8.9 DEVELOPMENT OF THE LAND PLUME AND ITS STRUCTURE DURING INDOEX (1999)

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1. Introduction

The central hypothesis of the Indian Ocean Experiment (INDOEX) was related to the transport of an aerosol-laden air mass from the Indian subcontinent and the Asian landmass over the Indian Ocean and its effect on global radiation balance (Ramanathan et al 1995). The primary goals of INDOEX (1999) were to study the variations in the magnitude of solar absorption occurring near the surface and in the troposphere in the presence of sulfates and aerosols of continental origin. High concentrations of non-sea salt aerosols in the Arabian Sea appear to result from their transport from the Indian subcontinent and Arabia (Rajeev et al 2000). The high concentrations of absorbing haze/ aerosols appear 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 1970's (Krishnan and Ramanathan 2002). Thus, there is a need to investigate the mechanism of transport of aerosols and gases over the ocean.

Pre-INDOEX observations from ship cruises have shown spatial variations in thermodynamic profiles indicating 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 by Raman et al (2002). based on the air mass modification process described The objective of this paper is to discuss the mechanism of formation of the land plume and its growth offshore and the variation of the concentrations of gases such as ozone in the lower troposphere based on observations from INDOEX (1999).

2. Land Plume Structure

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* (11N, 68E) on 7 March 1999, 12 UTC is shown in Figure 1. Thermodynamic structure in the lower troposphere exhibits two distinct layers over the ocean for northeasterly 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 yet another strong inversion. The air is fairly well mixed with a θ_v of 303 K up to an altitude of 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.

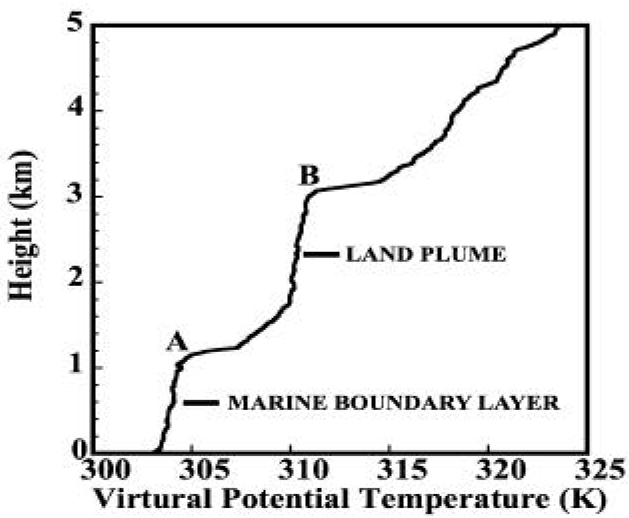

Figure 1. Virtual potential temperature profile taken from R/V *Ron Brown*.

An ozone concentration profile taken at a distance of 800 km off the west coast of India aboard R / V *Ron Brown* (11.3N, 68.3E) on 7 March 1999, 13:35 UTC (1835 LT) is shown in Figure 2. Ozone is fairly well mixed in the lower portion (500m) 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 northeasterly from 700 m to 3000 m (not shown). Change in wind direction to more northerly is believed to be the reason for increasing ozone concentrations near the top of the MBL. 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.

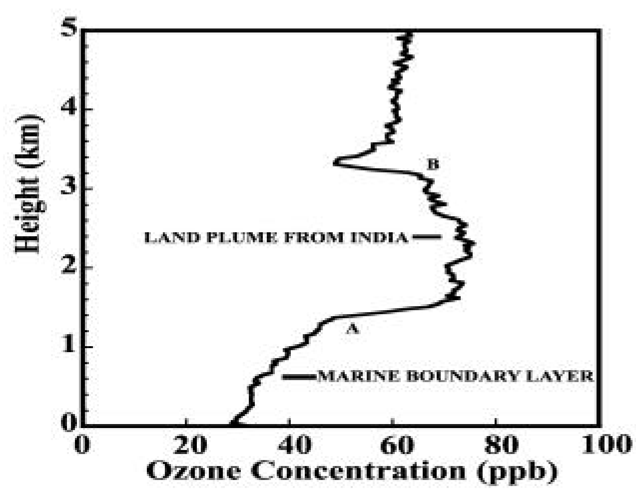

Figure 2. Ozone concentration profile taken from R/V *Ron Brown*.

A direct way of observing the dynamic structure of the land plume is to use downward looking lidar to obtain the aerosol scattering data over the Arabian Sea. Scattering distributions measured by a downward looking lidar on the French aircraft *Mystere* is shown in **Figure 3**. The data was collected on 9 March 1999 at 09Z (1400 LT) from 4.5N to 7.0N at 70E. 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 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.

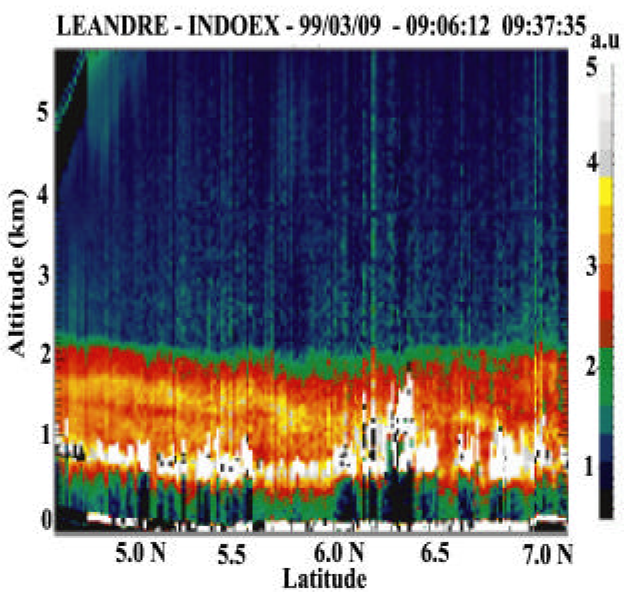

Figure 3. Lidar image taken from aircraft Mystere.

3. Land Plume Development

A parallel track experiment was conducted with R / V *Ron Brown* and R / V *Sagar Kanya* on 7 March 1999 to cross compare their observations and to study offshore variations of various parameters such as winds, and ozone concentration. North-south track of R / V *Sagar Kanya* was at a distance of 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. 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 taken from R / V *Ron Brown* (11N, 68E) and R / V *Sagar Kanya* (11N, 74.5E) at 12Z (17 LT) on 7 March 1999 are shown in Figure 4. The height of the MBL measured by R/V *Sagar Kanya* is about 500 m. However, the MBL height obtained by R/V *Ron Brown* profile is about 1000 m and the mixed layer is more uniform. In both the profiles, the characteristic elevated mixed layers are present. Assuming a transport wind of 10 m/s, the air arriving at R / V *Ron Brown* would have originated from India the previous day at 19:00 local time and deeper inversion above the MBL corresponds to the stable land boundary layer normally present at this time. The air mass at R / V *Sagar Kanya* originated at 1400 LT and is representative of the daytime convective boundary layer over land.

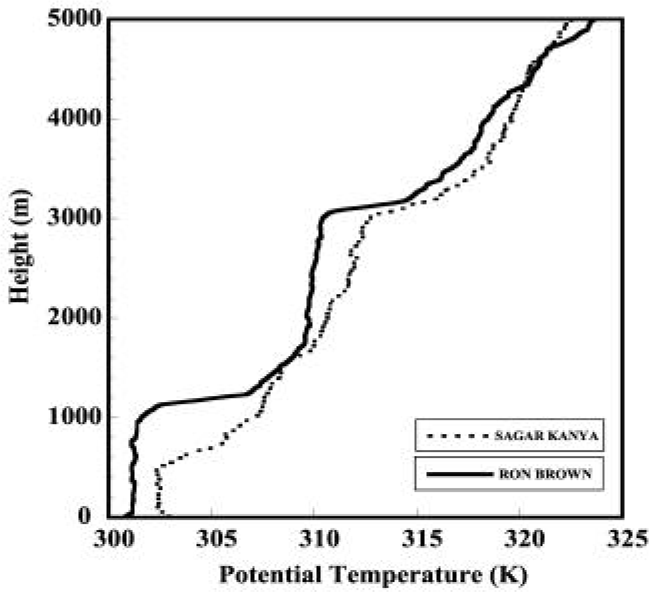

Figure 4. Potential temperature pofiles taken from R/Vs *Ron Brown* and *Sagar Kanya*.

4. Latitudinal Variation of Ozone

To get a better idea of the transport of ozone in the two layers, MBL and the land plume, integrated layer averages of ozone concentrations were calculated for each layer. 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 5. 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 concentration. Regression lines were plotted for both layers 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 18N 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 16N to 30 ppb at the equator. The slope of the regression line is 3.84 ppb/ deg., which is almost 3 times the variation of ozone in the MBL. As with the mixed layer, this regression line is well correlated with the data with a regression coefficient of 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.

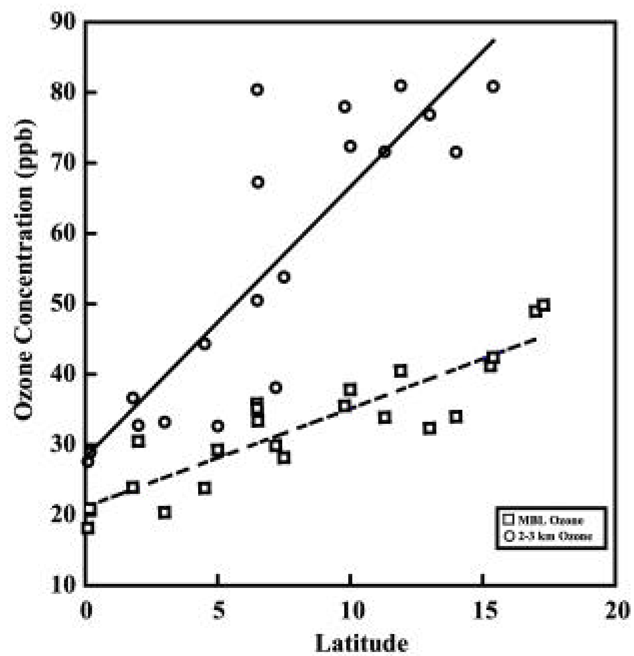

Figure 5. Latitudinal variation of ozone in the MBL (square) and in the land plume (circle).

5. 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. 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. The structure of the land plume appears to depend on the trajectory of the air mass and the time of origin at the coast.

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 kilometers away from the source region, the ozone concentration in the land plume is around 30 ppb, larger than the ambient concentration of 15 ppb observed for marine air mass.

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6. References

Krishnan, R., and V. Ramanathan, Evidence of surface cooling from absorbing aerosols, *Geophy. Res. Letters*, 29, 54, 1-4, 2002.

Manghnani, V., Raman, S., Niyogi, D.S., Parameshwara, V., Morrison, J.M., and Raman, S.V., 2000, Marine boundary-layer variability over the Indian Ocean during INDOEX (1998), *Boundary Layer Meteorology* 97, 411-430.

Rajeev, K., V. Ramanathan, and M. Meywerk, Regional aerosol distribution and its long range transport over the Indian Ocean, *J. Geophys. Res*., 105, 2029-2043, 2000.

Raman, S., Niyogi, D.S., Simpson, M., and Pelon, J., Dynamics of the elevated land plume over the Arabian Sea and the northern Indian Ocean during northeasterly monsoon (INDOEX), Geophysical Research Letters, In Press.

Ramanathan, V., Crutzen, P., Coakley, J., et al, 1995, *Indian Ocean Experiment (INDOEX) Whiter Paper*, C-4 Pulbication # 143, Scripps Inst. Ocean., UCSD.

Ramanathan, V., et al., The Indian Ocean Experiment: An Integrated Analysis of the Climate Forcing and Effects of the Great Indo-Asian Haze, *J. Geophys. Res*., 106(D22), 28,371-28,398, 2001