Mausam, (1987), **38,** 2, 171-176

551.465 : 551.584.33 (267)

A comparison of the significant features of the marine boundary layers over the east central Arabian Sea and the north central Bay of Bengal during MONEX-79

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(*Received 20 November 1985*)

सार — अरब सागर तथा बंगाल की खाड़ी में मानसून सीमा परतों की विशिष्ट संरचनाओं की तुलना करने के लिए, मानेक्स 1979 के दौरान, राष्ट्रीय वायुमंडलीय अनुसंधान केन्द्र (एस.सी.ए.आर.) इलैक्ट्रा वायुयान से ड्राप विंड सौंदे के संयोजन तथा जलयान प्रेक्षणो से प्राप्त निम्न सतह औसत तथा विक्षोभ के आंकड़ों का प्रयोग किया गया है। विश्लेषण से औसत तथा विक्षोभ की संरचनाओं में सार्थक अन्तर दिखाई देता है। पूर्वी मध्य अरब सागर में प्रबल निम्न-सतह वाले सोमाली जेट की उपस्थिति से, विक्षोभ फलक्स तथा विचलनों में महत्वपूर्ण रूप में वृद्धि होती है। उत्तरी मध्य बंगाल की खाड़ी में, मानसून सीमा परतों में, जहां पवन का वेग काफी कम हो जाता है, ऊष्मा तथा संवेग फलक्स में पूरी सीमा परत में लगभग 10 से 30 प्रतिशत तक की कमी प्रदर्शित की है।

अरब सागर के ऊपर सीमा परत की ऊंचाई, बंगाल की खाड़ी की सीमा परत की ऊंचाई से, दो से तीन गुना अधिक थी। विक्षुब्ध गतिज ऊर्जा बजट में अपरूपण तथा उत्प्लावकता (बोयान्सी) उत्पादन, बंगाल की खाड़ी से अरब सागर की सीमा परतों में लगभग दुगुना था।

ABSTRACT. Low-level mean and turbulence data from the National Centre for Atmospheric Research (NCAR) Electra aircraft in conjunction with dropwindsondes and ship observations during MONEX-79 were used to compare the typical structures of the Arabian Sea and the Bay of Bengal monsoon boundary layers. Analysis indicates significant differences in both mean and turbulence structures. The presence of a strong low-level Somali jet over the east central Arabian Sea significantly increases turbulent fluxes and variances. Monsoon boundary layer over the north central Bay of Bengal in which wind speeds were significantly reduced showed a decrease in heat and momentum fluxes by approximately 10 to 30% throughout the boundary layer as compared to the Arabian Sea region. Boundary layer heights over the Arabian Sea were two to three times greater than those observed over the Bay of Bengal. Shear and buoyancy production in the turbulent kinetic energy budget are found to be significant to roughly twice the height in the boundary layer over the Arabian Sea as against the Bay of Bengal.

1. Introduction

A reasonable study of the atmospheric boundary layer should take into account the large scale features that govern the flow. Relationship of the marine boundary layer to large scale atmospheric flow has been the subject of several recent investigators (*e.g.*, Fitzjarrald and Garstang 1981; LeMone 1980; Augstein 1978). Boundary layers of a monsoon region, in which a number of not yet fully understood processes of different scales interact, greatly affect the lowest levels of the atmosphere. The influences of large scale monsoon features such as the monsoon trough, depressions and the low-level jet on the boundary layer, and *vice versa*, are not well understood. The monsoon circulation itself is a complex interaction of the land-ocean and the atmosphere. Differential heating due to heating of the earth by radiative processes and to the heating of the atmosphere by sensible and latent heat fluxes serves to drive the large scale mosoon. Upwelling along the coasts of Somalia and Arabia during late May or early June appears to affect the processes of the ocean-atmosphere interaction and the marine boundary layer over the Arabian Sea. Saha (1974) hypothesized that the feed-back effect of the interaction of advected cold upwelled waters off Somalia with the atmosphere over the Arabian Sea was responsible for some of the observed monsoon features. The transformation of air masses as they are advected over changing sea surface temperature fields appears to have an effect on the formation of the low-level Somali jet as well as the strengthening of the ITCZ and the influencing of cloud distributions and rainfall over eastern Arabian Sea and the west coast of India. The heat low system extending from Somalia to northwest India and its relationship to subtropical cyclones to the northeast as well as coastal upwelling also serve to influence monsoon boundary layer features (Ramage 1966; Bunker 1965). Due to its intensity and dimension, the Indian monsoon thus represents one of the largest disturbances of the overall global circulation pattern as seen through changes in cross-equatorial flows and interactions between the northern and southern hemispheres.

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 east central Arabian Sea and the north central Bay of Bengal during MONEX-79. These two oceans differ in geography as well as synoptic and mesoscale features pertaining to the Indian southwest monsoon with reference to the cross-equatorial flows, Somali (or East African) jet and the relative location of the monsoon trough. By no means are these results representative of the entire monsoon region over the Arabian Sea and Bay of Bengal, but they do provide an understanding of the structure and properties of the monsoon boundary layer and their relationship to the important physical processes governing the low-level flow.

2. Data and analysis

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 Fig. 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 Fig. 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 of wind speed (u, v, w), ambient temperature (T) and specific humidity (q) for altitudes from approximately 80 to 700 metres. Data were collected along boundary layer legs of approximately eight minutes (48 km in length) flown at various altitudes over each region. The time series data were not filtered but editing was performed to eliminate spurious spikes. Low frequency measurements of turbulence were used primarily as a means of quality control. Mean, standard deviation (σ) and range of each variable were also obtained using standard statistical procedures. Analysis of surface turbulent fluxes involved only 20 Hz data and consisted of cross-covariance analysis of two time series.

Mean values of virtual potential temperature (θ_V) and equivalent potential temperature (θ_E) from the surface to 700 mb were calculated from pressure, temperature and moisture values obtained from the Electra flights as well as dropwindsondes and ship observations. Boundary layer height h was estimated as the height of the lowest inversion base in the θ_V profiles. Energy dissipation rate ϵ of the turbulent kinetic energy was estimated from the inertial subrange of the longitudinal velocity spectrum using a Kolmogorov constant of 0.67 (Lenschow *et al.* 1980).

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

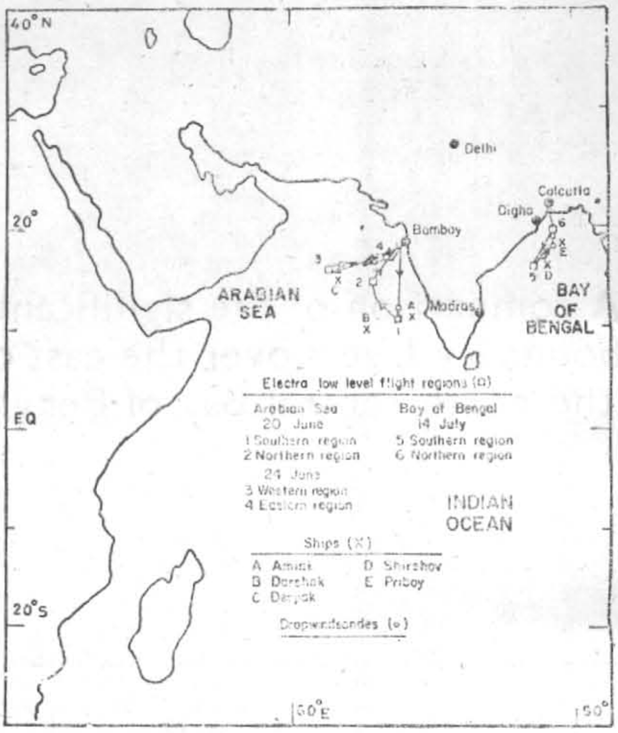

Fig. 1. Observational network over the Arabian Sea and the Bay of Bengal utilized in MONEX-79

Synoptic weather maps provided information concerning the location and movement of large scale system affecting boundary layer processes.

3. Large scale flow

An important aspect in the comparison of the marine boundary layers over the Arabian Sea and the Bay of Bengal is the difference in mesoscale forcings over the two regions. Unique geographical features of each region also modify the low-level monsoon 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; Banno 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, such as East African topography, geostrophic wind shear above the wind maximum, advective accelerations in the boundary layer and turbulent momentum transfers.

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 geographic and thermodynamic conditions in the Arabian Sea region enhance the development of a jet. Over the Bay of Bengal there is a low-level wind maximum which is not as strong as the Somali jet. Instead, the topographic effects of the Bay 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 northnorthwest track along the monsoon trough to the warmer and drier heat low region of Pakistan and western India. 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.

4. Results

Observational evidence from MONEX-79 data considered here for 20 and 24 June over the east central Arabian Sea and 14 July over the north central Bay of Bengal indicate both differences and similarities in mean structure as well as flux and turbulence structure of the marine boundary layers.

4.1. *Mean structure*

The primary difference observed in the mean structure between the Arabian Sea and the Bay of Bengal boundary layers for these specified regions and monsoon periods is the presence/absence of a strong low-level jet in the wind field. Fig. 2 illustrates typical mean profiles of θ_v and resultant 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 east central 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 Sethu Raman 1986). For example, monsoon break conditions over the northern Bay of Bengal on 14 July 1979 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 (resultant wind speeds 4-6 ms^{-1}) and a well-mixed boundary layer.

Analysis of boundary layer heights over the Arabian Sea and the Bay of Bengal 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 lie at or near the boundary layer height (Holt and Sethu Raman 1985). However, there exists a large difference in boundary layer heights. For both break and active monsoon conditions over the northern Bay of Bengal, typical height of the boundary layer was observed to be about 400 to 500 m as against about 800 to 1500 m reported for the east central Arabian Sea during strong southwest monsoon flow (Holt and Sethu Raman 1985).

Mean thermal structure for the east central Arabian Sea region considered during MONEX-79 also indicates differences (Fig. 2). 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. For the Bay of Bengal, jet structure associated with break conditions generally showed near-neutral to slightly unstable stratification as opposed to slightly stable during active monsoon periods.

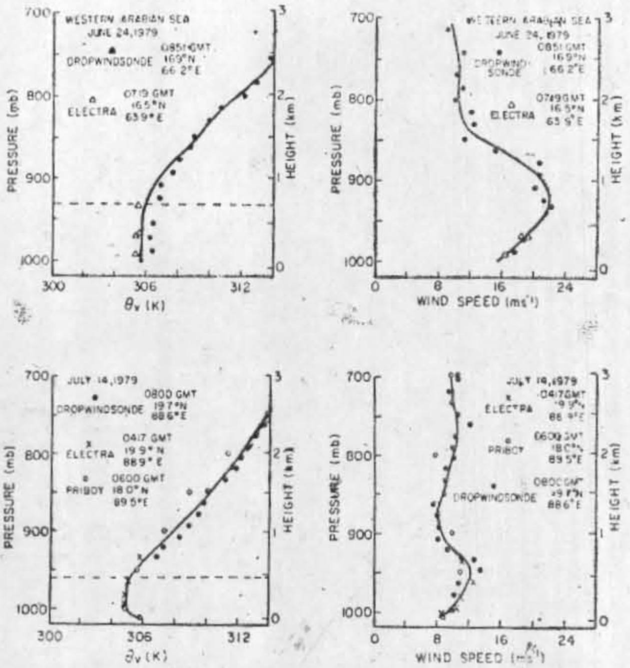

Fig. 2. Typical mean profiles of virtual potential temperature (θ_v) and resultant wind speed for the Arabian Sea (top) and the Bay of Bengal (bottom). Observations are from low-level Electra flights, dropwindsondes and ships. Profiles are drawn best fit by eye. Dashed horizontal lines in θ_v plots indicated boundary layer height estimated as height of lowest inversion

4.2. *Flux and turbulence structure*

Both turbulence and flux profiles are dependent on location, *i.e.*, varying synoptic or mesoscale conditions occurring in that area. Differing synoptic 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 influencing 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 east central Arabian Sea region considered here tend to be larger (10 to 30%) throughout the boundary layer as opposed to the north central Bay of Bengal region.

Regions of more convective activity over the Arabian Sea (20 June northern region and 24 June western region indicated in Fig. 1) 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_* is the convective velocity, θ_* is the convective temperature defined as $(\overline{w'T_v'})_0/w_*$ and σ_u, σ_v and σ_T are standard deviations of

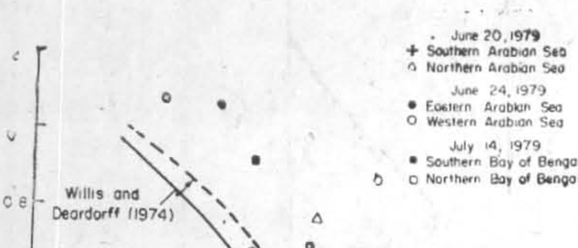

Fig. 3. Vertical variation of standard deviation of vertical velocity σ_w normalized by w_* for the Arabian Sea and the Bay of Bengal. Laboratory curves from Willis and Deardorff (1974) as well as AMTEX and Kansas free convection predictions (Kaimal *et al.* 1976) are given

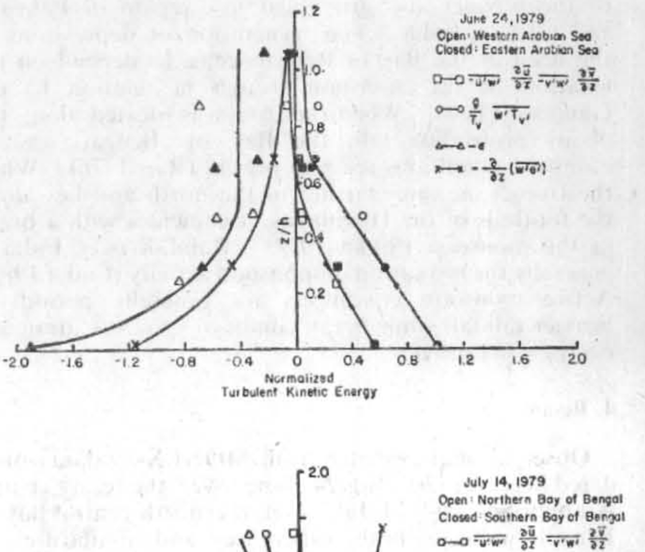

Fig. 4. Turbulent kinetic energy budget normalized "by surface" heat flux plotted *versus* z/h for the Arabian Sea (top) and the Bay of Bengal (bottom). Lines are drawn best fit by eye. Surface values are obtained from bulk methods

east-west wind speed u, north-south wind speed v and temperature T, respectively. For the regions of less convective activity, the same observation is true. This result is evident from σ_w/w_* data shown in Fig. 3. However, an important difference realized from flux and turbulence anaylsis of the Arabian Sea and the Bay of Bengal areas is that the effects of multiple cloud patterns and possible entrainment are more prominent over the north central Bay of Bengal region than over the east central Arabian Sea area studied during this period of MONEX-79. The increased occurrence of monsoon depressions and associated weather patterns over the Bay of Bengal would have an influence on the boundary layer turbulence.

The budget of turbulent kinetic energy (TKE) in the boundary layer is important because it showsthe 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 $\bar u\,\frac{\partial \bar e'}{\partial x}$ and time rate of change of kinetic energy $\frac{\partial \bar e'}{\partial t}$ may be written as :

$$\frac{g}{T_v}\,\overline{w'T_v'} - \left[\overline{u'w'}\,\frac{\partial \bar u}{\partial z} + \overline{v'w'}\,\frac{\partial \bar v}{\partial z}\right] - \frac{\partial}{\partial z}\left[\overline{w'e'} + \frac{\overline{w'p'}}{\rho}\right] - \epsilon = 0 \qquad (1)$$

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 regions show important differences as seen in Fig. 4. The most obvious difference is the importance of buoyancy in the lower levels of the monsoon boundary layer over the east central Arabian Sea area. Buoyancy decreases almost linearly with height over the Arabian Sea but over the Bay of northern 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). Similar conclusions can be drawn concerning the shear profiles when comparing the Arabian Sea and 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 regions considered here from MONEX-79 observations than over the Bay of Bengal area. 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 $30\times 10^{-4}\ \mathrm{m^2\ s^{-3}}$ as opposed to $5\times 10^{-4}\ \mathrm{m^2\ s^{-3}}$ 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 $0.04\ \mathrm{m\ s^{-1}\ C}$ near the surface and became negative about $z=0.3\ h$. Values near the surface over the Arabian Sea were about three to five times larger.

Vertical turbulent transport also shows differences over the Arabian Sea and the Bay of Bengal observation areas. Transport is negative throughout the boundary layer (TKE sink) over the east central Arabian Sea regions (Fig. 4 top) but indicates a transport of energy from the lower half of the boundary layer to the upper half over the northern Bay of Bengal (Fig. 4 bottom), similar to baroclinic convective boundary layers (Lenschow *et al.* 1980).

5. Conclusions

Analysis of mean and turbulence structure of the marine boundary layer during MONEX-79 from low-level Electra measurements, ship observations and dropwindsondes revealed differences and similarities of the marine boundary layers over the east central Arabian Sea and the north central Bay of Bengal. Large scale differences in the geography of the two regions play a major role in the development and enhancement of monsoon features characteristic of each region, such as the Somali jet over the Arabian Sea or the monsoon trough (and depressions) over the Bay of Bengal.

Significant comparisons include :

(*i*) the presence of the low-level jet over the Arabian Sea that is not as significant over the Bay of Bengal. This jet appears to play an important role in both mean and turbulence structure. Budgets of turbulent kinetic energy throughout the boundary layer as well as turbulence statistics over the Arabian Sea show values greater than those observed by others for tropical boundary layer flows without a strong low-level jet,

(*ii*) boundary layer heights are situated at or near the capping inversion layer observed in the mean virtual potential temperature profile for both the Arabian Sea and the Bay of Bengal.

(*iii*) boundary layer heights over the east central Arabian Sea range from roughly 800 to 1500 m in relatively undisturbed flow as opposed to 400 to 500 m observed over the north central Bay of Bengal region.

(*iv*) heat and momentum fluxes are roughly 10 to 30% larger throughout the east central Arabian Sea boundary layer than those observed over the north central Bay of Bengal.

(*v*) the turbulent kinetic energy (TKE) budget shows that buoyancy and shear are important source terms to roughly twice the height in the boundary layer over the Arabian Sea regions as against the Bay of Bengal.

These results are based on the MONEX-79 marine boundary layer data base which is rather limited. Further studies are needed to improve our knowledge of the boundary layer processes over the Bay of Bengal and the Arabian Sea. Planetary boundary layer processes over the Indian subcontinent are also important about which little is known.

Acknowledgements

This work was supported by the Global Atmospheric Research Program of the National Science Foundation under the grant ATM-82-17960.

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