Dynamics of the elevated land plume over the Arabian Sea and the Northern Indian Ocean during northeasterly monsoons and during the Indian Ocean experiment (INDOEX)

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[1] We describe the dynamics of the formation of an elevated land plume over the Arabian Sea and northern Indian Ocean observed during the 1999 Indian Ocean Experiment (INDOEX). The presence of the elevated plume above the marine boundary layer for a depth of about 2000 m could be inferred from the thermodynamic profiles of the lower troposphere obtained from research vessels in 1997, 1998, and 1999, and in the lidar data obtained from aircraft during the INDOEX. Formation of the elevated plume was investigated further using a three-dimensional high-resolution mesoscale modeling system. The plume extends for hundreds of kilometers and its strength and coherence is influenced by the diurnal variation of the upwind continental boundary layer. *INDEX TERMS:* 9340 Information Related to Geographic Region: Indian Ocean; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 4247 Oceanography: General: Marine meteorology; *KEYWORDS:* Indian Ocean, Air/Sea Interactions, Land/Atmosphere Interactions, Marine Meteorology, Boundary layer processes

1. Introduction

[2] Indian Ocean Experiment (INDOEX) was a multi-disciplinary field program conducted from January to March 1999 over the Indian Ocean [*Ramanathan et al.*, 1995]. During the boreal winter, continental aerosols are transported from the Indian subcontinent towards the Inter Tropical Convergence Zone (ITCZ) by the prevailing north-easterly winds. One of the core objectives of this experiment was to assess the variation of aerosol concentrations and their effect on cloud properties, radiation, and global climate change.

[3] During the pre-INDOEX northeast monsoons, two observational cruises were undertaken over the Indian Ocean. Prior observations from an ocean research vessel (ORV) indicated high concentrations of aerosols near the ocean surface hundreds of kilometers offshore of the Indian subcontinent [e.g., *Rhoads et al.*, 1997]. Analysis of the thermodynamic profiles obtained during pre-INDOEX cruises indicated the existence of a distinct elevated thermal layer over the ocean suggesting the presence of an elevated land plume during the northeast monsoon [*Warrior*, 1999; *Manghnani et al.*, 2000]. This elevated land plume is believed to be a manifestation of the effects of land-ocean-atmosphere interaction near the coast and air mass modification by the ocean as the long-range transport of polluted air takes place [see e.g., *Chatfield et al.*, 1996; *Ansmann*, 2000]. Physical modeling of air mass modification over a heat island was performed by one of the authors [*Sethuraman and Cermak*, 1974] and the results indicated the development of a boundary layer with increasing height as the air in lower levels gets modified and an elevated plume develops. The objectives of this paper are to present observations and mesoscale modeling results to discuss the dynamics of the formation of this elevated plume in which high concentrations of aerosols and gases have been observed during INDOEX [*Ramanathan et al.*, 2000]. Presence of such an aerosol plume over the Indian Ocean [and over the Atlantic Ocean as discussed in *Ansmann et al.*, 2001] could have significant impact on radiative forcing, and its analysis can lead to a better understanding of the role of anthropogenic aerosols on global climate.

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2. Observations

[4] There were two pre-INDOEX *ORV Sagar Kanya* cruises in this region, one in 1996–97 from December 26, 1996 to January 31, 1997 and the other from February 19 to March 30, 1998, both during northeast monsoons. During the INDOEX field phase (January to March, 1999), two research vessels, *ORV Ron Brown* and *ORV Sagar Kanya* were deployed along with numerous observational platforms that included several research aircraft, surface based soundings and satellites. Observations discussed here pertain to those observed from the two ships, and from the French aircraft *Mystere*, which was equipped with a downward looking lidar [*Ramanathan et al.*, 2001].

[5] In the 1997 cruise, 47 CLASS (Cross-chain Loran Atmospheric Sounding System) sondes were launched from *ORV Sagar Kanya*'s transit from 15 N to 15 S. Boundary layer heights were derived from the thermodynamic profiles. They indicated the variability of the marine boundary layer (MBL) heights ranging from 400 m to 1100 m depending on the location as shown in Figure 1. Here 'D' refers to 'daytime' (~2 pm LT), 'E' refers to 'evening' conditions (~5 pm LT), and 'N' refers to 'nighttime' conditions (~6 am LT or 8 pm LT), and the solid line is a

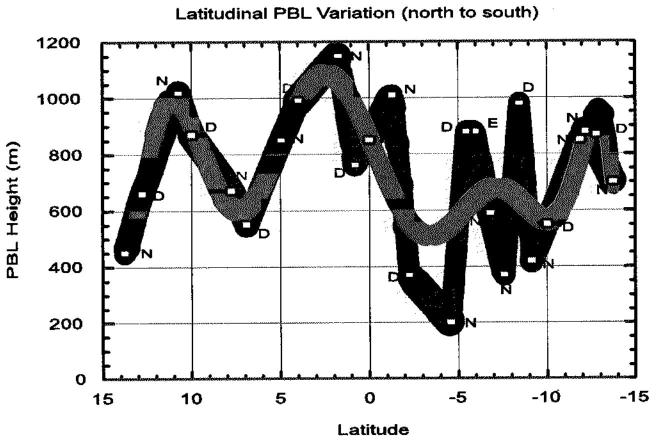

Figure 1. Latitudinal Planetary Boundary Layer (PBL) height variability over Arabian Sea and Indian Ocean during pre-INDOEX 1997. Similar results were obtained during 1998 and 1999. 'D' refers to daytime (~noon), 'N' refers to night, and 'E' refers to evening (~5 pm).

smoothed fit. The variability in the MBL height in the northern hemisphere has no prominent local diurnal variation. Values ranged from about 400 m near the coast to about 1000 m near the equator. This increase in the boundary layer height with distance appears to be related to continued air mass modification over the ocean with a different surface temperature [*Sethuraman and Cermak*, 1974]. However, in the southern hemisphere, MBL heights varied significantly with the time of the day. It is believed that this difference in the variation of MBL heights is related to the existence of the land plume north of the equator. Variation of the MBL heights is further discussed in *Mohanty et al.*, [2001] and *Manghnani et al.*, [2000].

[6] The variability in the MBL structure obtained from the 1997 observations was confirmed with the data set obtained during the 1998 *ORV Sagar Kanya* cruise. Figure 2 shows a typical vertical profile of virtual potential temperature at 15 N, 69 E (about 500-km downwind of the landmass). Multiple layers with differing thermal characteristics are evident. The air mass originated from the land, as the winds were predominantly northeasterly, creating an elevated plume that could potentially transport anthropogenic aerosols and gases over the open ocean as hypothesized in *Lelieveld et al.* [2001]. As can be seen from the Figure 2, the MBL was about 700 m deep capped with a strong shallow inversion and then a layer of nearly uniform temperatures of about 1200 m thickness. Vertical profiles of specific humidity (not shown) also indicated the existence of this layer with constant values in between the moist MBL and dry air aloft. The constant temperature and moisture layer is a characteristic of the existence of the land plume in this region. Such profiles were obtained even for a distance of about 600 to 800 km away from the nearest landmass. The land plume could have a lateral extent of several hundreds of kilometers depending on its trajectory and distance from the coast.

[7] The elevated land based plume appears to modulate the MBL height [*Manghnani et al.*, 2000] and this effect obviously contributes to the dampening of local diurnal variations north of the equator (in Figure 1). Also, the variability in the depth of the land plume offshore could be a manifestation of the diurnal change in the PBL over land and the travel distance of the daytime and nighttime air masses [see also *Ansmann et al.*, 2001]. Height of the typical daytime PBL over Indian subcontinent during this period is of the order of 2000 m [*Raman et al.*, 1990] and the nocturnal boundary layer about 300 m. Thus there is a distinct difference in the land air mass characteristics that travel over the ocean between day and night. This feature is discussed further with the presentation of numerical modeling analysis and airborne lidar data.

[8] Aerosol distributions and hence the structure of different land plumes are shown in Figures 3a–3d based on measurements from a downward looking lidar aboard the French aircraft: *Mystere*. Observations in Figure 3a were taken around 1500 LT in a flight track with north-south direction between the longitudes 70 E and 75 E. Southern tip of India is located near 8 N. A striking feature in this observation is the existence of an elevated aerosol plume with the base at the top of the boundary layer at approximately 800 m and extending vertically to about 2 km. The plume diffuses more as the distance from the continent increases. These features are consistent with the virtual temperature profile structures seen in the profiles observed during the 1997 and 1998 pre-INDOEX cruises [*Manghnani et al.*, 2000]. Width of the plume appears to be several hundreds of kilometers as inferred from the lidar-based cross section at 7 N in Figure 3b.

[9] The lidar observations in Figures 3c and 3d show the impact of diurnal variations of the boundary layer over the land on the structure of the land plume over ocean. Observations in Figure 3c were taken close to 1100 LT. Vertical extent of the plume is narrow and appears to be weakly turbulent. For a wind speed of 10 m s^{-1} (typically observed in the land plume above the boundary layer during

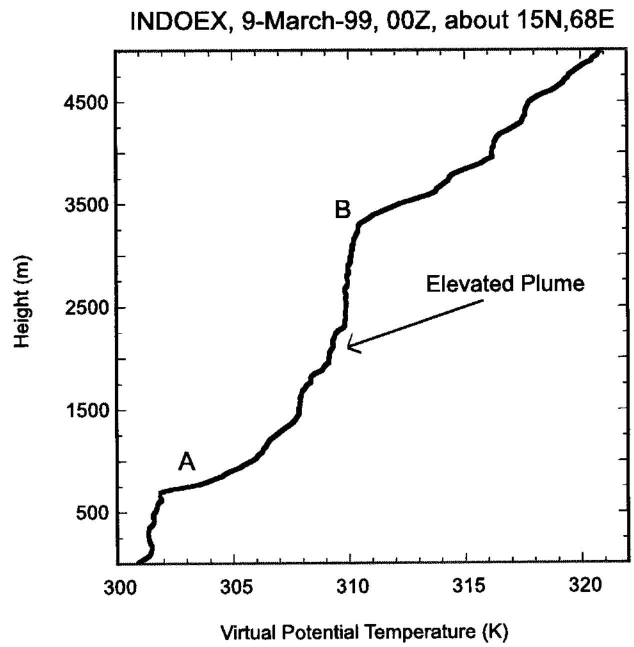

Figure 2. Typical thermodynamic profile over the INDOEX study region about 500-km downwind of landmass. Region between 'A' and 'B' indicates the depth of the aerosol rich land plume over the ocean.

northeast monsoon) the back trajectories (discussed ahead) indicate an exit time at the coast of 0500 LT [*Krishnamurti et al.*, 1998; *Mohanty et al.*, 2001]. At this time, a shallow stable nocturnal boundary layer is present over land and the source for aerosols in the land plume is the residual layer aloft. Lidar observations taken about four hours later (Figure 3d), indicate a more coherent and deeper plume. This air mass would have exited land in the presence of a much deeper convective PBL. Thus the diurnal variation in the land plume over the Indian Ocean appears to be affected by the aerosol source region, and the boundary layer processes both over land.

3. Numerical Modeling Results

[10] To study the three-dimensional background flow over the region, MM5, a non-hydrostatic mesoscale model [*Grell et al.*, 1995] was used. The model simulations discussed here are for a 48-hour period from 00Z March 8 to 00Z March 10, 1999, which corresponds to the observations presented in Figures 2 and 3. This model has been used before in a tropical region [*Roswintiarti et al.*, 2001] and has the ability to realistically simulate different features observed during the INDOEX field phase.

[11] Analyses of the synoptic conditions (from global analysis, and satellite imagery) during the simulation period indicate the presence of a high-pressure system over the eastern Arabian Sea. The direction of 925-hPa winds was northeast over northern India and the Arabian Sea. The strongest NE winds (10 to 15 m s^{-1}) were located over the northern region of India's west coast. Figure 4 shows two 48-hour forward, and two 48-hour backward model trajectories starting at 00Z March 8 and ending at 00Z March 10, 1999 based on the MM5 simulations. The trajectories in the model originated at a height of 2 km above the surface for F1 and F2 and at heights of 500 m and 2 km for the backward trajectory B1. Trajectory F1 originates along the northern region of India's west coast at 18 N, 73 E and travels ~1000 km to end in the Arabian Sea at 12 N, 67.5 E. Trajectory F2 originates along the southern region of India's west coast at 12.5 N, 75 E and travels to 12 N, 72.5 E, located in the Arabian Sea. Trajectory F2 travels less distance than trajectory F1 because the simulated winds in the southern region of the west coast are weaker. Trajectory F2 also was caught in a strong coastal circulation initially. The trajectories over 10N, 73E (Trajectory B1) at 500 m and 2 km, correspond to the location close to the aircraft/lidar tracks cited in Figure 3. A clear land-based air mass source is identified. The interaction of such a land-based air mass, with the boundary layer variations, is discussed ahead. Overall, the trajectories agree well with the observations showing stronger coastal circulations along the southern region of India's west coast where the boundary layer winds were lighter than to the north. Further, it is obvious that the low altitude air forming the plume originated from the Indian subcontinent in the model simulation.

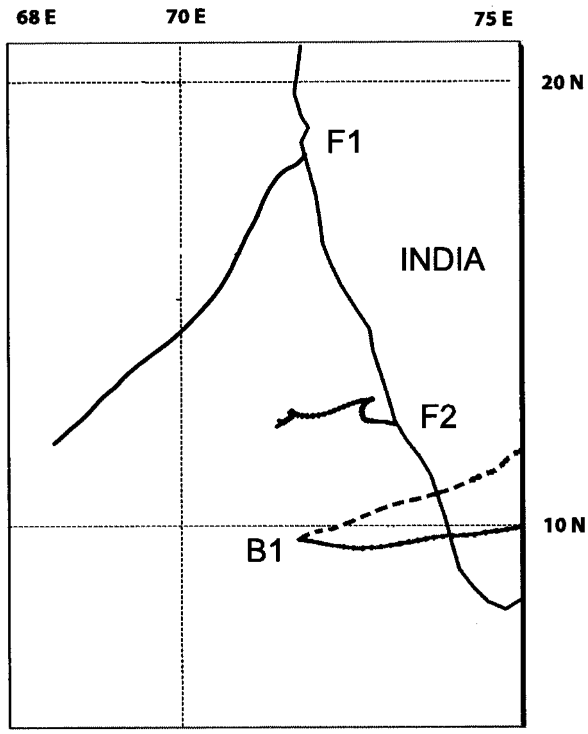

Figure 4. 48-hour forward (F1 and F2), and the backward (B1, where dashed line is for 500 m and solid line is for 2 km) model trajectories from 0Z March 8 to 0Z March 10, 1999. This period corresponds to the observations shown in Figures 2 and 3. The trajectory analysis clearly shows transport of the land plume from the land sources in the western part of the Indian subcontinent (location 1) towards the Indian Ocean as indicated by the soundings. Offshore transport also involves coastal circulations caused by sea and land breezes (Location 2).

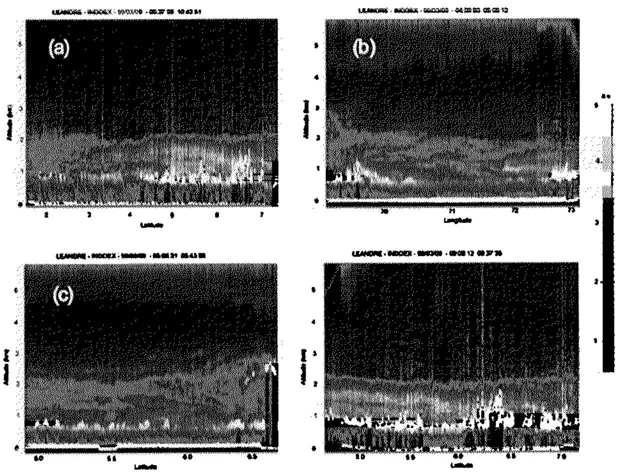

Figure 3. Aerosol distribution using lidar data over the Arabian Sea and the Indian ocean for March 9, 1999: (a) latitudinal cross section between 70 E and 75 E at 1510 LT with the land plume signature between 1 and 2 km; (b) longitudinal cross section at 7 N indicating the plume can extend hundreds of kilometer over the ocean, (c) at 1100 LT a weaker land plume structure corresponding to the residual layer over land, (d) at 1500 LT near the same location indicating a more coherent and deeper aerosol rich layer. These images confirm the presence of a diurnally varying, wide aerosol land plume over the Indian Ocean.

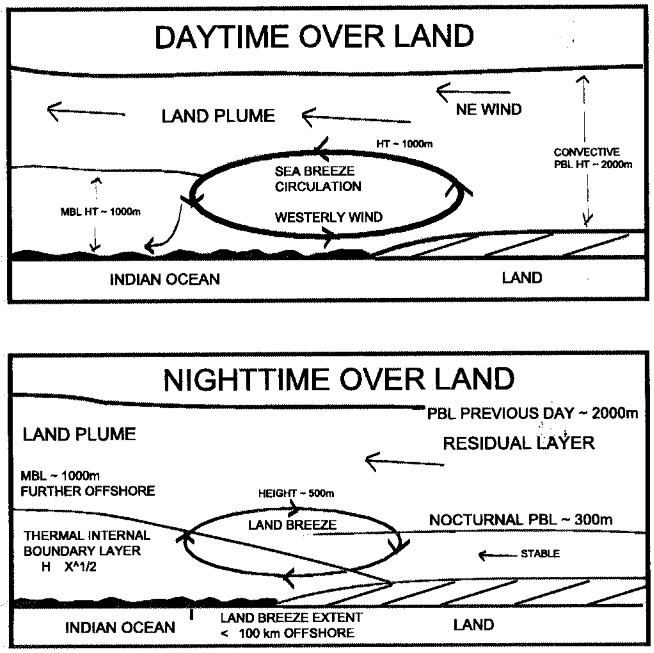

Figure 5. Conceptual depiction of the interaction between the coastal circulations and the land plume over the Indian ocean for day and night.

[12] Because of the variability in the surface winds and interactions with small-scale features, there is a significant variability along the trajectories, but different features (sea breeze circulation, and long range transport of air mass beyond the sea breeze circulation) are well simulated in the forward and backward trajectory analyses.

[13] During the northeast monsoon, sea and land breezes form along the Indian coasts and particularly along the west coast, on almost a daily basis. It is expected that the surface conditions on the Indian subcontinent and the topography will have a significant effect on the height, depth, structure and the temporal variations of the land plume that forms aloft [e.g., *Mohanty et al.*, 2001]. Idealized schematic of the interaction between the coastal circulations and the land plume is shown in Figures 5a–5b. The diagrams show the interaction between the coastal circulations in daytime and nighttime and the land plume as it forms above the air mass modified by the ocean with offshore flow. Much of the polluted air in the 2 km deep daytime convective boundary layer over land is transported in this plume while some are re-circulated in the coastal sea breeze circulation. During the nighttime, the land boundary layer becomes stable and the residual layer aloft is cut off from the surface. This results in a reduction of pollutants in the land plume originating during nights, as observed by the air borne lidar offshore.

4. Conclusions

[14] Observations during INDOEX (1999) show that the marine boundary layer over the Arabian Sea and the northern Indian Ocean is influenced by the existence of an elevated land plume. This land plume is formed by air mass modification and its structure is apparent in thermodynamic profiles and in aerosol measurements. The land plume extends to several hundreds of kilometers from the continent and has a diurnal variation dependent on the place and time of origin over land. Marine boundary layer itself has a diurnal variation with maximum heights during nights and minimum during daytime and this variation is more pronounced south of the ITCZ.

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References

Ansmann, A., Vertical profiling of the Indian aerosol plume with six-wavelength lidar during INDOEX: A first case study, *Geophys. Res. Lett.*, *27*, 963–966, 2000.
Ansmann, A., et al., European pollution outbreaks during ACE 2: Lofted aerosol plumes observed with Raman lidar at the Portuguese coast, *J. Geophys. Res.*, *106*, 20,725–20,734, 2001.
Chatfield, R. B., J. A. Vastano, H. B. Singh, and G. W. Sachse, A generalized model of how fire emissions and chemistry produce African/oceanic plumes (O3, CO, PAN, smoke) in TRACE A, *J. Geophys. Res.*, *101*, 24,279–24,306, 1996.
Grell, G., J. Dudhia, and D. Stuaffer, *A Description of the Fifth- Generation Penn State/NCAR Mesoscale Model* (*MM5*), NCAR Technical Note NCAR/TN - 398 + STR, 122 p., 1995.
Krishnamurti, T. N., B. Jha, and V. Ramanathan, Aerosol and pollutant transport and their impact on radiative forcing over the tropical Indian Ocean during the January–February 1996 Pre-INDOEX cruise, *Tellus*, *50B*, 521, 1998.
Lelieveld, J., et al., The Indian Ocean Experiment: Widespread Air Pollution from South and Southeast Asia, *Science*, *291*, 1031–1036, 2001.
Manghnani, V., S. Raman, D. S. Niyogi, V. Parameshwara, J. M. Morrison, and S. V. Ramana, Marine boundary-layer variability over the Indian Ocean during INDOEX (1998), *Bound.-Layer Meteorol.*, *97*, 411–430, 2000.
Mohanty, U. C., D. Niyogi, S. Raman, and A. Sarkar, Numerical study of the role of land-air-sea interactions for the northeasterly monsoon circulations over Indian Ocean during INDOEX, *Current Science*, *80*, 60–68, 2001.
Raman, S., et al., Structure of the Indian southwesterly pre-monsoon and monsoon boundary layers: Observations and numerical simulation, *Atmos. Environ.*, *24A*, 723–734, 1990.
Ramanthan, V., et al., *Indian Ocean Experiment* (*INDOEX*) *White Paper*, C-4 Publication # 143, Scripps Inst. Ocean., UCSD, 1995.
Ramanathan V., et al., The Indian Ocean Experiment: An integrated assessment of the climate Forcing and effects of the great Indo-Asian haze, *J. Geophys. Res.*, *106*, 28,371–28,398, 2001.
Rhoads, K. P., et al., Composition of the troposphere over the Indian Ocean during the monsoonal transition, *J. Geophys. Res.* (*Atmos.*), *102*, 18,981, 1997.
Roswintiarti, O., S. Raman, U. Mohanty, and D. Niyogi, Application of three dimensional triple nested mesoscale model for assessing the transport and boundary layer variability over the Indian Ocean during INDOEX, *Current Science*, *80*, 69–76, 2001.
SethuRaman, S., and J. E. Cermak, Physical modeling of flow and diffusion over an urban heat island, *Adv. in Geophys.*, *18B*, 223–240, 1974.
Warrior, H., *Study of the Mesoscale Land-Air-Sea Interaction Processes in the Tropics during INDOEX*, M. S. Thesis, Dept. of Marine, Earth, and Atmospheric Sciences, N.C. State University, 153 pp., 1999.

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