concentration calculated from (1) are expected to have some uncertainty. Nevertheless, several estimates of aerosol concentrations, as referred to before, have been made in the past.

To examine the degree of uncertainty in calculating the number concentrations from (1), we have compared our conductivity-derived values with those measured directly with an Electrical Aerosol Analyzer system on six fair-weather days during the IFP-99 period when the measurements with both the Gerdien's condenser and the EAA system were made. Figure 7 shows these values on two typical fair-weather days. The conductivity-derived values are almost consistently higher than the observed values of aerosol concentration. Similar trend is observed on other fair-weather days. The difference may be either due to the uncertainty in the conductivity-derived values of aerosol concentration as discussed above or due to the different size ranges of aerosol particles being covered in the two techniques. The particle-size range covered in our EAA measurements is 13 to 1000 nm. On the other hand, conductivity strongly responds to charged particles of size even <13 nm. Our aerosol size-distribution measurements in this region strongly indicate very large concentrations and perhaps a maximum for particles of diameter <13 nm. This can very well justify the higher values of particle concentration from our conductivity measurements.

A study to specify the conditions under which the measured and conductivity-derived values of aerosol concentration should reconcile with each other is underway by the authors. Irrespective of such attempt, however, some conclusions based on the relative values of latitudinal distribution of aerosols can be drawn from the presented data. Figure 8 shows the variation of aerosol concentration with latitude, calculated from our data of conductivity values averaged for 2° latitude and presented in Figure 6. A general north-to-south decrease in the aerosol concentration is apparent. Continuous lines show the lines of best fit for the data obtained during each individual cruise and illustrate the north-to-south decreasing trend in aerosol concentration for the individual cruises in the 3 different years. The slope of the line is higher if the aerosol concentration near to the Indian coastline is higher. Although the slopes of the three lines are different, they tend to approach some common minimum value of aerosol concentration at 20° – 25°S which is likely to be close to the pristine level of aerosol concentration in the southern hemisphere. The observations very well illustrate

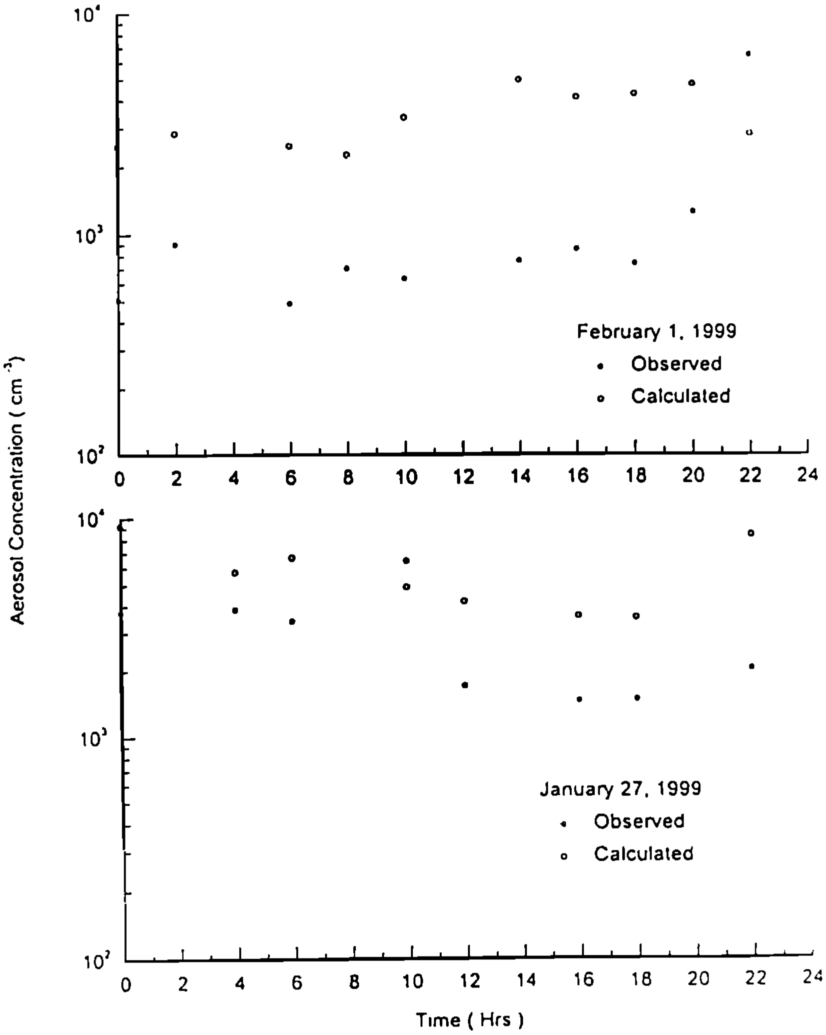

Figure 7. Comparison of the conductivity-derived and the measured values of aerosol concentrations on January 27 and February 1, 1999.

that the average aerosol concentration in any latitudinal belt, particularly over the northern Indian Ocean, may be vastly different from year to year during the northeast monsoon season. The range of variation of aerosol concentration observed over the northern Indian Ocean is much larger than over the southern Indian Ocean. This is true even for the individual cruises in different years. As compared to 1998 values, aerosol concentration over the northern Indian Ocean is approximately 4 and 5-6 times higher during the 1996-1997 and 1999 cruises, respectively. The ranges of the aerosol concentration variation over the southern hemisphere for the corresponding years are much less than those observed over the northern Indian Ocean.

6. Discussion

During the Asian winter monsoon season, in which all these three cruises fall, the northwesterly winds prevail over the northern Indian Ocean. These winds bring aerosol pollutants and trace gases from the Asian continent and can carry them all the way into the ITCZ where this polluted air meets the pristine air from the southern hemisphere. In this season, since the ITCZ is shifted to about 0°-15°S in this region, the pollutants are transported well across the equator and enter into the southern hemisphere. While being transported from north to south, the aerosol particles keep settling down to the surface, and hence their concentration decreases as one goes away from the coastline. Our observations support such transport of aerosol particles.

Our observations also show that the amount of aerosols introduced into the atmosphere from the land surface may be vastly different in the northeast monsoon season from year to year or even for different time periods within a single season. Such a result is expected because the introduction of particles from land to the atmosphere will depend upon several factors such as the soil condition, vegetation, surface winds, atmospheric vertical stability, synoptic meteorological condition, etc.

It has been attempted by several investigators to estimate the secular change in the background air pollution from the measurements of conductivity over the open oceans [e.g., *Cobb and Wells*, 1970; *Kamra and Deshpande*, 1995]. Our measurements during different cruises show that it may be a futile exercise to make such estimates from observations made over the North Indian Ocean in the Asian winter monsoon season in view of the large variability of aerosol concentration observed

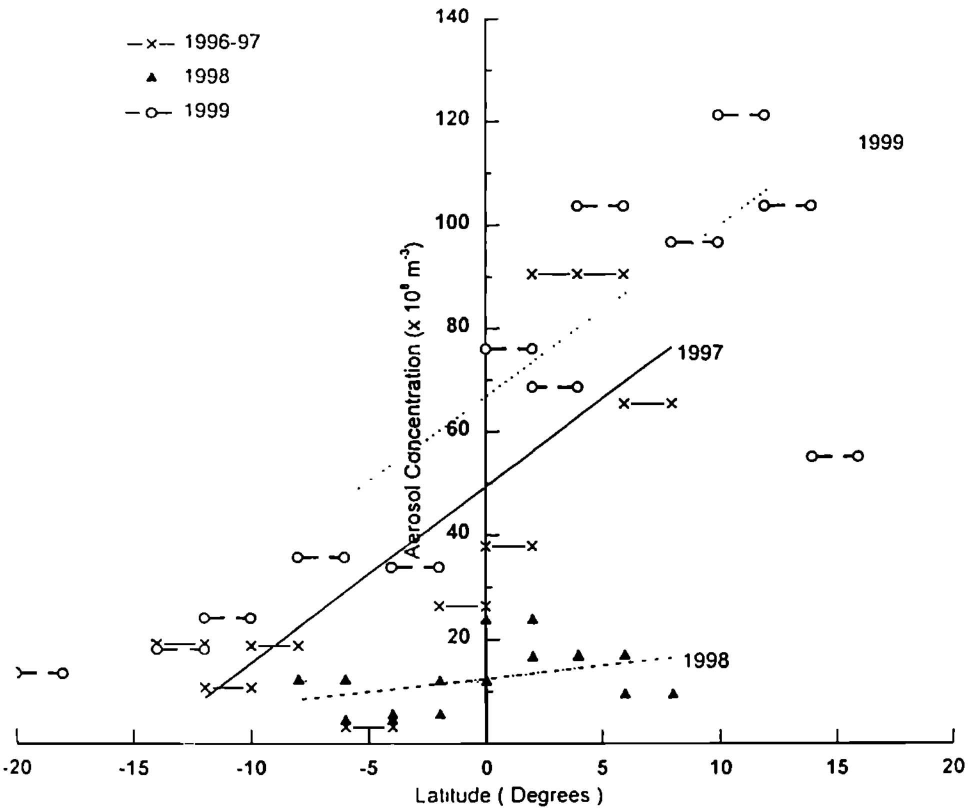

Figure 8. The variation of calculated aerosol concentration with latitude. The slanting lines are the best linearly fitted lines for the corresponding years.

there. The interseasonal and perhaps intraseasonal variabilities in air pollution over the northern Indian Ocean in this season may well mask any secular change in the air pollutants.

7. Conclusions

1. Our measurements of the atmospheric electrical conductivity over the Indian Ocean show that the values of conductivity in the southern hemisphere are 2 or even 3 times of that measured in the northern hemisphere.

2. The north–to–south positive gradients in aerosol concentration observed during the northeast monsoon season over the Indian Ocean extend up to the ITCZ and have large interseasonal and intraseasonal variability.

3. Since the aerosol concentrations in the marine atmosphere over the Indian Ocean strongly depend on the season during which such measurements are made, any attempt to study the secular change in the background air pollution is a futile exercise in this region.

Acknowledgments. We express our thanks to the organizers of INDOEX for providing facilities to take observations on ORV *Sagarkanya*. We are also thankful to the India Meteorological Department for the meteorological data.

References

Cobb, W. E., and H. J. Wells, The electrical conductivity of oceanic air and its correlation to global atmospheric pollution, *J. Atmos. Sci.*, *27*, 814-819, 1970.

Dhanorkar, S., and A. K. Kamra, Relation between electrical conductivity and small ions in the presence of intermediate and large ions in the lower atmosphere, *J. Geophys. Res.*, *97*, 20,345-20,360, 1992.

Gopalakrishnan, V., and A. K. Kamra, Measurements of the atmospheric electric field and conductivity made over Indian Ocean during December 1996 – January 1997, *Curr. Sci.*, , 76, 990-993, 1999.

Hoppel, A. W., Ion-aerosol attachment coefficients, ion depletion, and the charge distribution on aerosols, *J. Geophys. Res.*, *90*, 5917-5923, 1985.

Kamra, A. K., and C.G. Deshpande, Possible secular change and land-to-ocean extension of air pollution from measurements of atmospheric electrical conductivity over the Bay of Bengal, *J. Geophys. Res.*, *100*, 7105-7110, 1995

Kamra, A. K., C. G. Deshpande, and V. Gopalakrishnan, Challenge to the assumption of the unitary diurnal variation of the atmospheric electric field based on observations in the Indian Ocean, Bay of Bengal, and the Arabian Sea, *J. Geophys. Res.*, *99*, 21,043-21,050, 1994

Krishnamoorthy, K., and A. Saha, Aerosol study during INDOEX: Observation of enhanced aerosol activity over mid Arabian Sea during the northern winter, *J. Atmos. Sol. Terr. Phys.*, *62*, 65-72, 1999.

Manes, A., Particulate air pollution trends deduced from atmospheric electrical conductivity measurements at Bet-Dagan (Israel), in *The Electrical Processes in Atmosphere*, edited by . H. Dolezalek and R. Reiter, pp.109-118, Steinkopff, Darmstadt, Germany, 1977.

Misaki, M., M. Ikegami, and J. Kanazawa, Atmospheric electrical conductivity measurement in the Pacific Ocean, exploring the background level of global pollution, *J. Meteorol. Soc. Jpn.*, *50*, 497-500, 1972.

Morita, Y., H. Ishikawa, J. Nagasaka, and M. Kanada, The land-to-ocean transitional behaviour of the atmospheric electrical parameters and their relation to atmospheric pollution, *J. Meteorol. Soc. Jpn.*, *51*, 294-306, 1973.

Sagalyn, R. C., and G. A. Faucher, Space and time variations of charged nuclei and electrical conductivity of the atmosphere, *Q. J. R. Meteorol. Soc.*, 428-445, 1956.

Swann, W. F. G., The atmospheric-electric observations on the third cruise of 'Carnegie', 1914, *Terr Magn. Atmos. Electr.*, 20, 13-48, 1915.

Torreson, D. W., W. D. Parkinson, O. H. Gish, and G. R. Wait, Scientific results of cruise VII of the `Carnegie' ocean atmospheric-electric results, *Publ. Rep. 568*, pp. 1-176, Carnegie Inst., Washington, D. C., 1946.

V. Gopalakrishnan, A. K. Kamra, P. Murugavel, and S. D. Pawar, Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune 411 008, India. (kamra@tropmet.ernet.in)

(Received July 19, 2000; revised October 12, 2000; accepted March 15, 2001.)