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A COMPARISON OF THE SIGNIFICANT FEATURES OF THE MARINE BOUNDARY LAYERS OVER THE ARABIAN SEA AND THE BAY OF BENGAL DURING MONEX 79

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1. INTRODUCTION

An important aspect in the comparison of the marine boundary layers over the Arabian Sea and the Bay of Bengal is the difference in the mesoscale forcings over the two regions. Unique geographical features of each region also modify the low-level flow. The strong southwest Somali Jet is by far the dominant feature of the low-level monsoon flow over the Arabian Sea. Numerous authors have considered this jet stream based on observational work (Nordgarden, 1983; Pant, 1982; Hart et al., 1978; Findlater, 1969) and theoretical and model studies (Krishnamurti et al.,1983; Bannon, 1982; Rubenstein, 1981; Hart, 1977). It is generally agreed that this jet is a complicated phenomenon whose dynamics are influenced by many factors related to monsoon flow. One of the major differences between the low-level flow in the boundary layer over the Bay of Bengal as opposed to the Arabian Sea is the absence of this strong low-level jet. The geographical and thermodynamic conditions in the Arabian Sea region which enhance the development of a jet are not as prevalent over the Bay of Bengal. Instead, the topographic effects of the Indian peninsula and the bay itself serve to promote the development of monsoon depressions rarely found over the Arabian Sea. These depressions generally form in the region of warm moist air located in the Bay of Bengal and move from that region in a north-northwest track along the monsoon trough to the warmer and drier heat low region of Pakistan and western India. Latent heat release due to organized convection (Shukla, 1978) and barotropic instability (Krishnamurti et al., 1980; Nitta and Masuda, 1981) have been shown to be important mechanisms in the development of depressions. The generation of depressions at the head of the Bay of Bengal seems to depend on the location of the monsoon trough in relation to the Gangetic plains. When the trough is located along the plains protruding into the Bay of Bengal, active monsoon conditions seem to prevail (Rao, 1976). When the trough migrates farther to the north and lies along the foothills of the Himalayas, it coincides with a break in the monsoon (Sikka, 1978). Rainfall over India is generally the indication of monsoon activity (Cadet, 1982). Active monsoon conditions are generally periods of heavier rainfall while break conditions show a dramatic decrease in rainfall.

The purpose of this paper is to compare important features of the mean and turbulence structure of the marine boundary layers observed over two Indian southwest monsoon regions, the Arabian Sea and the Bay of Bengal, during MONEX 79. These two oceans differ in geography as well as synoptic and mesoscale features pertaining to the southwest monsoon, with reference to the cross-equatorial flows, Somali (or East African) Jet and the relative location of the monsoon trough.

A number of observation platforms were used during MONEX 79 to collect boundary layer data over the Arabian Sea and the Bay of Bengal regions some of which are shown in Figure 1. Aircraft data from the NCAR Electra comprise a majority of the boundary layer information. Electra flight tracks and low-level flight regions in which stepped legs were flown for the two observation days over the Arabian Sea considered in this study, 20 and 24 June 1979, are also given in Figure 1 along with dropwindsonde locations and ship positions. Flight tracks and observation regions over the Bay of Bengal for 14 July 1979 are also shown. Low-level flight data from the gust probe system of the Electra consisted of time series data of both low (1 Hz) and high (20 Hz) frequency fluctuating components

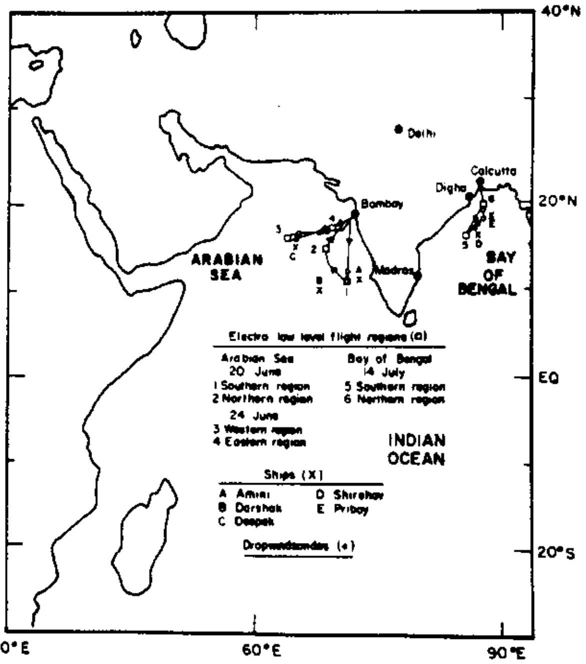

Figure 1. Observational network over the Arabian Sea and the Bay of Bengal utilized in MONEX 79.

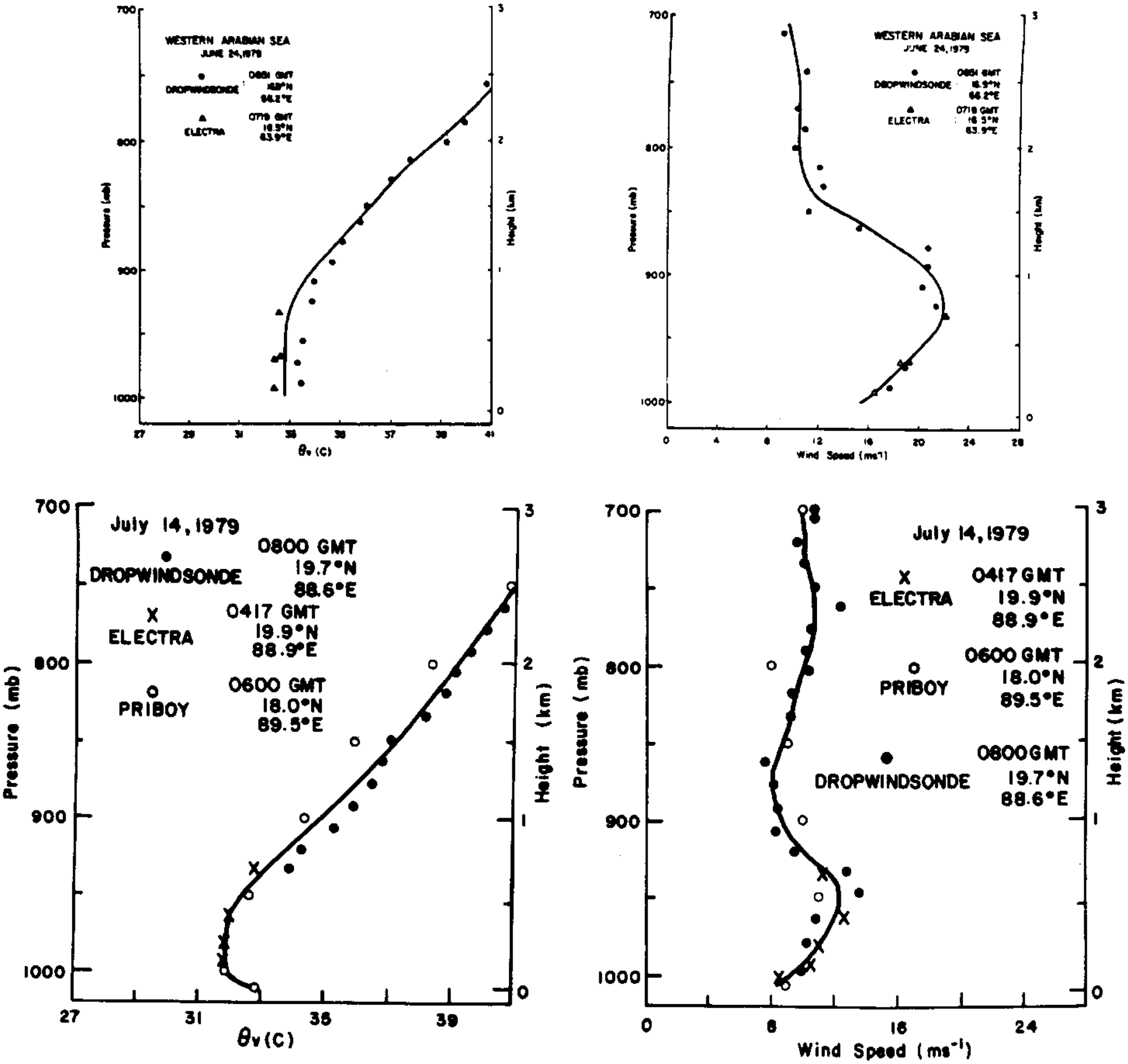

Figure 2. Typical mean profiles of virtual potential temperature (θ_v) and wind speed for the Arabian Sea (top) and the Bay of Bengal (bottom). Observations are from low-level Electra flights, dropwindsondes and ships. Profiles are drawn best fit by eye.

of wind speed (u,v,w), ambient temperature (T) and specific humidity (q) for altitudes from approximately 80 to 700 meters. Data were collected along boundary layer legs of approximately eight minutes (48 km in length) flown at various altitudes over each region.

Ships in the observational areas made surface measurements every six hours of pressure, height, dry bulb and dew point temperature. Radiosonde soundings were also taken every six hours with a resolution of 50 mb. Dropwindsondes shown in Figure 1 were made at strategic locations along the flight tracks.

2. RESULTS

Observational evidence from MONEX 79 data considered here indicate both differences and similarities in mean structure as well as flux and turbulence structure of the marine boundary layers over the Arabian Sea and the Bay of Bengal.

2.1 Mean Structure

The primary difference observed in the mean structure between the Arabian Sea and the Bay of Bengal boundary layers is the presence/absence of a strong low-level jet in the wind field. Figure 2 illustrates typical mean profiles of virtual potential temperature θ_v and wind speed for both the Arabian Sea and the Bay of Bengal. Maximum wind speeds in the boundary layer of 20 to 25 ms^{-1} are commonly observed over the Arabian Sea during the southwest monsoon. In contrast, maximum winds over the Bay of Bengal are greatly reduced (10 - 15 ms^{-1}) and are highly dependent on monsoon conditions (Holt and SethuRaman, 1985a). For example, monsoon break conditions over the Bay of Bengal generally show a weak low-level jet with maximum speeds of about 10 - 13 ms^{-1} at an altitude of approximately 500 m. However, monsoon active conditions indicate a lack of low-level jet and a well-mixed boundary layer.

Analysis of boundary layer heights over the two oceanic regions also shows similarities to the mean wind structure. Maximum wind speeds for the boundary layers of both the Arabian Sea and the Bay of Bengal (during monsoon break conditions) lie at or near the boundary layer height (Holt and SethuRaman, 1985b). However there exists a large difference in the boundary layer heights. For both break and active monsoon conditions over the Bay of Bengal, height of the boundary layer was observed to be about 400 to 500 m as against about 800 to 1500 m reported for the Arabian Sea (Holt and SethuRaman, 1985b).

Mean thermal structure for the central Arabian Sea region considered during MONEX 79 also indicates differences. Regions of multiple cloud layers as seen in the virtual temperature structure were associated with a more elevated jet situated roughly at the height of the capping inversion layer. A more well-mixed boundary layer was generally associated with a jet structure depressed in height.

2.2 Flux and turbulence structure

Both turbulence and flux profiles are dependent on location, i.e. varying synoptic or mesoscale conditions occurring in that area. Different synoptic or mesoscale conditions existed for each of the days studied over the Arabian Sea and the Bay of Bengal during MONEX 79 considered here. Even different orographic factors are important for each area as previously mentioned, such as the strong cross-equatorial flow deflected by mountains at the Somali coast and long over-water fetch in the Arabian Sea region and the importance of the Indian sub-continent in changing the air flow over the Bay of Bengal. These differences are evident in the heat and momentum flux profiles. Comparing magnitudes, heat and momentum fluxes over the Arabian Sea tend to be larger (10 to 30 %) throughout the boundary layer as opposed to the Bay of Bengal.

Regions of more convective activity over the Arabian Sea (20 June Northern region and 24 June Western region) show values of σ_u/w_*, σ_v/w_* and σ_T/θ_* similar to the more convective Northern Bay of Bengal region, where w_* and θ_* are convection velocity and convection temperature respectively and σ_u, σ_v and σ_T are standard deviations of east-west wind speed u, north-south wind speed v and temperature T, respectively. The same is true for the regions of less convective activity. This result is evident from σ_w/w_* data shown in Figure 3. However, an important difference realized from flux and turbulence analysis of the two areas is that the effects of multiple cloud patterns and possible entrainment are more prominent over the Bay of Bengal than over the Arabian Sea. The increased occurrence of monsoon depressions and associated weather patterns over the Bay of Bengal would appear to have an influence on the boundary layer turbulence.

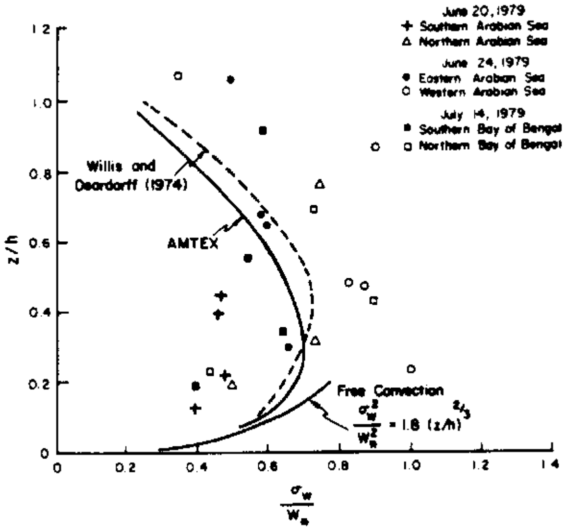

Figure 3. Vertical variation of standard deviation of vertical velocity σ_w normalized by w_* for the Arabian Sea and the Bay of Bengal. Laboratory curves from Willis and Deardorff (1974) and AMTEX and free convection predictions are given.

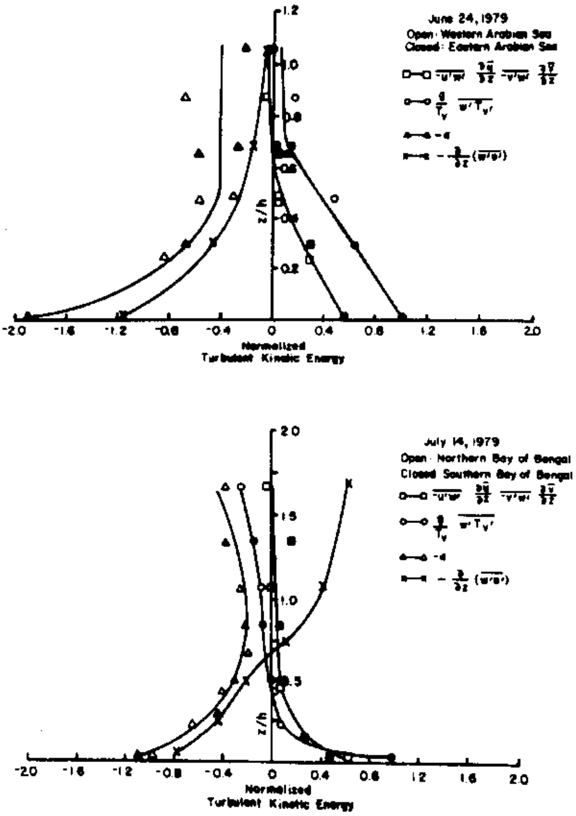

Figure 4. Turbulent kinetic energy budget normalized by surface heat flux plotted versus z/h for the Arabian Sea (top) and the Bay of Bengal (bottom). Lines are drawn best fit by eye. Surface values are obtained from bulk methods.

The budget of turbulent kinetic energy (TKE) in the boundary layer is important because it shows the relative importance of forces (buoyancy, shear, viscous dissipation, etc.) which drive the boundary layer processes. The TKE budget in the boundary layer, under the assumption of negligible advection of kinetic energy $\overline{u}\ \partial \overline{e'}/\partial x$ and time rate of change of kinetic energy $\partial \overline{e'}/\partial t$ may be written as:

$$\frac{g}{T_v}\overline{w'T_v'} - [\overline{u'w'}\frac{\partial \overline{u}}{\partial z}+\overline{v'w'}\frac{\partial \overline{v}}{\partial z}] - \frac{\partial}{\partial z}[\overline{w'e'}+\frac{\overline{w'p'}}{\rho}]-\varepsilon = 0 \quad (1)$$

where the first term on the left hand side is buoyancy production, the second shear production, the third turbulent transport and the fourth viscous dissipation. The TKE budgets over the Arabian Sea and the Bay of Bengal show important differences as seen in Figure 4. The most obvious difference is the importance of buoyancy in the lower levels of the monsoon boundary layer over the Arabian Sea. Buoyancy decreases almost linearly with height over the Arabian Sea but over the Bay of Bengal buoyancy decreases much more rapidly in the lowest half of the boundary layer. Also, buoyancy production approaches zero at a much greater altitude over the Arabian Sea ($z = 0.85\ h$ versus $z = 0.4\ h$ over the Bay of Bengal). Shear production shows a near linear decrease with height over the Arabian Sea approaching small values at a greater altitude ($z = 0.6\ h$) than over the Bay of Bengal. Thus buoyancy and shear appear to be important production terms through a greater depth of the boundary layer over the Arabian Sea than over the Bay of Bengal. The increased shear over the Arabian Sea is obviously due to the presence of the low-level jet. Values of shear production at 100 m over the Arabian Sea on 24 June 1979 were approximately $30 \times 10^{-4}\ m^2s^{-3}$ as opposed to $5 \times 10^{-4}\ m^2s^{-3}$ over the Bay of Bengal on 14 July 1979. The importance of buoyancy is evident in the relative magnitudes of virtual temperature flux. Values of $\overline{w'T_v'}$ over the Bay of Bengal were approximately $0.04\ ms^{-1}C$ near the surface and became negative above $z = 0.3\ h$. Values near the surface over the Arabian Sea were about three to five times larger. The suppressed convection observed throughout the boundary layer during monsoon break periods over the Bay of Bengal (including 14 July) could result in weaker buoyancy production in the lower levels. Convection over the Eastern and Western Arabian Sea regions flown by the Electra on 24 June was generally larger than that over the Bay of Bengal.

Vertical turbulent transport also shows differences over the Arabian Sea and the Bay of Bengal. Figure 4 (top) for the Arabian Sea regions shows negative values of vertical turbulent transport throughout the boundary layer indicating a sink in the TKE budget. Horizontal transport of turbulent energy due in part to increased wind speeds in the boundary layer over the Arabian Sea would then appear to be an important source term. In contrast, the profile of vertical turbulent transport over the Bay of Bengal (Figure 4 bottom) indicates transport of energy from the lower half of the boundary layer to the upper half similar to observations from baroclinic, convective boundary layers (Lenschow et al., 1980). With decreased wind speeds in the boundary layer over the Bay of Bengal, horizontal transport is not expected to be as major a source term in the TKE budget.

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