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Effect of relative humidity on the electrical conductivity of marine air

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SUMMARY

Measurements of the atmospheric electric conductivity made in the equatorial Indian Ocean and Arabian Sea in August and September 1991 show that the value of conductivity decreases from 2.3×10^{-14} mho m^{-1} in the equatorial Indian Ocean, where relative humidity of the surface air is 70–80%, to 1.1×10^{-14} mho m^{-1} in the region of the Somali current, where relative humidity of the surface air increases to 80–90%. The inverse relationship observed between conductivity and relative humidity, in spite of showing a large scatter, is stronger in the case of negative than positive conductivity. The sharp increase in the sizes of ions and marine aerosol particles when the relative humidity exceeds 75–80% is proposed as the cause of the observed decrease in conductivity in the region of the Somali current.

KEYWORDS: Atmospheric electricity   Indian Ocean   Marine aerosols   Somali current

1. INTRODUCTION

Since the radioactivity of sea water and the air over it is negligibly small, the ionization of air over the oceans is mainly caused by cosmic rays. The intensity of cosmic rays shows hardly any variation over lower geomagnetic latitudes around the equator. Therefore, the ionization and the resulting electrical conductivity of the air over open oceans is almost constant. Consequently, the electrical conductivity of oceanic air has often been proposed to serve as an index of air pollution. Any secular change in the marine air conductivity has, therefore, been interpreted as indicating a change in background air pollution (Cobb and Wells 1970). Also, an increase in the conductivity of marine air with distance from the coastline is suggested to occur because of the decrease in the particle content of the air (Misaki and Takeuti 1970; Misaki *et al.* 1972; Morita *et al.* 1973; Morita and Ishikawa 1977; Kamra and Deshpande 1995).

Besides the number concentration of ions, the atmospheric electric conductivity also depends on the mobility of ions. Both these factors may be influenced by the prevailing meteorological conditions. However, the authors are not aware of any attempt to investigate the effect of meteorological conditions on the conductivity of marine air. In this paper, we report our measurements of the atmospheric electric conductivity made aboard an oceanographic ship, ORV *Sagarkanya*, in the equatorial Indian Ocean and Arabian Sea, and analyse the data to examine the effects of the prevailing meteorological conditions on conductivity.

2. INSTRUMENTATION

Atmospheric electric conductivity of both polarities was measured with an apparatus consisting of two identical cylindrical Gerdien condensers joined with a U-tube (Dhanorkar and Kamra 1992). Air is sucked through the two condensers with a common fan. The critical mobility of the apparatus for both polarities of ions is 2.93×10^{-4} m^{2}V^{-1}s^{-1}. The signal from each condenser is amplified separately using high-impedance amplifiers (AD 311K) having low temperature drift ($10 \ \mu$V K^{-1}) and recorded continuously on a strip-chart recorder kept inside a room 9 m away from it. Maintenance of the apparatus, especially cleaning its insulators with methanol and drying them for a few minutes with a hair-drier,

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was done at least daily. Since slow deposition of salt on insulators in a marine atmosphere may cause development of a leakage of current, the zero-shift was checked by switching off the suction fan, and any errors corrected, every 4–5 hours. Since no significant zero shift was observed over this period, the checking interval was considered to be sufficient. To check the equivalence of the two condensers, the polarity of conductivity measured by each condenser was reversed; however, no measurable difference in output was noticed between them.

Conductivity apparatus was mounted on a 1 m high wooden stool on the balloon launching platform of the ship, which is 9 m above sea level. Direction of movement of the ship with respect to the prevailing wind was such that most of the time during the cruise the apparatus was either upwind of, or perpendicular to, the exhaust from the chimney. Sometimes, when the air around the apparatus was visually observed to be polluted by the exhaust, the measurements were excluded from our analysis. However, there were only six such occasions over the whole 34 days of the cruise, and none of these lasted for more than one and a half hours.

Meteorological data collected by the India Meteorological department were used in our analysis. Measurements of the dry- and wet-bulb and sea surface temperatures (SSTs) were made with mercury thermometers with 0.1 degC accuracy, the wind speed with an anemometer with 0.2 m s^{-1} accuracy, and the atmospheric pressure with an aneroid barometer with 0.1 hPa accuracy. The relative humidity was determined from dry- and wet-bulb temperature data. Because of uncertainty in dry- and wet-bulb temperature measurements, the uncertainty in calculated values of relative humidity is $\pm 1\%$.

3.   OBSERVATIONS

(a)   Weather and climate of the region of measurements

Figure 1 shows the route of the cruise which started from Goa, India, on 17 August 1991 and ended on 20 September 1991 at the same place. Also shown are the wind speeds and directions and the cloud coverage plotted twice every day at 0000 UTC and 1200 UTC, and the minimum and maximum values of atmospheric temperature and relative humidity for each preceding day plotted at 0000 UTC along the cruise, derived from 3-hourly meteorological observations taken on the ship. The predominant south-westerly direction of winds in the Arabian Sea, which is a characteristic climatic feature of the south-west monsoon season in this region, is well illustrated. Air over the equatorial Indian Ocean, except off the Arabian coast and central Arabian Sea, is warmer and has lower relative humidity compared with that over the western Arabian Sea closer to the Somalian coast. These meteorological observations also show that the atmospheric pressures range between 1009.5 and 1017.1 hPa, the sea surface temperatures between 22.8 and 29.5 °C, and the visibilities between 2 and 20 km. The wave height was less than 2 m during the period of the cruise.

Figures 2 and 3 show contour diagrams drawn from our data of the 6-hourly averaged values of the SST (T_0) and relative humidity, respectively. Drawing a contour diagram of SST based on the cruise data only is appropriate, because diurnal variation is small, and any change at a place over the whole period of the cruise is not expected to be substantial. Contour diagrams of the relative humidity (Fig. 3) are discussed later. SSTs are relatively lower and relative humidities are higher in the region extending eastward from the Somalian coast compared with the central Indian Ocean. Both parameters have a north-west to south-east gradient running almost perpendicular to the Somalian coast. The SSTs in the region extending east of roughly the 27 °C isotherm are higher than the temperatures of the air over it, and lower in the region extending west of the 27 °C isotherm.
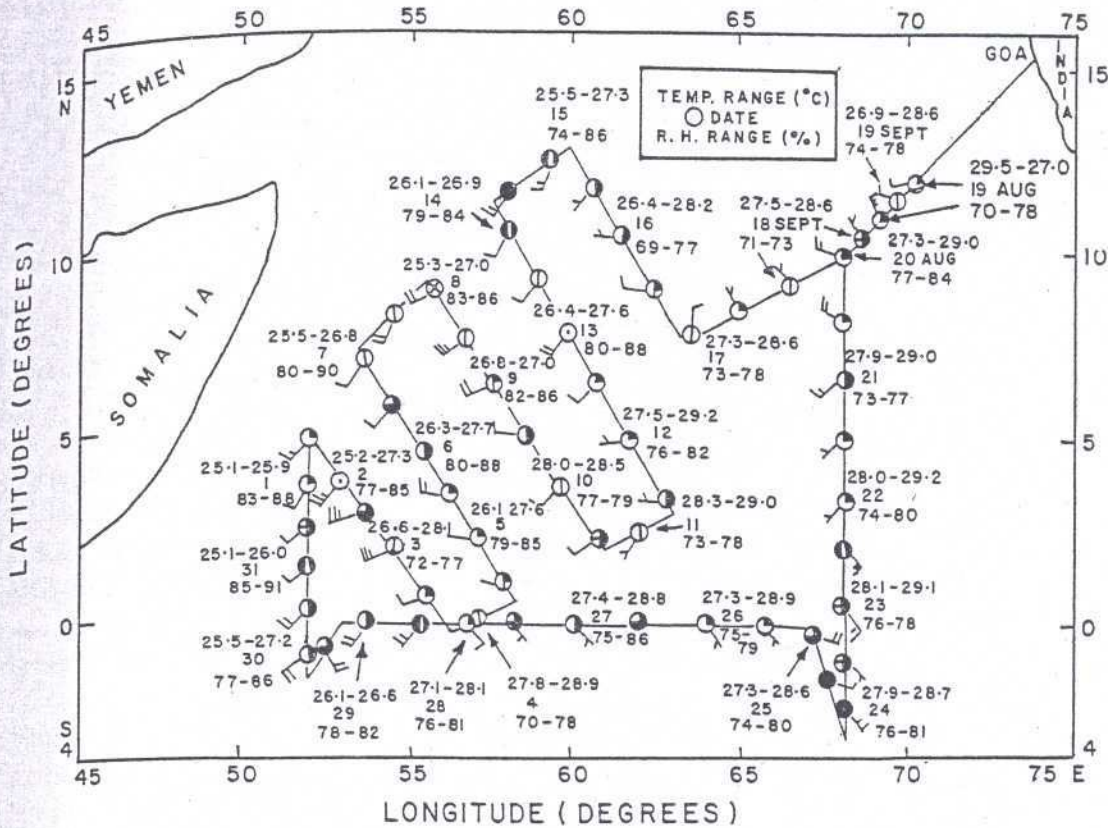
Figure 1. The route of ORV *Sagarkanya* and the values of wind speed and direction, cloud coverage, and the diurnal ranges of atmospheric temperature and relative humidity during the cruise from 17 August to 20 September 1991.
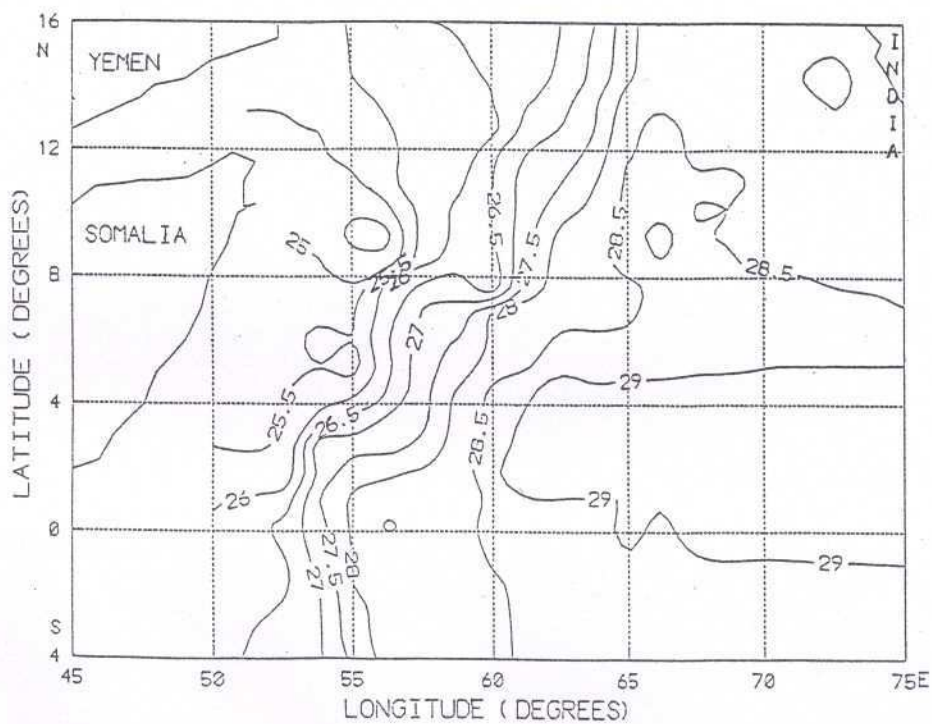

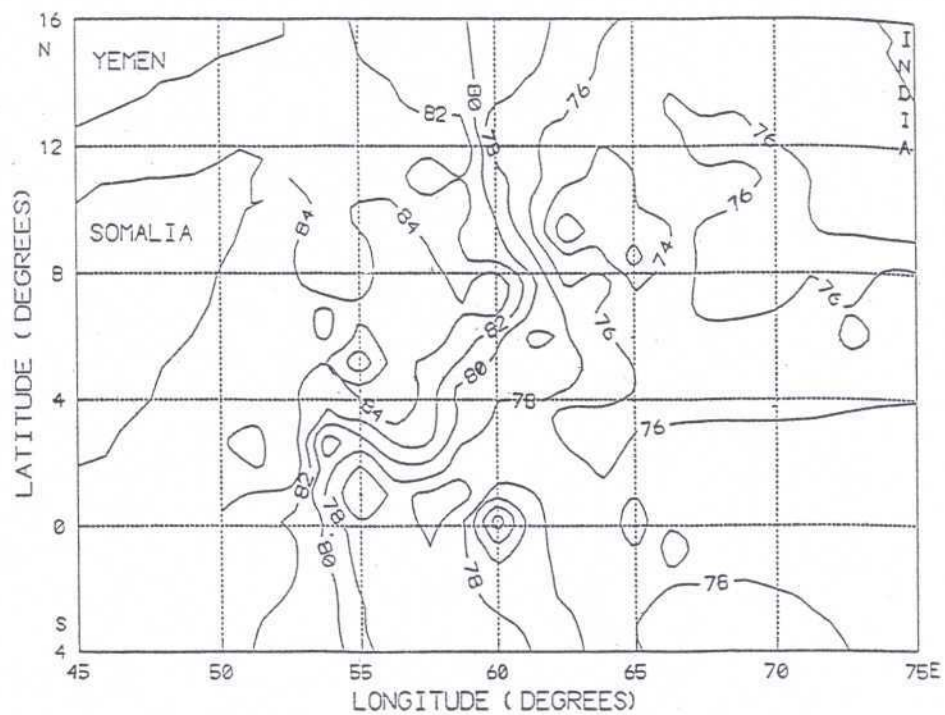Figure 2. Sea surface temperature (°C) for the period of the cruise.

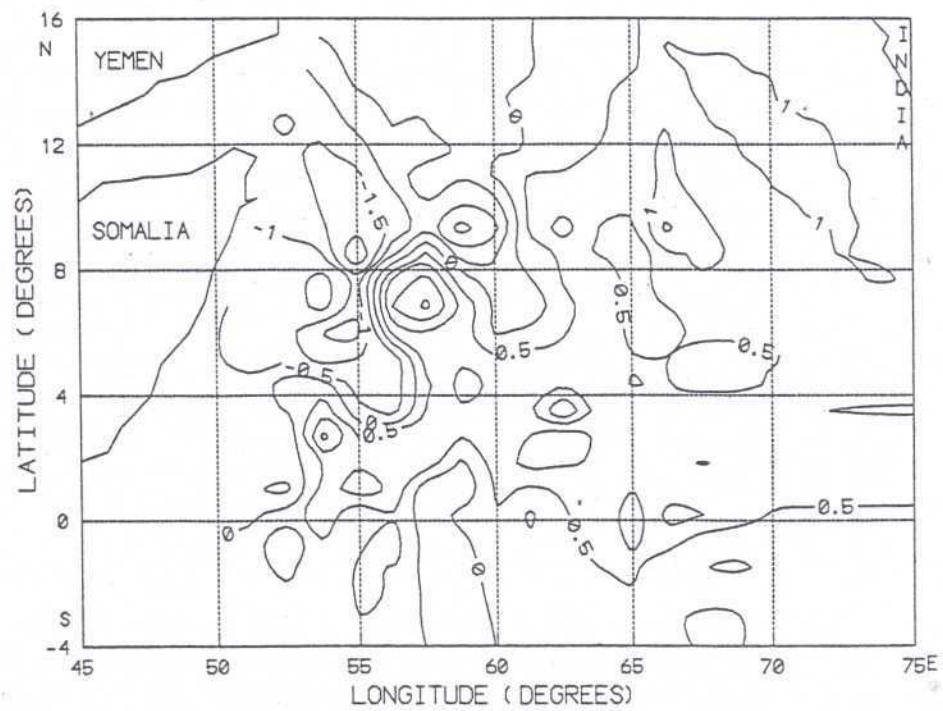Figure 3.   Relative humidity (%) for the period of the cruise.

Figure 4.   Difference (degC) between sea surface temperature and dry-bulb temperature for the period of the cruise.

This is effectively demonstrated in the contour diagram of $(T_0 - T)$ in Fig. 4 (T is the dry-bulb temperature), which shows convectively unstable air in the central Indian Ocean. The increase in relative humidity as the SST and air temperature approach each other can be seen from a comparison of Figs. 3 and 4.

In order to interpret our conductivity measurements correctly, the main meteorological features of the region in this season are summarized below (Keshavamurty and Sankar Rao 1992; Asnani 1993). The east African low-level jet and the associated upwelling of cool water off the coast of Somalia are characteristic features of the south-west Arabian Sea in the northern summer. The region of low SSTs which, initially in the month of May is confined to the west Arabian Sea, appears to spread eastwards with the advance of the monsoon. The upwelling of cool water is most pronounced from July to August. However, the equatorial Indian Ocean, except the region off the Arabian coast, maintains its temperature. The distribution of the various meteorological elements shown in Figs. 2–4 for this cruise are in agreement with this climatological distribution.

South-easterlies in the southern hemisphere swing across the equator in August and September and flow as south-westerlies in the south-west Arabian Sea. This cross-equatorial flow ensures that, except close to the north–south oriented east African coast, the air flowing over the equatorial Indian Ocean and Arabian Sea south of near 9°N has a long history of travel over ocean. North of near 9°N, however, the low-level east African jet stream emerges over the Arabian Sea after flowing over the flat coastal strip of Kenya and lower lands of Somalia. Consequently, the air south of 9°N in this region will be typical of maritime air and thus low in aerosol content, whilst the air north of near 9°N may be richer in aerosol content near the coast, with the concentration decreasing with distance from the coastline. However, since every point on the cruise is more than 350 km away from the coastline, any land-to-sea advection of aerosols up to the measuring site is not expected to be substantial.

(b) Conductivity measurements

Electrical conductivity data, continuously recorded during the cruise, were also averaged for every 6-hours duration for the whole period of the cruise. Any modification of the 6-hourly averaged values of conductivity because of charge generation due to the splashing of raindrops or occurrence of whitecaps on the sea surface was not considered to be significant, since only periods of light precipitation not exceeding a few minutes were observed to occur (five times during the cruise), and areas of whitecaps were sighted only for short periods and were neither frequent nor widespread. The atmospheric electric field, also recorded during the cruise, was never observed to be sufficiently intense for corona to occur from any object on the ship. Therefore all data, except at points where the exhaust of the ship was visually observed to pollute the air over the measuring site, were included in the analysis.

Figure 5 shows contours drawn from our data of the 6-hourly averaged values of the total electrical conductivity. A comparison of the data west of 63°E in Fig. 5 with that of Figs. 2–3 shows that the regions extending eastward from the Somalian coast, with lower SSTs and ambient air temperatures and higher relative humidities, have comparatively lower values of conductivity. It also shows some similarity in gradients of all these parameters in a north-west to south-east direction, which is almost perpendicular to the Somalian coast. The increase in SST and air temperature, and the decrease in relative humidity in this direction, are accompanied by an increase in conductivity. The correlation is best demonstrated inside the area enclosed by the dashed lines in Fig. 5, which runs almost perpendicular to the Somalian coast and will be further analysed in section 5. A similar correlation is seen along the equator, where the gradients of these parameters are
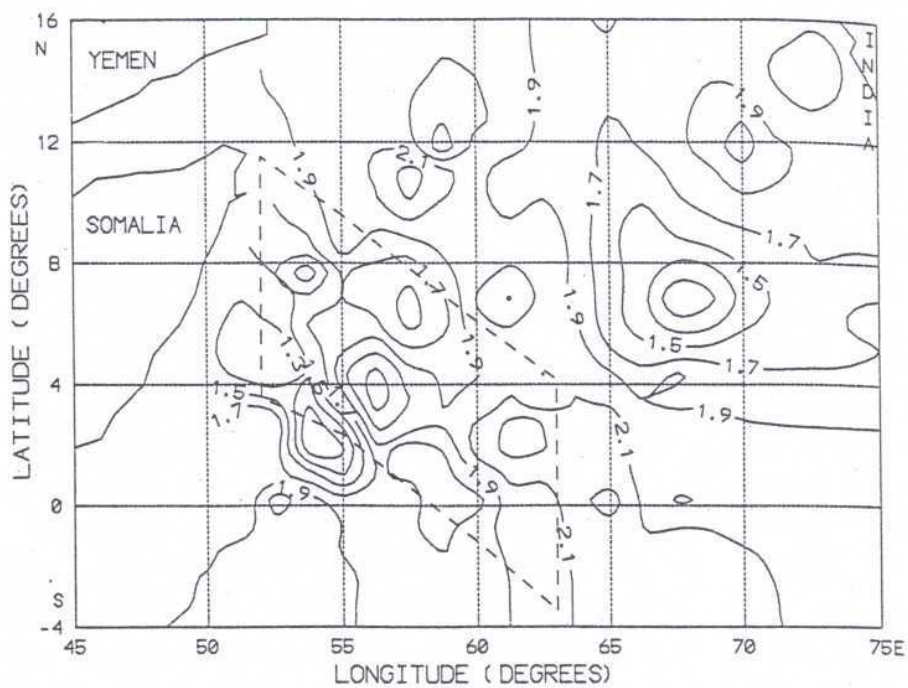
Figure 5.   Total conductivity ($\times 10^{-14}$ mho m^{-1}) for the period of the cruise. The relationship between conductivity and relative humidity/sea surface temperature is examined within the area enclosed by dashed lines.
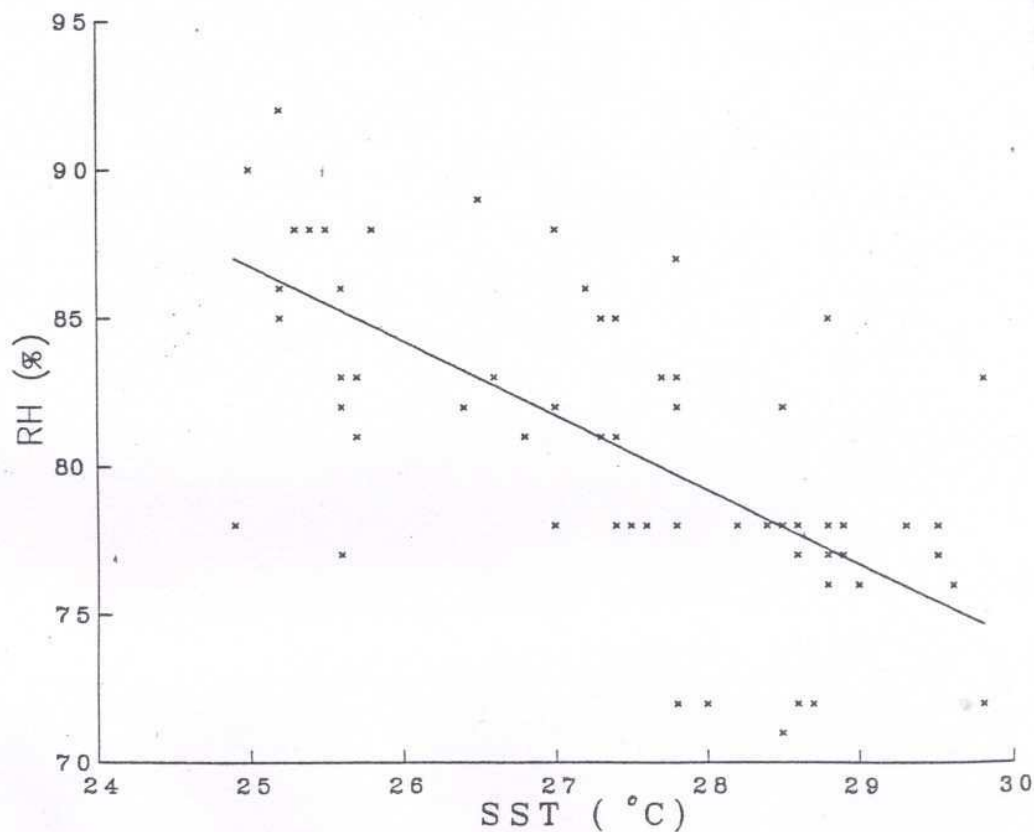

Figure 6.   Scatter diagram of relative humidity (RH) versus sea surface temperature (SST) for the area inside the dashed lines in Fig. 5.

somewhat weaker but all almost perpendicular to the equator. The distributions of the parameters shown in the upper left portions of Figs. 2–5 are not reliable, as no measurements are made there; the contours drawn there show only computer-extrapolated values of the parameters.

The situation is much different east of 63°E. The SST is more uniform over this region. Also the conductivity values are comparatively lower at the geomagnetic equator and increase with the geomagnetic latitude on either side of the equator.

4. RELATIVE HUMIDITY VERSUS SST

When the SST is above ambient air temperature (T) the air could become convectively unstable and transport moisture from the lower to the upper layers of the atmosphere. On the other hand, as the SST and the air temperature approach each other, the relative humidity increases. This is demonstrated when we compare Figs. 3 and 4. Relative humidity is comparatively low roughly east of the zero-value contour for $(T_0 - T)$ where $(T_0 - T)$ is positive, and high west of this contour where $(T_0 - T)$ is negative. Led by this observation and the similarity observed between the distributions of SST and relative humidity (Figs. 2 and 3), we examined the correlation between these two parameters. A scatter diagram of the relative humidity against SST for the area inside the dashed lines in Fig. 5 (to be described later) shows that the relative humidity increases as the SST decreases (Fig. 6).

5. VARIATION OF CONDUCTIVITY WITH RELATIVE HUMIDITY AND SST

In view of the relation between the relative humidity and SST, we examined the variation of conductivity against relative humidity only. Figure 7 shows that the conductivity decreases with the increase in relative humidity. Negative conductivity changes more than positive conductivity. The larger scatter in conductivity plotted against relative humidity is most probably because of the much larger diurnal variation of relative humidity; it may also be due to the hysteresis effect which the change in NaCl particle size shows in decreasing values of relative humidity (Pruppacher and Klett 1978).

Compared with daytime values, the conductivity generally decreases and the relative humidity increases during night-time. This inverse trend between diurnal variations of conductivity and relative humidity is not very regular and systematic when observed on a day-to-day basis. However, when the data inside the dashed box in Fig. 5 are averaged, the inverse relation between relative humidity and total conductivity is well demonstrated (Fig. 8). This inverse relation is very good in the case of negative conductivity (λ_-), and very poor in the case of positive conductivity (λ_+). Joining points by straight lines in the case of λ_+ seems inappropriate, but has been done only to show its relative variability with respect to λ_-.

6. DISCUSSION AND CONCLUSIONS

Any change in atmospheric electric conductivity over the ocean surface may be caused by:

(i) any local generation of charge or aerosols by mechanisms such as raindrop splashing, bubble break-up on the sea surface or the exhaust of the chimney of the ship;

(ii) a change in background air pollution;

(iii) the advection of air pollution from land;

(iv) the latitudinal variation in cosmic ray intensity; or

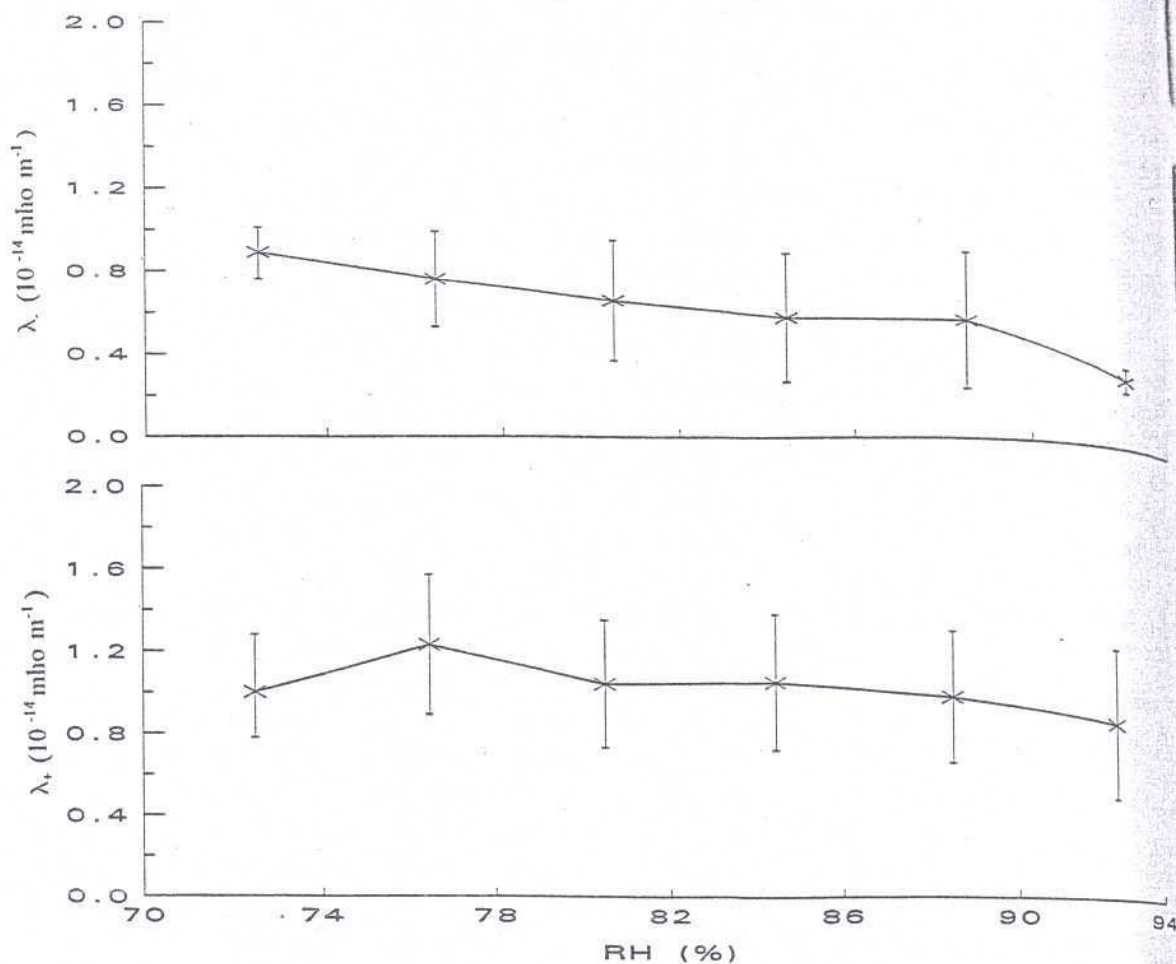(v) changes in the mobility of ions and aerosol size due to changes in some meteorological parameters.

Figure 7.   Plots of positive conductivity (λ_+) and negative conductivity (λ_-) versus relative humidity (RH). Each point is an average of all conductivity values for corresponding relative humidity values in the range of $\pm 2\%$. The vertical bars represent the standard deviations from the mean.

By suitably choosing the location of the apparatus on the ship and the period for which the data are analysed, we avoid any significant change in the average values due to factor (i). Moreover, any short-term effect of this nature is not likely to contribute significantly to any change in the spatial distribution of long-time averages. Since the period of the cruise extends to only one month, the possibility of any change in conductivity due to the second factor is also unlikely. Weather observed during the period of cruise showed no significant departures from normal climatic features of the region during the months of August and September, thus only air north of about 9°N is likely to be contaminated by the aerosol particles picked up by the east African low-level jet during its flow over coastal lands of Kenya, Ethiopia and Somalia. Air blowing south of about 9°N has a long history of travel over ocean since the south-easterlies in the southern hemisphere swing across the equator and blow as south-westerlies over the south-west Arabian Sea. Moreover, the nearest point on the cruise was more than 350 km away from the east African coast. Observations of Morita *et al.* (1973) and Kamra and Deshpande (1995) show the dependence of conductivity on the age of an air mass, and how the land-to-ocean dispersion of pollutants by diffusion is curtailed and its extension confined to about 100 km from the coastline when the airflow is nearly parallel to the coastline. So, except close to the east African coast, the air south of about 9°N can be safely assumed to be free of air pollution from land; therefore, the third factor is not likely to have any significant effect
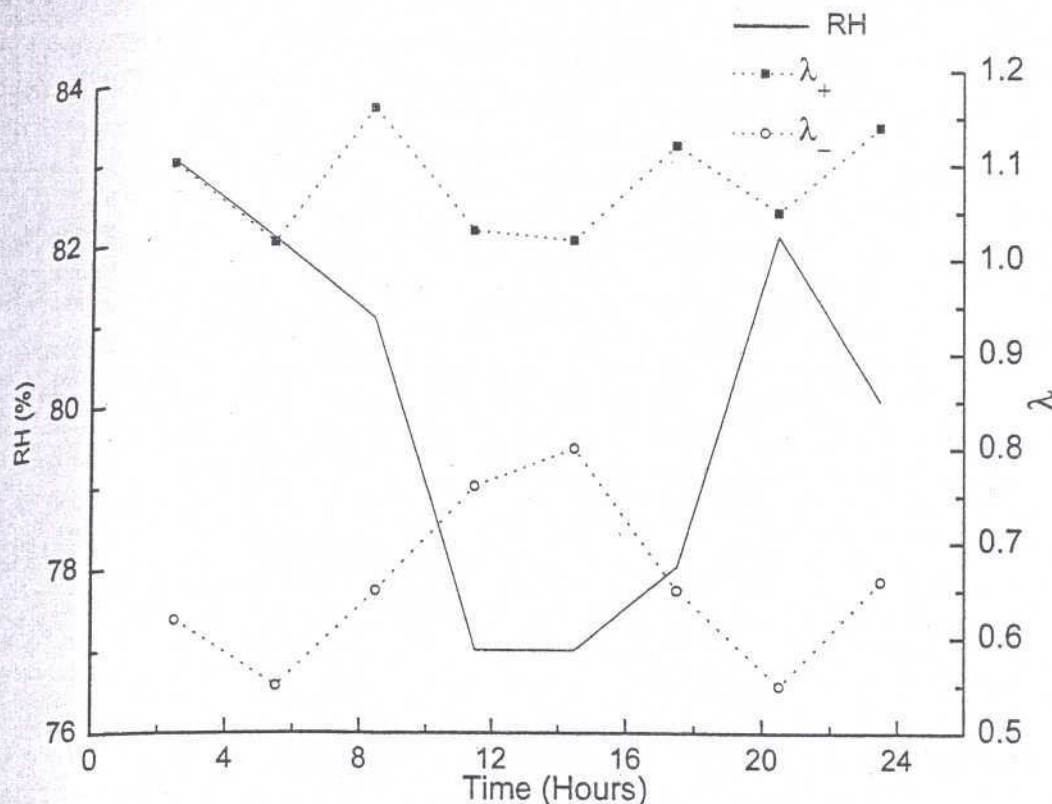
Figure 8. Average diurnal variation of relative humidity (RH), and the mean values of positive (λ_+) and negative (λ_-) conductivity ($\times 10^{-14}$ mho m^{-1}).

on our conductivity measurements. Any possibility of the variation in conductivity being due to the fourth factor is also unlikely, since our measurements are conducted within a narrow belt (2°S to 12°N) around the geomagnetic equator where the cosmic ray intensity at sea level does not show any appreciable change (Millikan and Neher 1936). Below we examine our conductivity measurements in view of the meteorological conditions of the region described earlier.

The size of marine aerosol particles increases sharply with relative humidity when the relative humidity exceeds 70–80% (Pruppacher and Klett 1978), so the size of aerosol particles and ions will be relatively bigger in a region with higher values of humidity. This will cause a decrease in the value of conductivity in two ways: firstly, the larger ions will be relatively less mobile, and thereby contribute less to the electric conductivity of the air; secondly, the enlarged aerosol particles will provide a larger area for the collection of small ions, which will cause greater removal of small ions by attachment to aerosol particles, making the ions almost immobile. This will result in the availability of fewer small ions which make a major contribution to conductivity. Lower values of conductivity observed in regions with lower SST and higher humidity may thus be a consequence of the combined effect of these two causes. Decreasing values of conductivity associated with the decrease in the SST and increase in relative humidity inside the dashed lines in Fig. 5, and along the equator in a westward direction, strongly support such a hypothesis. A similar increase in conductivity observed in the north-west direction from the low-conductivity region near the Somalian coast, can also be associated with the increase in SST and decrease of relative humidity in that direction. But when the airflow is from the land to sea, the possibility of the increase in conductivity being associated with the decreasing aerosol content of the air as one goes away from the coast cannot be ruled out, in view of the observations of Kamra and Deshpande (1995).

The above argument on the change of the size of aerosol particles and ions can be tested numerically. Assuming a simple ion-balance equation,

$$q - \alpha n^2 - \beta Nn = 0,$$

where q is the ion production rate, α the ion–ion recombination coefficient, β the ion-aerosol attachment coefficient, and n and N the ion and aerosol number concentrations respectively. We have calculated the approximate values of the change in n via changes in β due to mobility and radius. Assuming a dry particle radius of 0.01 μm, we calculated the change in radius as the relative humidity increases from 70 to 85% from Pruppacher and Klett (1978). Then using the size-dependent values of β from Hoppel (1985), the values of the small-ion number concentrations are calculated when the relative humidity is 70 or 85%. The ratio of these two values is 1.89. The ratio of the maximum to minimum values of conductivity in our observations in the dotted region of Fig. 5, as we go from the region of low to high relative humidity, is 1.77. The rough agreement between the two ratios supports our argument presented above. Also supporting this argument is the conclusion of Parts (1995), that the negative ions change their size with the increase in relative humidity due to the solvation of more water molecules to clusters, and that the mobility spectra of ions are influenced by the relative humidity. The change in mobility spectra of negative ions, which is reported to occur in the region of relative humidity from 30 to 80%, is in the right direction to support our observations. In the case of positive ions, however, this change is in the opposite direction but occurs only for relative humidity greater than 65%. Further, since the ion mobility varies inversely with the ionic mass and so attains an asymptotic value with increase in ion hydration, the effect of the removal of ions by enlarged aerosols is likely to dominate.

Our observation that the inverse relation between electrical conductivity and relative humidity is better in the case of negative ions can be explained by the relatively greater mobility of negative ions, which will enhance their chance of being attached to aerosol particles. The greater mobility of negative ions can be explained by the fact that positive ions, such as hydronium, have a stronger polarizing centre and substantial screening by hydrating molecules; thus further hydration of positive ions from ambient relative humidity effects is unlikely to occur. Calculations of Pilinis et al. (1989) show that the existence of water in the particulate phase is strongly dependent on aerosol composition, which may be different for ions of opposite polarity. Parts (1995) concludes that the mobility spectra of negative ions are influenced by relative humidity in the whole region from 30 to 85%. The influence of relative humidity greater than 65% is perhaps due to the uptake of gaseous components (having NH_3 and HNO_3) to aerosol phase (NH_4NO_3).

The region and period of observations of this cruise are very suitable for investigating the observed effect because of the prevailing meteorological conditions, viz:

(i) Sharp gradients of relative humidity and SST.

(ii) Change in relative humidity in the critical transition region from 70 to 90% required for the change in particle size to occur.

(iii) The surface air having a long history of travel over ocean because of the cross-equatorial flow.

(iv) Confinement of the continental aerosol-bearing winds to the east African jet current emerging from land to the Arabian Sea at about 9°N.

(v) Lack of very strong winds and heavy rains.

(vi) Location of the region at and near the geomagnetic equator sufficiently away from any landmass.

Because opportunities to collect data under such a unique set of conditions are rare,

we have chosen to analyse our data in such detail. However, more measurements are needed to confirm the observed inverse relation between the conductivity and relative humidity.

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