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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 northeasterly 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.

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

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