ROLE OF THE LAND PLUME IN THE TRANSPORT OF OZONE OVER THE OCEAN DURING INDOEX (1999)

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Abstract. Observations from aircraft, an island station, and two research vessels are used to investigate the development of an elevated mixed layer or land plume over the Arabian sea during the Indian Ocean Experiment Intensive Field Phase 1999 (INDOEX) through air mass modification. Much of the transport of aerosols and gases occurs in this plume located above a well-mixed convective marine boundary layer with a depth of 800–1000 m. The depth of the land plume is approximately 2000 m with the peak ozone concentrations occurring near the centre of this land plume. Significant latitudinal variations in the concentration of ozone occur in the marine boundary layer and in the plume. Mean ozone concentrations in the land plume decreased with distance from the Indian coastline.

Keywords: Indian Ocean, INDOEX, Land/atmosphere/ocean interactions, Land plume, Marine boundary layer, Ozone transport.

1. Introduction

The central hypothesis of the Indian Ocean Experiment (INDOEX) was that the transport of an aerosol-laden air mass from the Indian subcontinent and Asian landmass over the Indian Ocean could alter the global radiation balance (Ramanathan et al., 1995). Ships, aircraft, balloons, satellites, and weather stations were used to obtain observations over the Arabian Sea and equatorial Indian Ocean from 21 January to 30 March 1999 during the Intensive Field Phase (IFP) of INDOEX to study this phenomenon. This time period during the north-east monsoon was chosen because the prevailing north-east winds transport aerosols and gases from the Indian subcontinent over the ocean. The emphasis of the IFP measurements was on lower troposphere meteorological data and air chemistry. The primary goals of INDOEX (1999) were to study the variations in the magnitude of solar absorption occurring at the surface and in the troposphere in the presence of sulfates and aerosols of continental origin. A pre-INDOEX research study observed a spatial gradient in aerosol optical thickness that suggested long-range transport of aerosols from India to the North Indian Ocean (Satheesh, 1998). High concentrations of non-sea salt aerosols in the Arabian Sea appear to result due to transport from the Indian subcontinent and Arabian peninsula (Rajeev et al., 2000). The high concentrations of absorbing haze/aerosols tend to decrease the surface solar radiation by an amount comparable to 50% of the total ocean heat flux (Ramanathan et al., 2001). Observational analysis of sea surface temperatures has shown that the absorbing aerosols have led to a statistically significant cooling of about 0.3 °C since the 1970s (Krishnan and Ramanathan, 2002). Anthropogenic influences on the radiation balance over the Indian Ocean are caused by agricultural burning and bio-fuel use that have greatly increased carbon monoxide concentrations over the Arabian Sea (Lelieveld et al., 2001). Thus, there is a need to investigate the mechanism of transport of aerosols and gases over the ocean.

Thermodynamic profiles obtained during Pre-INDOEX ship cruises have shown the presence of an elevated mixed layer or land plume in the region (Manghanani et al., 2000). A hypothesis for the development of the land plume was suggested based on the air mass modification process by Raman et al. (2002). The objective of this paper is to further discuss the mechanism of formation of the land plume and its structure and also study the growth of the marine boundary layer (MBL) offshore based on a comprehensive set of observations during the field phase of INDOEX in 1999. In addition, latitudinal variation of the concentrations of gases such as ozone in these two distinct layers in the lower troposphere will be presented. Understanding the transport processes of pollution in the land plume and the marine boundary layer over the Arabian Sea will contribute to the main goal of INDOEX (1999), which is assessing the magnitude of radiative forcing caused by aerosols and gases.

2. Observations

Various observation platforms were used during the intensive field phase of INDOEX (1999) to obtain a comprehensive dataset. The research vessels (R/V) used during the IFP were *Ron Brown* and *Sagar Kanya*. The research aircraft that participated in INDOEX (1999) are EC-130Q *Hercules*, *Citation II*, *Geophysica*, *Falcon*, and *Mystere*. Constant level balloons were deployed from Goa, India to study low level air trajectories. Radiosondes were released at various locations to obtain vertical profiles of winds, temperatures, moisture, and ozone concentrations in the troposphere. Surface observations were made at the Kaashidhoo Climate Observatory located in Maldives, in Mauritius, and at Mt. Abu, Pune, and Trivandrum, India and Tromelin Island, Reunion. Remotely sensed data were obtained using the following satellites: EOS, FY-2, ScaRaB (RESURS), Meteosat 5, NOAA 14 and 15, and the Tropical Rainfall Measuring Mission (TRMM) satellite. The individual data platforms used in this paper are described below.

2.1. Kaaishidoo observation station

Kaaishidoo Meteorology Station (KCO) is located in the Republic of Maldives at 4.97° N, 73.47° E. KCO was chosen to be the observation site for the measurements of most of the radiometric trace gas and aerosols so that they could be carried out in a relatively pollution-free environment. KCO also has a large locally clean air sector in the north-east that is important to pollution measurements made during the north-east monsoon season.

Chemistry of trace gases and meteorological parameters were the primary measurements made at KCO during INDOEX. Ten minute averages of carbon monoxide mixing ratios were made near the surface using a CO analyzer. A gas chromatograph was used to determine 40-min atmospheric mixing ratios for CFC's, chlorinated gases, nitrous oxide, and sulfur hexafluoride. Ten-second averages of atmospheric ozone mixing ratios were measured with an ozone analyzer. Rawinsondes were released twice a day and ozonesondes were released once daily from KCO and provided vertical profiles of pressure, temperature, humidity, wind speed and direction, and ozone concentration. Meteorological parameters such as 10-sec averages of wind speed and direction, air temperature, relative humidity, atmospheric pressure, and rain amounts were measured near the surface. Radiation measurements were made with broad and narrowband radiometric sensors. A continuous scattering coefficient for aerosols and for particle/soot absorption was obtained using a three-stage, high volume impactor.

2.2. Research vessels

The ship data used in this research were collected by the R/Vs *Ron Brown* and *Sagar Kanya* during INDOEX (1999). R/V *Ron Brown* is operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). Some of the important atmospheric instrumentation on R/V *Ron Brown* during INDOEX (1999) included a C-Band Doppler Radar, wind profiler, and rawinsondes. Data from the three or four daily rawinsonde releases consisted of vertical measurements of pressure, temperature, humidity, latitude and longitude, and wind speed and direction every 10 seconds.

R/V *Sagar Kanya* is operated by the Indian Department of Ocean Development. Rawinsondes were released twice a day from R/V *Sagar Kanya* during the INDOEX (1999) and they obtained the same meteorological variables as from R/V *Ron Brown*. During the period, 6–9 March 1999, additional radiosondes were released as R/V *Sagar Kanya* was closer to the coast. The major observation systems used by R/V *Sagar Kanya* during INDOEX included an Eppley Total Solar Pyranometer, handheld sunphotometer, high volume bulk aerosol filter sampler, multi wavelength radiometer, pyrheliometer, surface CO and CH4 analyzer, surface ozone sampler and surface meteorological instruments.

2.3. Aircraft data

All of the high-resolution airborne measurements used in this study were obtained by the EC-130Q *Hercules* and the French research aircraft *Mystere*. The meteorological data taken from the C-130 aircraft were sampled 20 times per sec. Some of the instrumentation on the C-130 included a gust probe to measure turbulence, cloud physics instrumentation, radiometers, and in-situ trace gas samplers (CO, CO_2 and O_3). The parameters used in this study from the C-130 include pressure, potential temperature, altitude, latitude, longitude, wind speed, and turbulence.

Aerosol distributions are presented from measurements made by a downward looking lidar aboard the French aircraft *Mystere*. The goal of *Mystere*'s participation in INDOEX was to observe latitudinal and longitudinal distributions of aerosols.

3. Discussion of Results

The cruise tracks of the research vessels R/Vs *Ron Brown* and *Sagar Kanya* during INDOEX (1999) are shown in Figure 1. R/V *Ron Brown* started from Port Louis, Mauritius at 20° S, and moved north to near 20° N. The atmosphere is generally more pristine south of the equator due to less pollution from land masses. However, as R/V *Ron Brown* moved further north along the west coast of India, ozone concentrations are expected to increase due to the presence of the continental air mass. R/V *Sagar Kanya* started from Goa, India located at a latitude of 14.2°N. The two research vessels had tracks that enabled measurements to determine latitudinal and longitudinal variations in aerosol and anthropogenic gas concentrations over the Indian Ocean.

Locations of the various data platforms used in this study for the period 7–9 March 1999 are shown in Figure 2. It includes the flight tracks of the C-130 aircraft on 7 March 1999 and the French aircraft *Mystere* on 9 March 1999. At 08 Z on 7 March 1999 the C-130 research aircraft was 1100 km off the west coast of India. The locations of the R/Vs *Ron Brown* and *Sagar Kanya* on 7 March 1999 are also indicated in Figure 2. They had a parallel track to observe offshore variations of different parameters. At 12 Z, R/V *Ron Brown* was 800 km from India's west coast while R/V *Sagar Kanya* was only 140 km from the shore. The location of the Kaaishidoo Meteorology Station is also indicated in Figure 2 to show its relative location to the west coast of India.

Daytime sea-breeze circulations along the west coast of India are a common feature during the north-easterly monsoon because of the contrast between sea (about 30 °C) and land temperatures (about 40 °C). This contrast in surface temperatures induces a strong sea-breeze circulation that can extend up to a distance of 100–200 km off shore as observed by R/V *Sagar Kanya* wind data and inferred from the infrared satellite imagery (not shown).

3.1. Land Plume Structure

Vertical ozone concentration profiles provide a reliable way of characterizing the land plume over the ocean. Over the Arabian Sea, ozone concentrations depend on wind direction and trajectories from land account for maximum values. Observations made at the Kaaishidoo Climate Observatory (KCO) provide a good source of

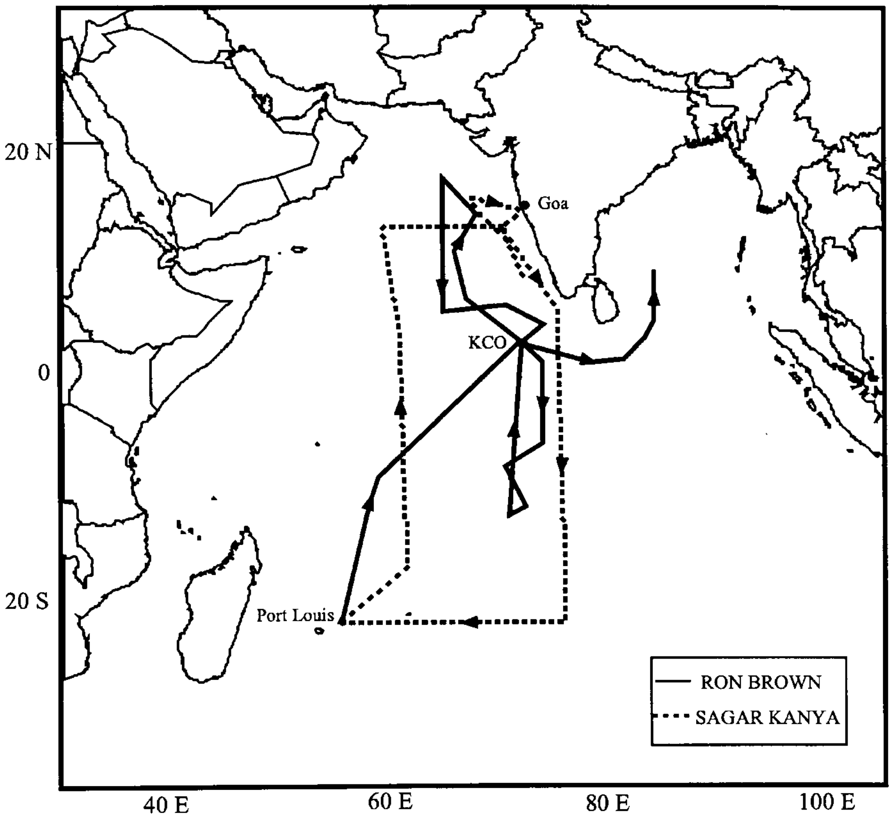

Figure 1. Ship tracks for research vessels *Ron Brown* and *Sagar Kanya* during INDOEX (1999).

data for establishing any relationship between wind direction and ozone concentrations and also the structure of the land plume. Ozone soundings were taken at KCO during INDOEX (1999) once a day. The ozonesondes were released at 0900 UTC (1400 Local Time) to coincide with the NOAA-14 satellite overpasses. A complete description of the ozone experiment at KCO can be found in Lobert et al. (1999).

A wind speed profile taken from KCO on 9 March 1999 at 1100 LT is shown in Figure 3a. The wind speed is constant within the 800 m depth of the marine boundary layer (MBL) with a mean value of 2 m s^{-1}. A strong elevated jet with a maximum value of 13 m s^{-1} is seen above the MBL at a height of 1400 m. The winds decrease above the jet to a value of 4 m s^{-1} at 2000 m.

A wind direction profile taken from KCO on 9 March 1999 at 1100 LT is shown in Figure 3b. The wind direction in the MBL varies from north-westerly near the surface to north-easterly in most of the MBL (800 m) and in the land plume (800 to 2000 m). North-westerly winds near the surface are believed to be due to local effects. North-westerly to northerly wind directions are seen above 2000 m. The

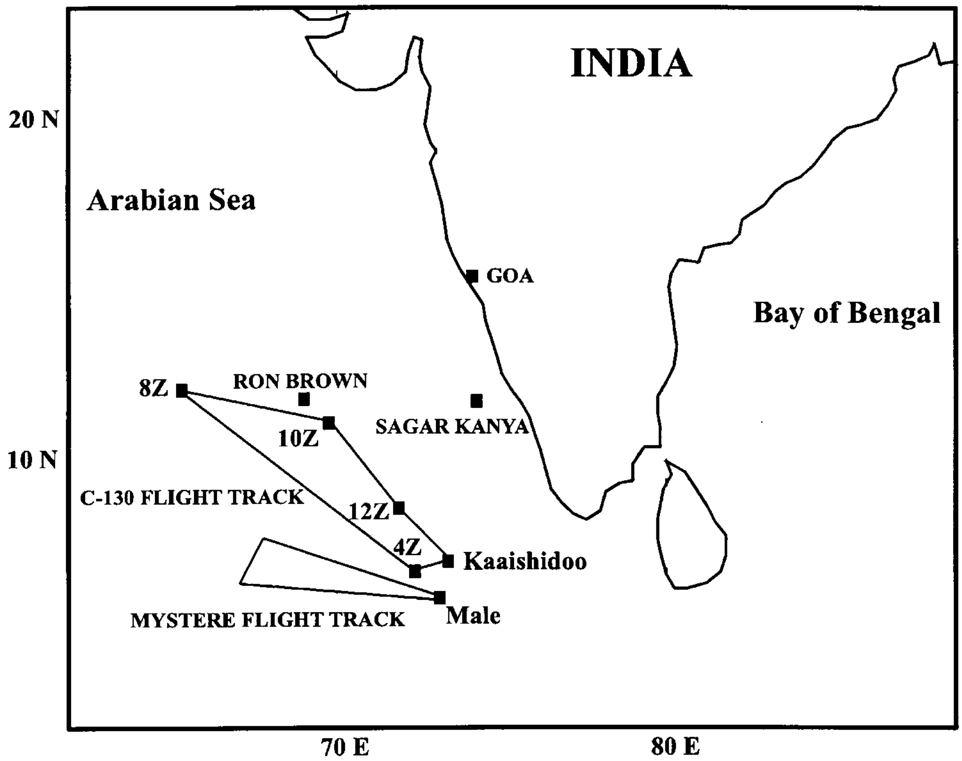

Figure 2. Location of various data platforms on 7 March 1999, flight tracks of the C-130 aircraft on research flight 09 and Mystere's track on 9 March 1999.

core of the elevated jet at 1400 m is in the layer of north-easterly winds occurring between 800 m and 2000 m.

The ozone concentration profile observed on 9 March at 0900 Z (1400 LT) is shown in Figure 3c as a solid line. High concentrations of ozone were observed in the land plume between the altitudes of 800 m and 2000 m. A maximum concentration of 90 ppb occurred at an altitude of 1600 m, the location of the jet maximum. In the 700 m depth of the MBL, the ozone concentration is approximately 30 ppb, appreciably lower as compared to the concentrations in the land plume.

Ozone concentrations depend very much on the trajectories of air masses (and hence the wind direction). The concentration profile (dashed) for 5 February 1999 at 0900 UTC is shown in Figure 3c. Winds at this time varied from southerly to westerly in the lower troposphere. Ozone concentrations are constant with values less than 20 ppb in the lowest 5000 m of the atmosphere as compared to values between 30 ppb to 90 ppb observed on 9 March with north-easterly air trajectories from the Indian subcontinent. The ozone concentrations on 5 February are low and show no variation with height because the southerly and westerly winds transport an unpolluted marine air mass.

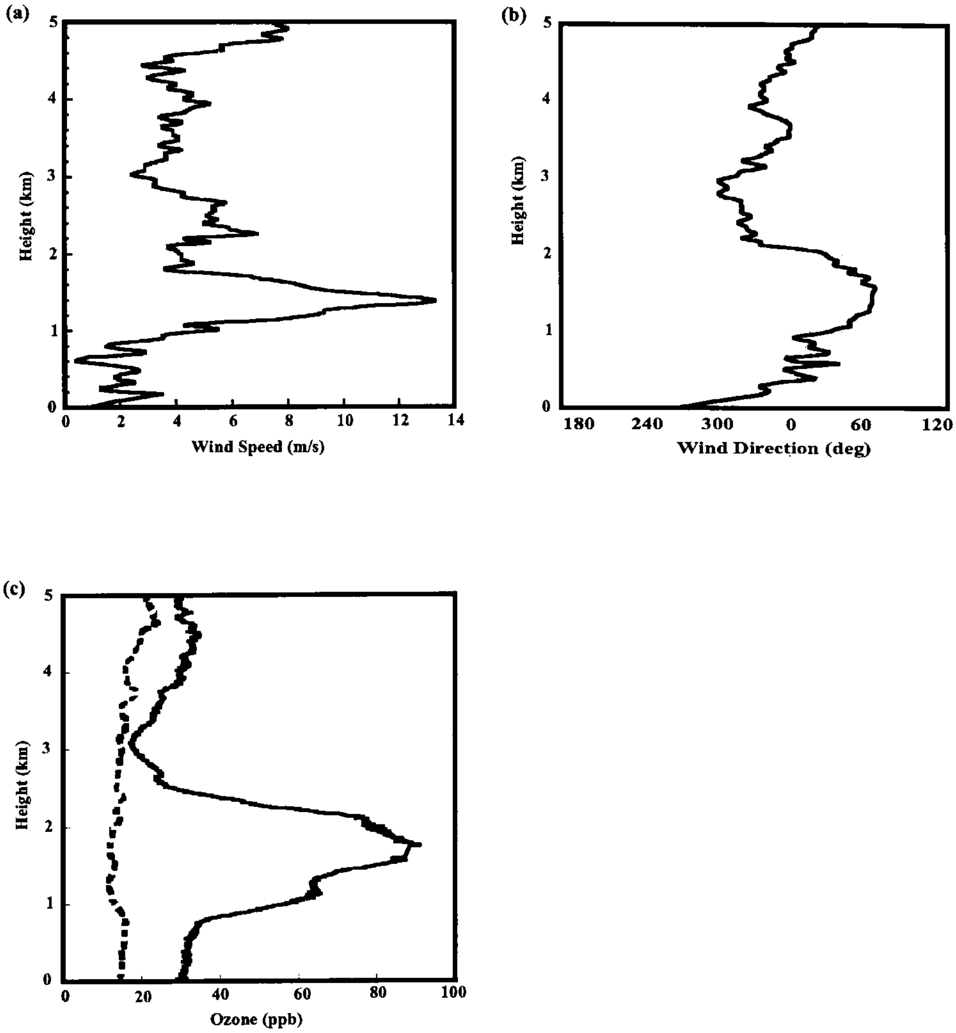

Figure 3. (a) Wind speed profile at KCO on 9 March 1999 showing an elevated jet of 13 m s^{-1} at a height of 1500 m. (b) Wind direction profile at the height of the jet was north-easterly. (c) Ozone concentration profiles taken at KCO on 5 February 1999 for south-westerly wind direction (dashed line) and on 9 March 1999 for north-easterly wind direction (solid line).

In summary, ozone concentrations in the lower troposphere at KCO were much higher on 9 March than that on 5 February because of north-easterly winds and KCO's location relative to the Indian peninsula (shown in Figure 2). North-easterly winds advect the polluted air mass from the Indian subcontinent and increase the ozone concentrations at KCO. The shift in wind direction from south-south-west to north-east increased the ozone concentrations at the surface by 100% and in the 1000–2000 m layer (land plume) by 400%. It appears that the bulk of the anthropogenic gases such as ozone are transported in the elevated land plume.

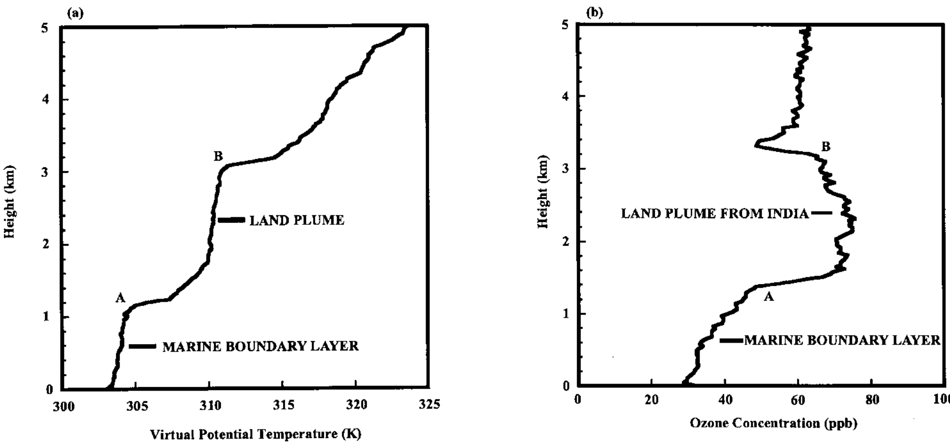

Figure 4. (a) Virtual potential temperature profile taken from R/V *Ron Brown* on 7 March 1999 at 1200 UTC showing the land plume in the 1–3 km height layer. (b) Ozone concentration profile taken from R/V *Ron Brown* (11.3° N, 68.3° E) on the same day at 1335 UTC showing the highest ozone concentrations in the land plume.

Enhancement of ozone concentration in the land plume may also occur as a result of photochemical reactions involving NO and NO_2 being transported in the plume.

Vertical profiles of potential temperature and ozone from R/V *Ron Brown* also show variations consistent with the presence of the land plume as a mixed layer above the MBL separated by a shallow inversion. A typical virtual potential temperature (θ_v) profile from R/V *Ron Brown* (11° N, 68° E) on 7 March 1999, 1200 UTC is shown in Figure 4a. Thermodynamic structure in the lower troposphere exhibits two distinct layers over the ocean for north-easterly winds. One is a convective MBL capped by a strong inversion and the other is another well-mixed layer above this inversion again capped by another strong inversion. The air is fairly well mixed with a virtual potential temperature, θ_v, of 303 K up to 1000 m within the MBL capped by a shallow inversion labeled A. An elevated mixed layer or land plume is present between 1600 and 3000 m. Virtual potential temperature, θ_v has a magnitude of 311 K in the elevated mixed layer. This layer represents the land plume where much of the transport of aerosols and gases from the continent occurs. Above the elevated mixed layer is a strong capping inversion labeled B. Above the second strong inversion, a stable layer exists.

An ozone concentration profile taken 800 km off the west coast of India aboard R/V *Ron Brown* (11.3° N, 68.3° E) on 7 March 1999, 1335 UTC (1835 LT) is shown in Figure 4b. Ozone is fairly well mixed in the lower portion (500 m) of the MBL with a value of about 30 ppb. However, the concentration begins to increase towards the top of the MBL because of a change in wind direction from northerly in the first 700 m to north-easterly from 700 m to 3000 m (not shown). Immediately above the MBL, ozone concentrations increase sharply with maximum values in the 1400–3200 m depth of the land plume. The layer-averaged concentration of ozone for the land plume is about 70 ppb. At the top of the land plume, concentrations drop sharply to 50 ppb because of mixing with the free atmosphere through entrainment and then remain constant at 60 ppb up to 5000 m. These values are larger than those observed in the MBL by a factor of about two. Large concentrations even above the land plume (with east-south-easterly wind direction) may be associated with upwind land based sources.

A potential temperature (θ) profile taken from the C-130 aircraft during Research Flight # 09 on 7 March 1999 at 1300 LT at location (12.3° N, 63° E), about 1100 km off the Indian coast over the Arabian sea is shown in Figure 5a. The characteristic elevated mixed layer associated with the land plume can be seen in this profile. Within the MBL, the potential temperature is well mixed up to 700 m with a value of 289 K. A strong capping inversion exists above the MBL. From 1000 to 3000 m, an elevated mixed layer is again present where a potential temperature of 308 K was observed. Another capping inversion is present just above the land plume at 3000 m.

A wind direction profile taken from the aircraft at 1300 LT on 7 March 1999 is shown in Figure 5b. Within the MBL up to an altitude of 700 m, the wind direction is from the north-east. Above the MBL, the winds are easterly up to a height of 3000 m. Presence of easterly winds in the 1000 to 3000 m altitude ranges agrees with the conclusion that the land plume is an air mass with a trajectory from the Indian subcontinent. Above the land plume, the wind direction shifts to northerly.

The location and magnitude of the entrainment zones associated with the land plume can be determined by profiles of turbulence. Vertical variation of the standard deviation of vertical velocity fluctuations, σ_w taken from the C-130 aircraft on 7 March 1999 at 1300 LT is shown in Figure 5c. The σ_w profile gives a good estimate of the degree of turbulence present at any particular level. Values of σ_w were averaged over layers of 100 m up to 5000 m. At the surface, σ_w has a value of 0.4 m s^{-1} increasing to a maximum value of 0.47 m s^{-1} at an altitude of 200 m, and then decreases to 0.2 m s^{-1} near the top of the MBL (700 m). Turbulence decreases above the MBL to 0.11 m s^{-1} at an altitude of 2000 m. Within the land plume, the turbulence varies only slightly until the top of the land plume where σ_w increases to 0.22 m s^{-1}. This region represents the entrainment zone between the land plume and the free atmosphere. The location of the entrainment zones at 1000 m and 3000 m altitudes determined by the turbulence profile agrees well with the R/V *Ron Brown* ozone profile shown in Figure 3c. Above the land plume, turbulence decreases to a value of 0.05 m s^{-1} and remains constant to 5000 m.

The ozone profile using the C-130 aircraft on 7 March 1999 at 1300 LT is shown in Figure 5d. Maximum ozone concentrations of 80 ppb are seen within the MBL up to a height of 500 m. Above the MBL, ozone concentrations decrease to 35 ppb at 1000 m. A layer of high ozone concentrations is seen above the MBL from 1000 to 3000 m representing the depth of the land plume. The maximum concentration in the land plume is 60 ppb and occurs at an altitude of 2000 m. Above the land plume, the concentrations remain well mixed at a value of about 20 ppb. Ozone

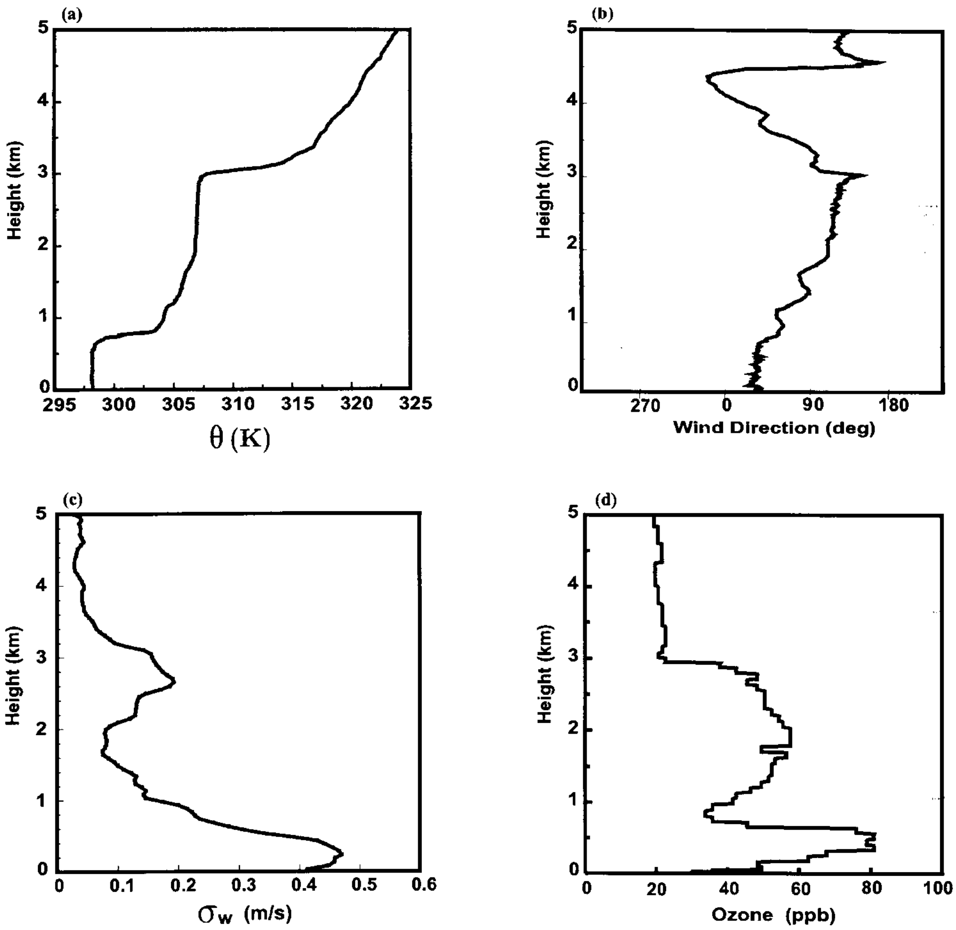

Figure 5. Profiles taken from aircraft on 7 March 1999 at 1400 LT. (a) Potential temperature profile showing the presence of the elevated mixed layer from 800 to 3000 m, (b) wind direction profile showing the wind direction within the land plume to be NE-E. (c) profile of σ_w, standard deviation of vertical velocity fluctuations showing minimum values in the core of the jet and (d) ozone concentration profile showing high concentrations within the land plume.

concentrations are lower in the land plume than in the MBL because the wind direction shifted to east-south-easterly (Figure 5b) in the land plume as compared to north-easterly winds in the MBL.

A direct way of observing the dynamic structure of the land plume is to use downward looking lidar to observe the aerosol distribution over the Arabian Sea. Scattering distributions measured by a downward looking lidar on the French aircraft *Mystere* are shown in Figure 6. The data were collected on 9 March 1999 at 0900 UTC (1400 LT) from 4.5° N to 7.0° N at 70° E. The flight track of Mystere is shown in Figure 2. A low concentration of aerosols is indicated within the MBL by minimal backscattering up to 800 m, the height of the MBL. A layer of large

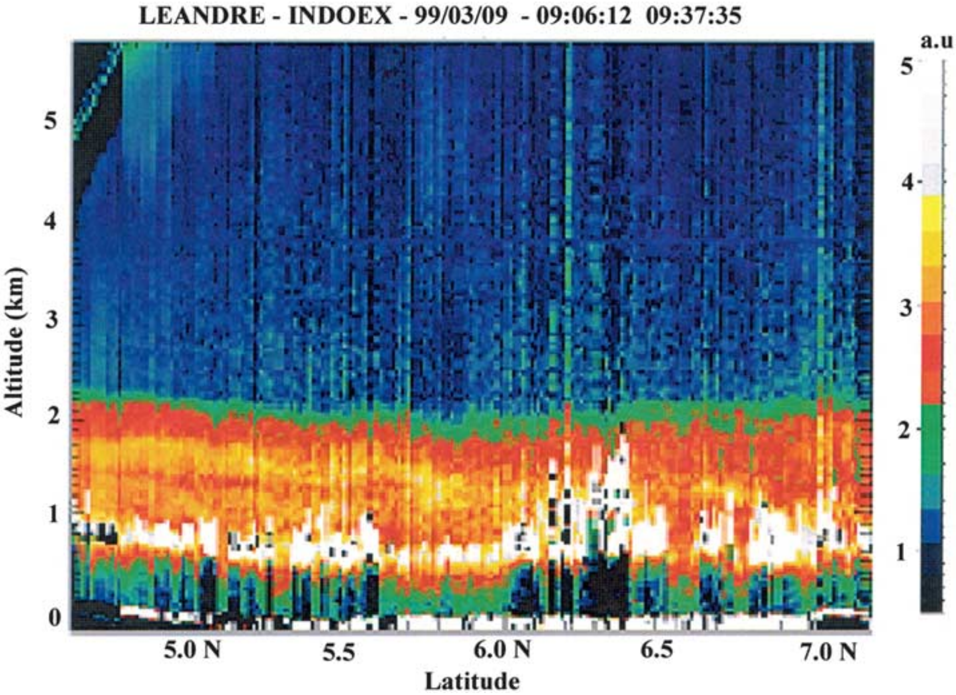

Figure 6. Aerosol distribution measured by airborne lidar aboard Mystere on 9 March 1999 at 1500 LT. The presence of a deep aerosol rich layer from 800–2400 m confirms the existence of the India land plume over the Arabian Sea.

backscattering indicating high aerosol concentrations is seen above the MBL from 800 to 2400 m. This layer of high aerosol concentration corresponds to the general location of the land plume.

A schematic of the process of development of the land plume near the coast during a typical daytime condition is shown in Figure 7a. Sea-breeze circulations form near the coast during daytime when opposing large-scale easterly flow is not too strong. Shallower land breezes occur during the night. An air mass modification results with offshore flow in this region as the warmer air flows over the cooler ocean surface. Static stability of this modified layer tends to be stable with a surface-based inversion close to the coast as shown in Figure 7b. With increasing distance the MBL becomes convective as the air closer to the surface adjusts to the warmer ocean temperatures and the land air mass gets modified. The height of the MBL grows with distance from the coastline through entrainment and this layer close to the ocean surface represents the air mass modified by the ocean and capped by a shallow, but strong inversion. Growth of the MBL offshore will be discussed further in the next section. This modified air mass tends to be moist and well mixed. The convective boundary layer over land in India frequently grows to a depth of 2000 m (Raman et al., 1990) and the aerosols and gases within the

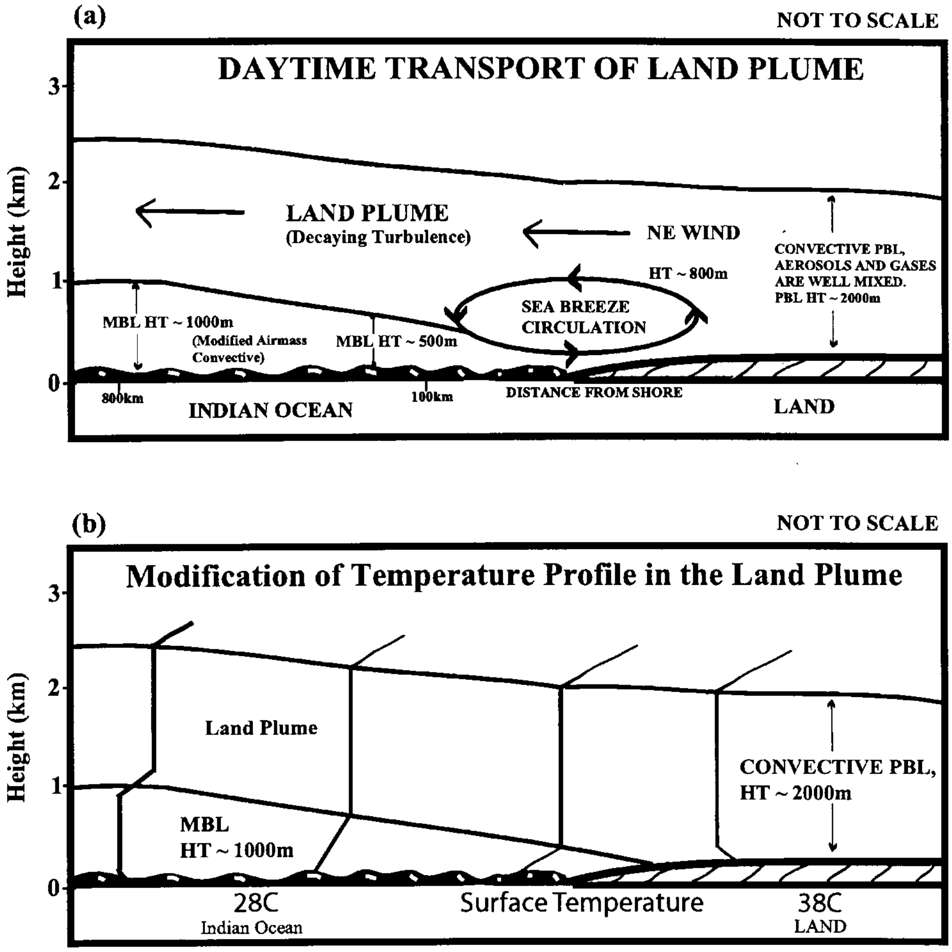

Figure 7. Schematic diagram showing the typical daytime processes involved in the development of the land plume through air mass modification caused by land–ocean interface.

boundary layer become well mixed. This air mass of about 2000 m depth above the MBL remains distinct from the modified air mass closer to the ocean surface even at large distances over the Indian ocean because of minimal large scale forcing. The second inversion above the land plume is the remnant of the inversion over the convective boundary layer over land as the air mass gets advected over the ocean.

3.2. Air Mass Modification and the Land Plume Development

A parallel track experiment was conducted with R/V *Ron Brown* and R/V *Sagar Kanya* on 7 March 1999 to compare their observations and to study offshore variations of various parameters such as winds, and ozone concentration. The north-south track of R/V *Sagar Kanya* was 140 km from the west coast of India, while R/V *Ron Brown* had a near-parallel track at 800 km from the west coast of India as shown in Figure 2. The parallel tracks of the two research vessels provided a unique opportunity to investigate the air mass modification, MBL growth offshore, and the development of the land plume over the Arabian Sea.

Potential temperature profiles from R/V *Ron Brown* (9.2° N, 69° E) and R/V *Sagar Kanya* (10.6° N, 74.5° E) are shown in Figure 8. Both profiles were taken at 0000 UTC (0500 LT) on 7 March 1999. The solid line is the R/V *Ron Brown* profile and the dashed line is the R/V *Sagar Kanya* profile. The height of the marine boundary layer measured by R/V *Sagar Kanya* is 600 m while the MBL height measured by R/V *Ron Brown* is 1000 m. A strong inversion exists between the marine boundary layer and the land plume in both the profiles as the MBL grows offshore through air mass modification. The land plume between 1400 m and 3400 m altitude is better developed at the location of R/V *Ron Brown* (800 km offshore) as compared to that of R/V *Sagar Kanya* (140 km). The reason for this difference is not known; however, one can speculate two possibilities. Assuming a wind speed of 10 m s^{-1}, air mass arriving at R/V *Ron Brown* 800 km offshore would have originated from India around 0900 LT. Therefore, the air aloft arriving at R/V *Ron Brown* could be the remnants of the previous daytime well-mixed boundary layer thus showing the characteristic land plume uniform temperature profile. However, the air arriving at R/V *Sagar Kanya*, 200 km offshore, would have originated from India at 0100 LT. This air mass will therefore be characteristic of the nighttime stable boundary layer and the residual layer aloft. Land-breeze circulations can also influence the advection of the nighttime air mass. These circulations would affect the profiles observed from R/V *Sagar Kanya* because of its proximity to coast.

To investigate any diurnal variation in the land plume structure, thermodynamic profiles obtained at different times of the day were analyzed. Potential temperature profiles taken from R/V *Ron Brown* (11° N, 68° E) and R/V *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC on 7 March 1999 are shown in Figure 9. The height of the MBL measured by R/V *Sagar Kanya* is now about 500 m as compared to 600 m at 0000 UTC shown in Figure 8. However, the MBL height obtained by R/V *Ron Brown* profile is still about 1000 m and the mixed layer is more uniform. In both profiles, characteristic elevated mixed layers are present. Again assuming a transport wind of 10 m s^{-1}, the air arriving at R/V *Ron Brown* would have originated from India the previous day at 1900 LT and the deeper inversion above the MBL corresponds to the stable land boundary layer. Unlike, the 0000 UTC sounding, the elevated mixed layer associated with the land plume is better defined in the R/V *Sagar Kanya* profile. The air mass at R/V *Sagar Kanya* probably originated at 1400 LT and is representative of the daytime convective boundary layer over land.

Moisture profiles are good indicators of air mass modification. One would expect the air to get moister with distance from the coastline. Specific humidity profiles taken aboard R/V *Ron Brown* (11° N, 68° E) and R/V *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC on 7 March 1999 are shown in Figure 10. Comparing the

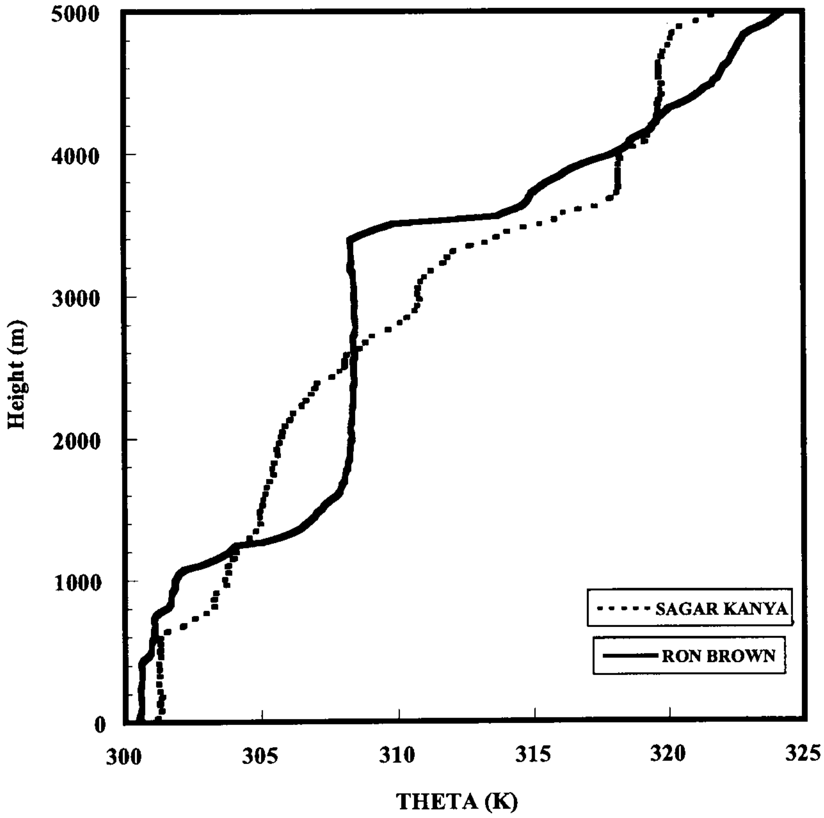

Figure 8. Potential temperature profiles taken from R/Vs *Ron Brown* (9.2° N, 69° E) and *Sagar Kanya* (10.6° N, 74.5° E) at 0000 UTC on 7 March 1999. The land plume is in a formative stage closer to the coast and is well formed farther away.

moisture profiles from R/Vs *Ron Brown* and *Sagar Kanya*, it is apparent that the MBL is moister at the location farther offshore. It is interesting to note that the land plume in the moisture profiles is characterized by a deep layer of near constant humidity corresponding to the land plume location indicating the remnants of the land based mixed layer.

Wind speed and direction profiles taken from R/V *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC on 7 March 1999 are shown in Figures 11a and 11b, respectively. The winds within the MBL are much weaker with a value of about 2 m s^{-1} at this location. Above the MBL, the wind speed profile has a well-defined jet-like structure with a maximum speed of 11 m s^{-1} at 1400 m. The altitude of this jet corresponds to the typical land plume layer discussed before. It appears the jet formation is related to entrainment of air at both the edges of the land plume and associated increase in turbulence (Figure 5c). Typical offshore ozone distributions also have the same vertical structure with maximum values near the middle of the plume (Figure 5d). The wind direction profile shown in Figure 11b indicates a

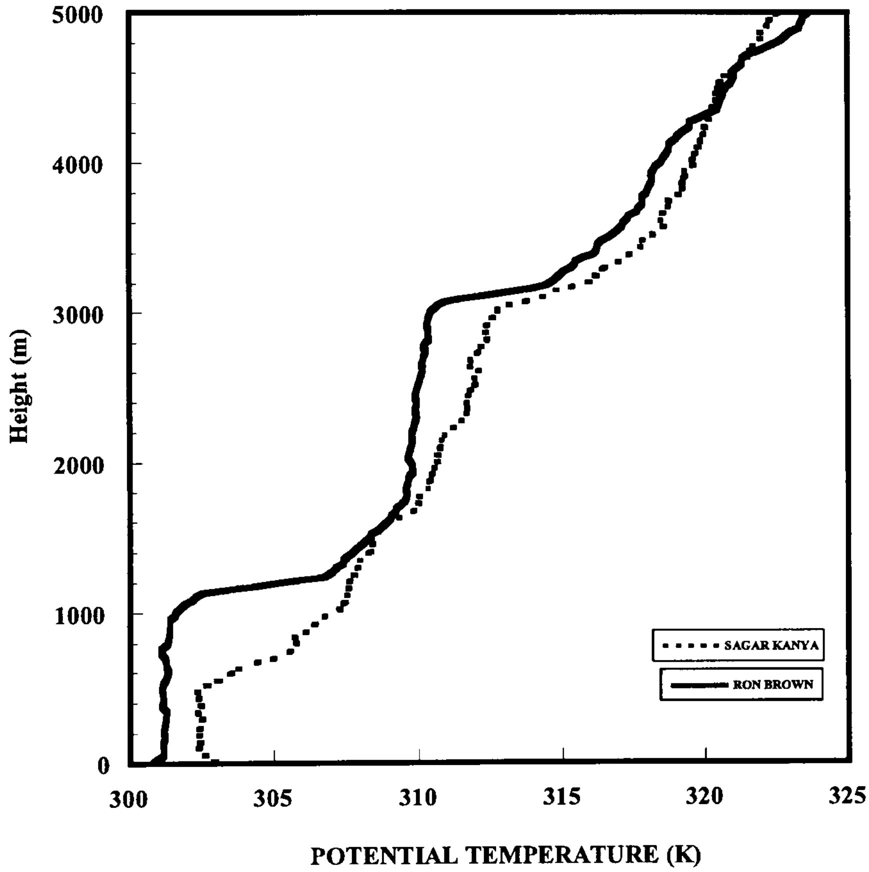

Figure 9. Potential temperature profiles taken from *Ron Brown* (11° N, 68° E) and *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC, 7 March 1999. The height of the MBL measured by *Sagar Kanya* is only 500 m because of its close proximity to the shore. The height of the MBL measured by *Ron Brown* is larger with a value of 1000 m as the convective boundary layer grows due to air mass modification.

north-easterly wind in the MBL and in the land plume between 800 m and 3000 m and corresponds well with the wind speed vertical profile in Figure 11a.

3.3. Latitudinal variation of ozone

Analysis of latitudinal variations in ozone concentrations over the Arabian Sea will determine the magnitude of air mass modification by the land plume. Latitudinal variations of ozone concentration measured at a height of 18 m over R/V *Ron Brown* for the period February 24–March 19, 1999 are shown in Figure 12. The track of R/V *Ron Brown* during INDOEX (1999) are shown in Figure 1. A TECO 49 ozone instrument was used and the data averaged into 30-min time bins. A complete description of the R/V *Ron Brown* ozone experiment is provided by Stehr

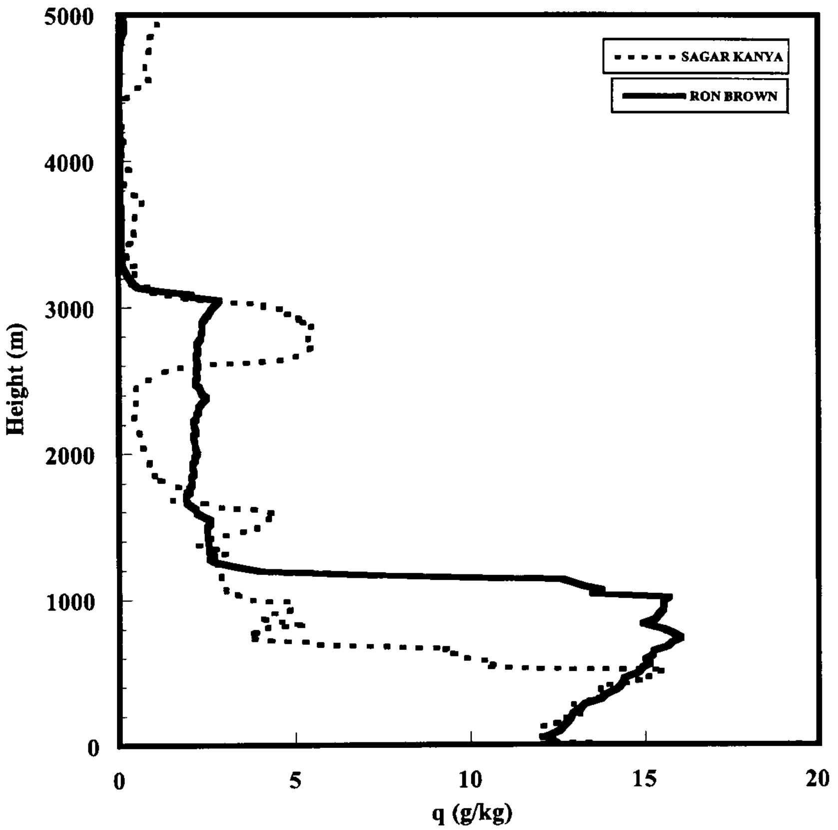

Figure 10. Specific humidity profiles taken from RVs *Ron Brown* (11° N, 68° E) and *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC on 7 March 1999. The MBL is shallow at the location of *Sagar Kanya*, but becomes deeper and more moist further offshore at the location of *Ron Brown* through air mass modification process shown schematically in Figure 7.

et al. (2002). Ozone concentrations decreased from 45 ppb at 18° N where R/V *Ron Brown* was close to the source region to 10 ppb at 10° S. A regression line with a correlation coefficient of 0.95 indicates a high correlation of ozone concentration with latitude. The slope of the regression line is 1.49 ppb per degree of latitude showing a gradual decrease in ozone concentrations towards the equator essentially due to entrainment and dispersion.

To obtain a better idea of the transport of ozone in the two layers, MBL and the land plume, averages of ozone concentrations were calculated for each layer. The latitudinal variation of average ozone concentration in the MBL and the land plume (defined as the layer between 2000 and 3000 m) is shown in Figure 13. Layer averages were calculated from ozone soundings made from R/V *Ron Brown* during its track across the tropical Indian Ocean and the Arabian Sea. Square data points represent MBL ozone concentration averages and circles represent the land plume average ozone concentrations. Regression lines were plotted for both layers

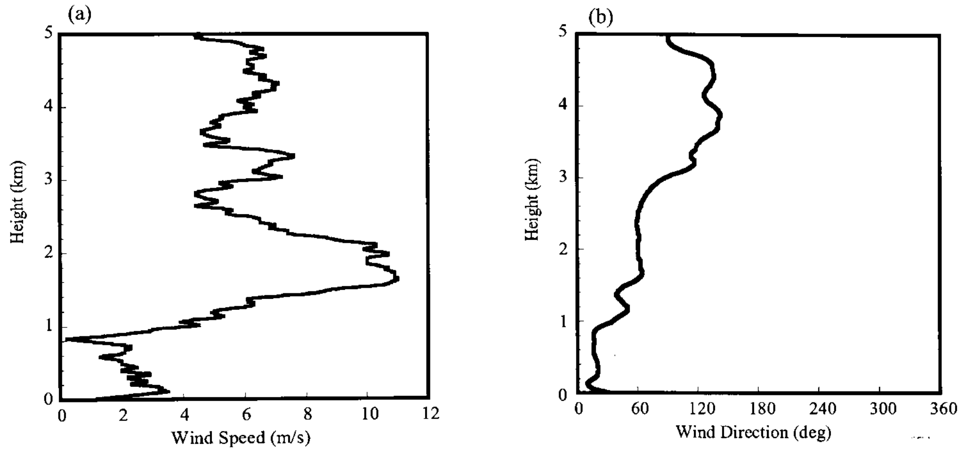

Figure 11. (a) Wind speed profile taken from RV *Sagar Kanya* (11° N, 74.5° E) at 1200 UTC on 7 March 1999 showing an elevated jet of about 11 m s^{-1} at a height of 2000 m; (b) wind direction profile showing the winds at the height of the jet to be north-easterly.

with the solid line representing the land plume and dotted line representing the MBL. Ozone concentrations in the MBL decrease by a factor of two from 40 ppb at 18° N to 20 ppb at the equator. There is a more dramatic decrease in the ozone concentrations in the land plume. Concentrations decrease from 80 ppb at 16° N to 30 ppb at the equator. The slope of the regression line is 3.84 ppb per degree, which is almost three times the variation of ozone in the MBL. As with the mixed layer, this regression line is well correlated with the data with $R = 0.86$. It is clear that the majority of ozone transport over the Arabian Sea is occurring in the land plume and the same would be true for aerosols.

4. Conclusions

An elevated land plume transports gases (and aerosols) from the Indian subcontinent over the Arabian Sea and the Indian Ocean. This well-mixed layer has a typical depth of 2000 m. Vertical wind distribution through this layer has a jet-like structure with the maximum winds occurring in the middle of the land plume. The marine boundary layer grows in height with offshore distance reaching a maximum depth of about 1000 m at a distance of 800 km. The MBL and the land plume are separated vertically by a strong inversion. This strong inversion is a general feature associated with the air mass modification and the formation of the land plume. The structure of the land plume appears to depend on the trajectory of the air mass and the time of origin at the coast. Analysis of high frequency aircraft turbulence observations indicate the jet-like structure of the plume to depend on the entrainments at the bottom and the top of the plume at altitudes of about 1000 m and 3000 m, respectively.

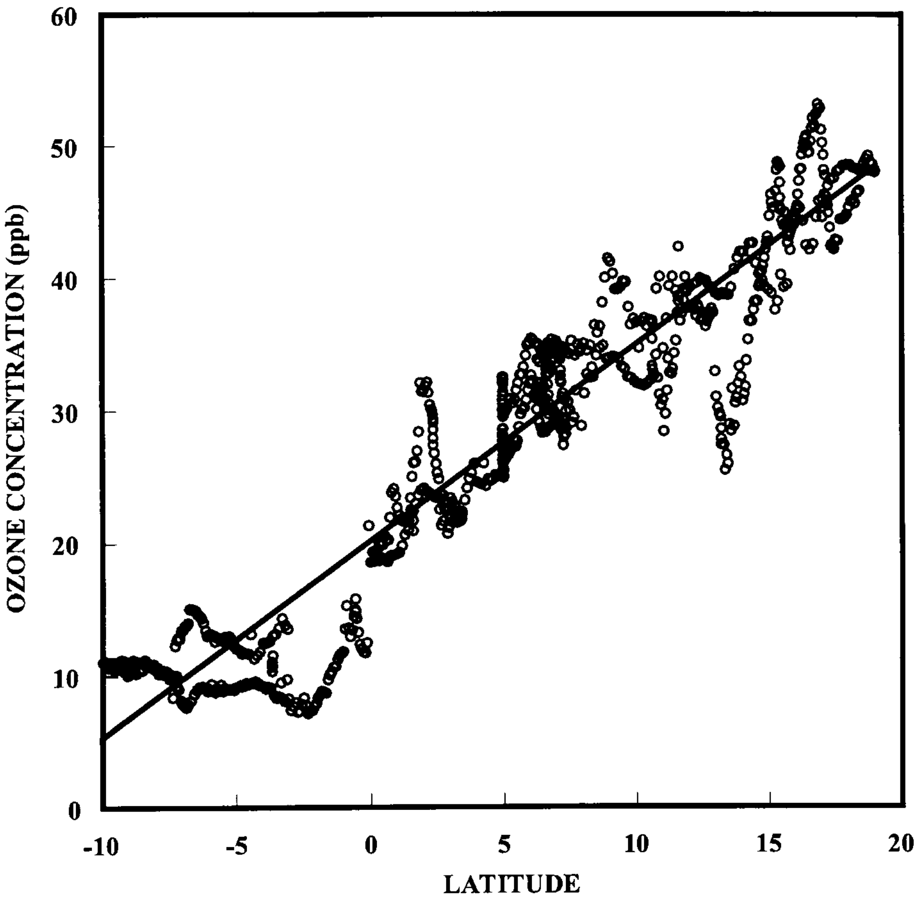

Figure 12. Latitudinal variation in ozone concentration measured at a height of 18 m from R/V *Ron Brown*.

The wind direction is an important factor in the variation of ozone concentration measured at the Kaaishidoo Observatory, Maldives. Ozone concentrations at the surface are 100% more when the winds are from the north-east as compared to other directions. In the land plume the ozone concentrations increase by about 400% for a northeasterly wind direction.

Ozone concentrations are consistently higher in the land plume than in the MBL. The ozone concentration in both layers (land plume and the MBL) decrease towards the equator with distance from the source region. However, the ozone concentrations in the land plume decrease faster. Entrainment processes with the free atmosphere and the MBL are believed to be the reason for the sharp decrease in concentration in the land plume. Even near the equator, several hundred kilometres away from the source region, the ozone concentration in the land plume is around

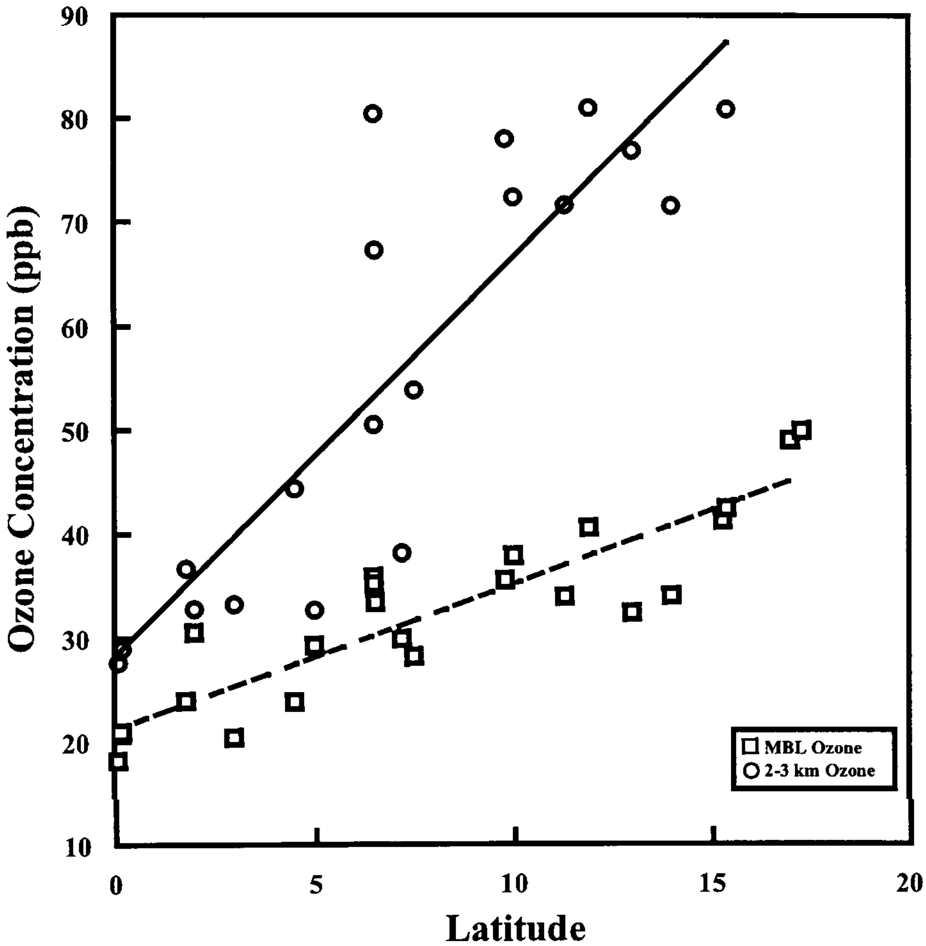

Figure 13. Latitudinal variation of mean ozone concentrations in the MBL and the land plume from RV *Ron Brown* observations indicating significantly higher values in the land plume.

30 ppb, larger than the ambient concentration of 15 ppb observed for a marine air mass.

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