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Convective boundary layer structure over the equatorial Indian oceanic region

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सार - इस शोधपत्र में ग्रीष्मकालीन मानसून ऋतु के दौरान भूमध्यरेखा के आसपास के क्षेत्र में संवहनी परिसीमा सतह (सी.बी.एल.) की संरचना के अन्वेषण से प्राप्त परिणामों को प्रस्तुत किया गया है। इन ऑंकड़ों को स्थायी अनुसंधान पोतों जैसे शिरशॉव, ओकीन, शॉकलस्काय और प्रिबॉय से मानसून- 77 के प्रयोग के दौरान प्राप्त किया था।

भूमध्यरेखा के आसपास इन चारों पोतों की अवस्थिति के संदर्भ में संवहनी सीमार सतह की संरचना की भिन्नताओं का अध्ययन किया गया है। इन भिन्नताओं को सपष्ट करने के लिए संतृप्ति स्थिति, मिश्रण रेखा तथा संरक्षित भिन्नता आरेख तकनीक का उपयोग किया गया है। इन चारों पोतों के संहवनी परिसीमा सतह सी.बी.एल. संरचना से यह पता चलता है कि भूमध्यरेखा के समीप कोई महत्वपूर्ण भिन्नता नही है। तथापि इस अध्ययन के दौरान किए गए विश्लेषण से भूमध्यरेखा तथा इसके उत्तर में अवस्थित पोतों की तुलना में भूमध्यरेखा के दक्षिण में अवस्थित पोतों पर अधिक संहवनी सक्रियता, नमी की उच्चतर मात्रा और सघन मेघों का पता चला है। भूमध्यरेखा पर अवस्थित दो पोतों पर लगभग सदृश संवहनी परिसीमा सतह संरचना का पता चला है।

ABSTRACT. Results of an investigation of the Convective Boundary Layer (CBL) structure over the oceanic region in the vicinity of the equator during the summer monsoon season are presented. The data were obtained from stationary research vessels *viz.* Shirshov, Okean, Shokalsky and Priboy during the MONSOON-77 Experiment.

Variations in structure between convective boundary layers over the four ships with respect to their position about the equator have been studied. The technique of saturation point, mixing line and conserved variable diagrams has been used to bring out these differences. The CBL structure over the four ships showed that in the vicinity of the equator there are no marked differences. However, the analysis carried out for the period of study revealed that the ships situated south of the equator represented more convective activity, higher moisture content and deep layer clouds as compared to the ships which were located at the equator and north of equator. The two ships, located at the equator, showed approximately similar convective boundary layer structure.

Key words - Convective boundary layer, Monsoon boundary layer, Marine boundary layer, Boundary layer over the equatorial regions, Vertical structure of the CBL, Updraft/downdraft structure in the CBL.

1. Introduction

Knowledge of the thermodynamic structure of the Atmospheric Boundary Layer (ABL) over the equatorial Indian oceanic regions during the summer monsoon would be valuable for understanding of the monsoonal flow. The structure of the marine boundary layer over the equatorial regions of Pacific and Atlantic oceans have been studied extensively (Augstein *et al.*,1973; Brummer, 1976; Firestone and Albrecht, 1986; Betts and Albrecht, 1987). Holt and Sethuraman (1987) made a detailed analysis of mean boundary layer structure over the Arabian sea and the Bay of Bengal during the active and break monsoon periods using MONSOON-77 and MONEX-79 data. Parasnis and Morwal (1993) revealed the thermodynamic structure of the ABL over the Arabian Sea with the help of aerological observations obtained during MONSOON-77 Experiment in the region (10-14°N, 64-68°E) by stationary research vessels.

The Convective Boundary Layer (CBL) plays an important role in controlling the surface fluxes over the ocean, where conventional observations are sparse. In order to study the processes of vertical mixing, a

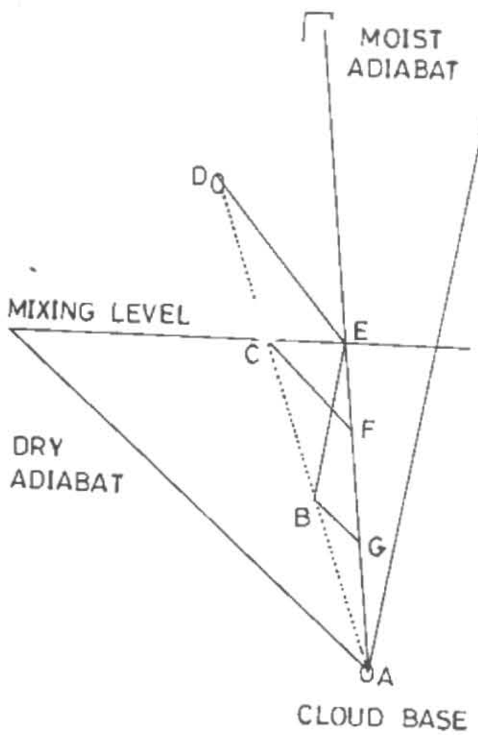


Fig. 1. Schematic diagram depicting the updraft/downdraft structure in the CBL. *A* and *D* are the SPs of cloud base air and environmental air respectively. *DE*, *CF*, and *BG* are the dry adiabats and *BE* represents the moist adiabat. Γ is the environmental stratification. *AD* is the mixing line and all possible cloud-environmental mixtures have SPs on this line

conserved variable method was developed by Betts in a series of papers (Betts, 1982 a, b; 1983; 1985; 1986). Betts (1982 a, b) showed how atmospheric convective structure, mixing processes and moist thermodynamics in general, could be simplified using air parcel Saturation Point (SP). Air parcels are characterized by Saturation Point properties *viz.* pressure, potential temperature and equivalent potential temperature at the saturation level, which are conserved under dry/moist adiabatic motion and also in mixing processes (Betts 1986). Valuable aerological data sets are available during the period 25-31 July 1977 over the equatorial regions of Indian ocean. The Saturation Point structure of equatorial marine boundary layer has been studied using this data set. An attempt has been made to explore the possibility of updrafts/downdrafts in the region of investigation using the mixing line and conserved variable approaches.

2. Data and method of analysis

Aerological observations used in the present investigations belong to the period 25-31 July 1977 during MONSOON-77. These observations were carried out by the erstwhile USSR research vessels *viz.* Shirshov (0°N, 80°E), Okean (2°N, 78°E), Shokalsky (0°N, 76°E) and Priboy (2°S, 78°E). These four ships formed a polygon over the equatorial Indian oceanic region and all the ships were stationary during the period of observation. 6 hourly radiosonde observations were collected over all the ships from surface up to 500 hPa at an interval of 25-30 hPa. These observations were subjected to linear interpolation in order to get the values of temperature (T) and dew point (T_d) at an interval of 10 hPa. Average values of T and T_d for each ship were used to compute mixing ratio (q, gm kg^{-1}), potential temperature (θ, K), virtual potential temperature (θ_v, K), equivalent potential temperature (θ_E, K), saturation equivalent potential temperature (θ_{ES}, K) and saturation level pressure (p_{SL}, hPa).

Saturation Point (*SP*): Saturation Point is defined as the point where the dry adiabat through the parcel temperature and constant mixing ratio line through the dew point intersect (Betts 1982a). It is represented by saturation level parameters *viz.* pressure, potential temperature and mixing ratio at the saturation level (p_{SL}, θ_{SL}, q_{SL}) and is invariant under the dry/moist adiabatic ascent/descent and thus can be considered as a thermodynamic tracer for an air parcel. The parameter P^* is defined as

$$P^* = p_{SL} - p$$

Here p is the air parcel pressure and P^* is an indicator of saturation in the layer. It is negative in the unsaturated regions and positive in the cloudy regions. Also, P^* is a useful parameter for delineating the different sub layers in the CBL (Parasnis and Morwal 1991a; Parasnis *et al.*, 1991).

Mixing Line analysis : The SP of the mixture of two air parcels at different levels can be obtained by taking the averages of the thermodynamic parameters such as potential temperature and mixing ratio associated with the SPs of two air parcels at different levels. If the Saturation Points of the two different air parcels are represented by A (P_{SL1}, θ_{SL1}, q_{SL1}) and B (p_{SL2}, θ_{SL2}, q_{SL2}) then the parameters at SP (p_{SLM}, θ_{SLM}, q_{SLM}) of the mixture of these two air parcels in equal ratio is computed as follows

$$P_{SLM} = \frac{P_{SL1} + P_{SL2}}{2}$$

$$q_{SLM} = \frac{q_{SL1} + q_{SL2}}{2}$$

$$\theta_{SLM} = \frac{\theta_{SL1} + \theta_{SL2}}{2}$$

The Mixing Line (ML) is obtained by joining the SPs of all mixtures (in any ratio) of the two air parcels. The ML on a Tephigram is slightly curved because of the unequal spacing of water vapour mixing ratio lines and saturated adiabats. The position of the mixing line with respect to the dry and moist adiabats gives the idea of the prevailing weather conditions (Betts 1982a).

Updraft/downdraft structure : The slope of the mixing line is important in determining the updraft/downdraft structures. Also, comparison of the mixing line with the environmental stratification is significant in determining the updraft/downdraft structure. This technique (Betts 1982a) of determining the updraft/downdraft structure in the CBL is illustrated through a schematic diagram as shown in Fig.1.

In Fig.1 cloud-environment mixtures can be categorised as follows :

(a) Mixtures with SPs between *D* and *C* are unsaturated and cooler than the environmental potential temperature at *E*, [*i.e.*, θ (*E*)]. These mixtures may sink to equilibrium between *E* and *F* to form unsaturated downdrafts.

(b) Mixture with SP at *C* is just saturated and has a minimum temperature and an equilibrium level *F*.

(c) Mixtures with SPs between *C* and *B* are saturated, cloudy and cooler than the environmental θ(*E*). These mixtures sink moist adiabatically to their SP and then dry adiabatically to their thermal equilibrium between *F* and *G*.

(d) Mixture with SP at *B* has the same potential temperature as the environment at *E* and the same θ_{ES}.

(e) Mixtures with SP between *B* and *A* are cloudy and warmer than the environment and may ascend along a moist adiabat.

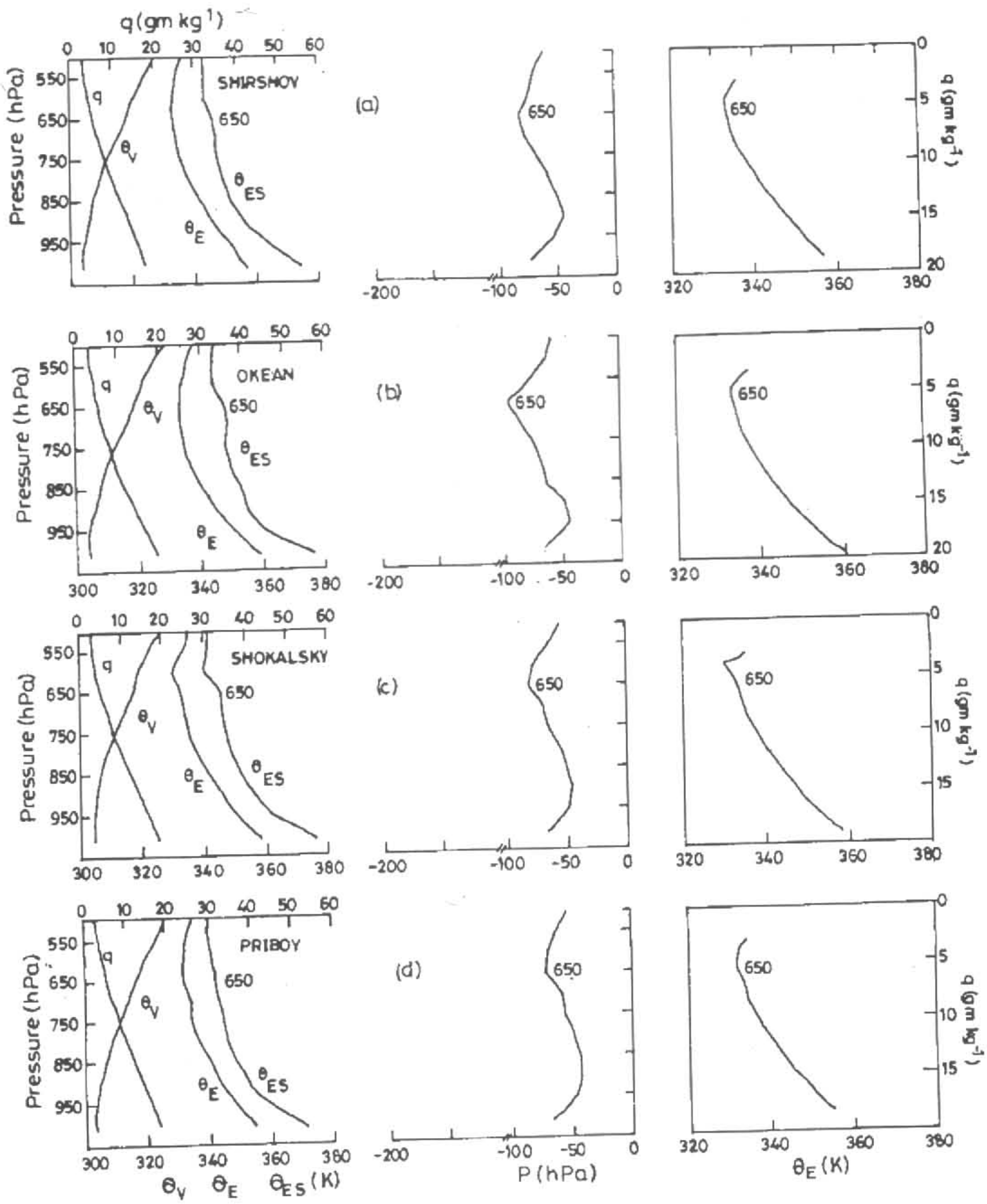
Fig.1 illustrates that there is more possibility of occurrence of cooler downdrafts between *D* and *B* and warmer updrafts between *B* and *A*.

Conserved variable diagrams : Conserved variable diagrams (θ_E - q) are useful in the study of the structure of the tropical atmosphere. In these diagrams, both the axes are represented by conserved variables (*i.e.*, θ_E and q). The use of conserved variables simplifies the consideration of phase changes and allows for representation that can be related to physical processes in the atmosphere (Betts 1985). Betts and Albrecht (1987) showed graphically how the radiation, precipitation and mixing processes maintain the characteristic structure of the CBL. The mixing lines are straight lines on these diagrams. A mixing line structure is produced when the vertical convective mixing dominates over processes that do not conserve air parcel SP, such as radiative cooling/warming or the processes of precipitation and evaporation of rain. Thus, these diagrams are useful in illustrating the role of physical processes in the CBL.

3. Results and discussion

CBL characteristics

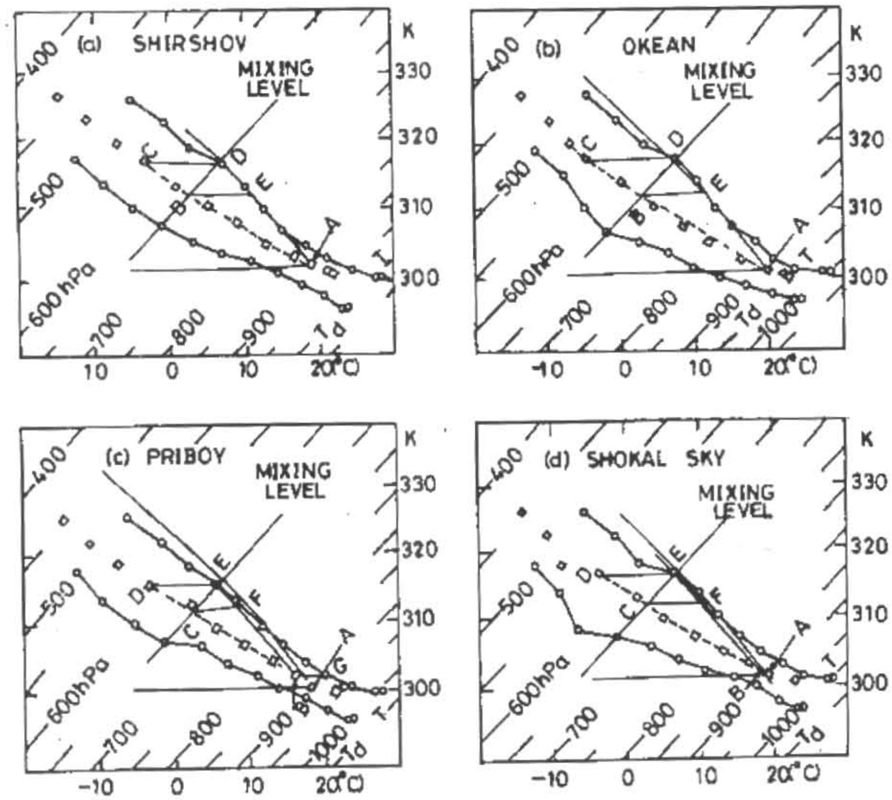
The average vertical profiles of q, θ_V, θ_E, θ_{ES} and P^* from surface up to 500 hPa at an interval of 50 hPa during the period 25 – 31 July 1977 are shown in Figs. 2 (a-d) for the research vessels Shirshov, Okean, Shokalsky and Priboy respectively. Shirshov and Shokalsky were located at the equator whereas Okean and Priboy were located in the northern and southern hemispheres respectively. It is noticed that the Convective Boundary Layer characteristics revealed by the vertical profiles of q, θ_V, θ_E, θ_{ES} and P^* are more or less similar over all the ships. The mixed layer depth as determined by constancy of θ_V, was found to be from surface up to 950 hPa over all the ships. Also, it is observed that the cloud layer is from 935 to 850 hPa over the two ships (Shirshov and Shokalsky), which were located at the equator Figs.2 (a-c). The cloud layer is very shallow (938 to 900 hPa) in the case of Okean, which is situated, in the northern hemisphere and it is deep (942 to 800 hPa) over Priboy (southern hemisphere). Thus, the deepest cloud layer is observed in the southern hemisphere and it becomes shallower from southern to northern hemisphere. More than 75% relative humidity was observed over all the ships up to cloud top levels. The CBL top is marked by the minimum of θ_E and P^* and maximum of θ_{ES} (Parasnis *et al.*, 1991; Parasnis and Morwal 1992). The CBL top was observed at 650 hPa over all the four ships. However, the minimum value of θ_E is not observed at the CBL top but in the layer 50 hPa above the CBL top. In general, it is noticed that θ_{ES} shows the maximum value at the CBL top in case of inversion soundings (Betts and Albrecht 1987; Parasnis and Morwal 1991a). As the soundings considered in the present study are not associated with the inversion



Figs. 2 (a-d). Average vertical profiles of q, θ_v, θ_E, θ_{ES} and P^* and θ_E - q diagrams for the ships (a) Shirshov (b) Okean, (c) Shokalsky and (d) Priboy during the period 25-31 July 1977

soundings, a flat θ_{ES} was observed at the CBL top. The P^* values observed at the CBL top are –95, –80, –82 and –72 hPa over the ships Okean, Shirshov, Shokalsky and Priboy respectively. From these values of P^* it is evident that the CBL progressively attains more and more saturation in the southern hemisphere as compared to northern hemisphere. This fact is also supported by the mixing ratio profiles and depth of the cloud layers. Thus the CBLs are more saturated in the southern hemisphere (*i.e.*, over Priboy) as compared to the northern hemisphere (*i.e.*, over Okean). The saturation criteria for the CBLs at the equator (*i.e.*, Shirshov and Shokalsky) lies in between the remaining two ships *i.e.*, Okean and Priboy.

$\theta_E - q$ diagrams



Figs. 3 (a-d). Average Tephigrams showing T, T_d mixing line structure and updraft/downdrafts in the CBL for the ships (a) Shirshov, (b) Okean, (c) Shokalsky and (d) Priboy during the period 25-31 July 1977

$\theta_E - q$ plots are shown in Figs 2(a-d) on the extreme right side from surface up to 500 hPa level for the ships Shirshov, Okean, Shokalsky and Priboy respectively. The q scale is reversed in all the diagrams as the mixing ratio is more in the lower layers and it shows gradual decrease upwards and hence it resembles the pressure scale. In each case the pressure at the CBL top is written and it is observed to be at 650 hPa in case of all the four ships. A single mixing line structure is observed in the CBL over all the ships. This shows that the mixing in the CBL is caused mainly due to the convective mixing processes. The processes like radiative cooling/warming or precipitation or evaporation of rain are either not present or are dominated by the convective mixing processes.

Mixing line characteristics and the updraft/ downdraft structure

Figs.3(a-d) shows the tephigram for the ships Shirshov, Okean, Priboy and Shokalsky during the period 25-31 July 1977. In all the plots T and T_d are shown by thick continuous lines. The open squares represent the Saturation Points (SP) computed for every 50 hPa level from surface to 500 hPa. Thin continuous lines represent the dry and moist adiabats drawn at SP level of the cloud base. A mixing line (ML) is drawn between the air at cloud base SP and the environmental air SP and is represented by a dashed line on the tephigram.

In Fig. 3(a), AC is the mixing line. CD and BE are dry adiabats and DA is the moist adiabat which coincides with the moist adiabat drawn from the cloud base level SP. Mixing line is situated towards the moist adiabat. The environmental curve more or less followed saturated adiabat between 800 to 650 hPa. Thus, the atmosphere has become nearly neutral to buoyant processes. Therefore, the parcels can sink with negative buoyancy if rain falls into the nearly saturated environment. The mixing of the cloud base air and environmental air produced cooler downdrafts, which penetrated up to the cloud base level. Between environmental SP, which is at C, and mixing level (*i.e.,CB*) the unsaturated cooler downdrafts are observed, which have equilibrium levels between *D* and *E*. The mixtures on the ML having SPs between *B* and *A* are saturated, cloudy and cooler than the environmental potential temperature at *D* and hence, may form cooler downdrafts. Thus, there is more possibility of cooler downdrafts in both the regions *viz.* unsaturated (*CB*) and saturated cloudy (*BA*).

Fig. 3(b) is similar to Fig. 3(a). From Fig. 3(b) it is seen that the mixing line (*AC*) which is drawn between the SPs of cloud base air (*A*) and environmental air (*C*) is situated in between dry and moist adiabats. Mixing line is cooler than the environmental curve at all levels. Therefore, there is more possibility of cooler downdrafts at all levels. The environmental curve is nearly parallel to the moist adiabat between 800 to 700 hPa and indicates neutral buoyancy. The mixtures are unsaturated between *C* and *B* and are cooler than the environmental potential temperature at *D* [*i.e.* θ(*D*)] and may form unsaturated cooler downdrafts and reach the thermal equilibrium between *D* and *E*. The mixtures are saturated between *B* and *A* and cooler than θ(*D*) and they may form cooler downdrafts. Thus, all the mixtures are found to be cooler between *A* and *C* and there is more possibility of occurrence of cooler downdrafts.

In the Fig. 3(c) for Priboy mixing line is drawn between SPs of cloud base (942 hPa) and CBL top (650 hPa). Here, *DE*, *CF* and *BA* are dry adiabats and *BE* is the moist adiabat which is indicative of more moist convective activity. The ML lies in between dry and moist adiabats and is shifted more towards the moist adiabat. It is cooler than environmental curve at all levels. All the SPs of the mixtures between *C* and *D* lie on the ML and are cooler than the environmental potential temperature at *E* [*i.e.*, θ(*E*)] and have equilibrium level between *E* and *F*. They form cooler unsaturated downdrafts. All the mixtures between *C* and *B* are saturated and cooler than the environment θ(*E*) and form cooler downdrafts. They descend to equilibrium levels between *F* and *G*. All the mixtures between *A* and *B* are cloudy and are found to be warmer than θ(*E*) and may form warmer updrafts. *G* is the lowest thermal equilibrium level up to which the negatively buoyant downdrafts can reach and it is observed that it is only 40 hPa above the cloud base level. Thus, cooler downdrafts are found to dominate over Priboy.

In Fig. 3(d), *A* is the saturation point of cloud base and *D* is the SP of the air at CBL top (650 hPa). In this Figure *DE*, *CF* and *BA* are the dry adiabats and *BE* is the moist adiabat. Mixing line is drawn in between *A* and *D*. It is observed to be cooler than environmental curve and is situated in between the dry and moist adiabats, which are drawn from the cloud base SP. Same type of

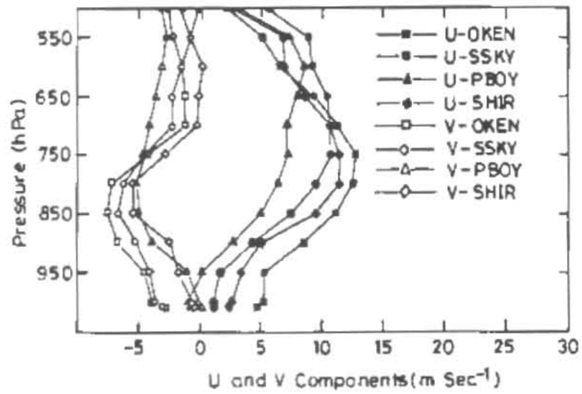


Fig. 4. Average vertical profiles of zonal (*U*) and meridional (*V*) components of wind over the four ships during the period 25-31 July 1977

mixing lines were observed over Deccan Plateau region during the summer monsoon season of 1980 in case of break and active monsoon conditions (Parasnis and Morwal 1991b). The environmental curve shows neutral buoyancy in the layer 800 – 650 hPa. The sounding shows the cooler downdrafts in all the regions *i.e.*, unsaturated (*CD*), saturated (*BC*) and cloudy (*AB*) and found to be cooler than θ (*D*). From this figure it is observed that the cooler downdrafts may reach up to the cloud base level.

It is seen from the above analysis that the region is dominated by downdrafts over all the ships. This is in support of the fact that the CBL characteristics do not show much variation over the four ships. However, over Priboy updraft structure was observed just above the cloud base level. CBL characteristics over Priboy, which are in favour of the different updraft/downdraft structure, are different as compared to the other three ships.

U and V components of wind

Averaged vertical profiles of zonal (*U*, m sec^{-1}) and meridional (*V*, m sec^{-1}) components of wind are shown in Fig. 4. From the profiles of zonal component of winds, existence of low level jet is clearly evident at all the four positions. The wind maxima are found in the layer 800 – 600 hPa and they are located above the cloud layer for all the ships. The zonal component is found to be westerly over all the ships. The westerly wind increases from surface upwards, reaches its maximum in the layer 800 – 600 hPa layer. Thereafter it weakens with height and seems to be changing to easterly in the higher levels. Below 700 hPa westerly winds are strongest at Okean (2°N, 78°E) and gradually weaken with the position of the ship *i.e.*, from northern hemisphere to southern hemisphere. More or less the same trend is seen in the

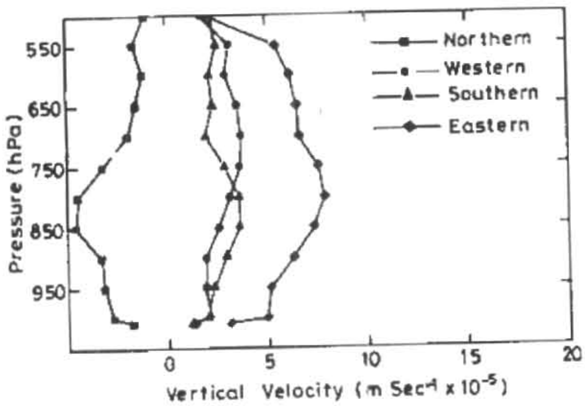


Fig. 5. Average vertical profiles of vertical velocity in the four regions during the period 25-31 July 1977

profiles of meridional component of wind. From the profiles of meridional component of wind it is noticed that they are northerly for all the four ships from surface up to 500 hPa. The northerly wind increases with height and attains the maximum strength in the layer 850 – 800 hPa and shows gradual decrease thereafter.

It is clearly seen from Fig. 4 that the westerly winds were stronger in the northern hemisphere as compared to those in the southern hemisphere. Also, in the higher levels the flow seems to be changing from westerly to easterly and northerly to southerly.

Profiles of vertical velocity

In order to compute the vertical velocity the observational area has been divided into four triangular regions *viz.* eastern (east of 78°E), western (west of 78°E), northern (north of equator) and southern (south of equator). The values of vertical velocities were computed at the centroid of these triangles (Ryan *et al.*, 1989). The values of divergences have been obtained using U and V observations from surface up to 500 hPa level. These values of divergences were adjusted using the method of O'Brien (1970) for the purpose of computing the vertical velocities.

The vertical velocity profiles for the four regions are shown in Fig. 5. It is observed that most of the regions *i.e.*, western, eastern and southern are associated with descending motions from surface up to 500 hPa level. In contrast to this, the northern region is dominated by ascending motions.

4. Results and discussion

The investigation of the Convective Boundary Layer, using the techniques of Saturation Point, Mixing Line, Conserved Variable diagrams, carried out over the equatorial Indian oceanic region utilizing the aerological observations from the stationary research vessels during the MONSOON-77 Experiment revealed the following :

(a) Sub-cloud layer is associated with nearly constant values of θ_v. The sub-cloud layer over the regions of study was observed to be from surface upto 950 hPa irrespective of the position of individual ships. It is found that the cloud layer was deep over the ship Priboy, which is situated in the southern hemisphere, as compared to the ships situated in the northern hemisphere (Okean) and at the equator (Shirshov and Shokalsky).

(b) The CBL top was observed to be at 650 hPa level for all the four ships. The CBL top is found to be associated with minimum values of θ_E and P^* and maximum value of θ_{ES} as observed by Betts and Albrecht (1987) over the equatorial Pacific Oceanic regions. However, as the aerological soundings considered in the present study are not associated with inversion soundings, the maximum value of θ_{ES} was not as pronounced as in case of inversion soundings over the Pacific Oceanic region as observed by Betts and Albrecht (1987).

(c) The mixing lines, as seen from the $\theta_E - q$ diagrams, showed a single mixing line structure in the CBL from surface upto the CBL top.

(d) The analysis of the updraft/downdraft structure in the CBL showed more possibility of cooler downdrafts when the cloud base air is mixed with the environmental air. Over all the ships mixing lines are situated towards the moist adiabat indicative of moist convective activity.

(e) The zonal component of wind showed westerly flow. The existence of low level jet, which is located above the cloud layer, is also evident from these vertical profiles. The meridional component of wind was observed to be northerly throughout the CBL.

(f) The profiles of vertical velocity computed for the four regions showed upward motion in the northern region whereas downward motion was observed over southern, eastern and western regions. It is noticed that the magnitude of these vertical velocities were small as compared to those obtained by Parasnis and Morwal (1993) over the Arabian Sea regions.

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References

Augstein, E., Riehl, H., Ostapoff, F. and Wagner, V., 1973, "Mass and energy transports in an undisturbed Atlantic trade-wind flow", *Mon. Wea. Rev.*, **101**, 101-111.

Betts, A.K., 1982a, "Saturation point analysis of moist convective overturning", *J. Atmos. Sci.*, **39**, 1484-1505.

Betts, A.K., 1982b, "Cloud thermodynamic models in saturation point coordinates", *J. Atmos. Sci.*, **39**, 2182-2191.

Betts, A.K., 1983, "Thermodynamics of mixed stratocumulus layers: Saturation point budgets", *J. Atmos. Sci.*, **40**, 2655-2670.

Betts, A.K., 1985, "Mixing line analysis of clouds and cloudy boundary layers", *J. Atmos. Sci.*, **42**, 2751-2763.

Betts, A.K., 1986, "A new convective adjustment scheme. Part I: Observational and theoretical basis". *Quart. J. Roy. Meteor. Soc.*, **112**, 677-691.

Betts, A.K., and Albrecht, B.A., 1987, "Conserved variable analysis of the convective boundary layer thermodynamic structure over the tropical oceans", *J. Atmos. Sci.*, **44**, 83-99.

Brummer, B., 1976, "The kinematics, dynamics and kinetic energy budgets of the trade wind flow over the Atlantic Ocean", *Meteorol. Forschungsergeb*, **B11**, 1-24.

Firestone, J.K., and Albrecht, B.A., 1986, "The structure of the atmospheric boundary layer in the central equatorial Pacific during January and February of FGGE", *Mon. Wea. Rev.*, **114**, 2219-2231.

Holt, T. and Sethuraman, S., 1987, "A comparison of the significant features of the marine boundary layer over the east central Arabian sea and the north central Bay of Bengal during MONEX-79", *Mausam*, **38**, 171-176.

O'Brien, J.J., 1970, "Alternative solutions to the classical vertical velocity problem", *J. Appl. Meteorol.*, **9**, 197-203.

Parasnis, S.S., and Morwal, S.B., 1991a, "Convective boundary layer over the Deccan Plateau, India during summer monsoon", *Bound-layer Meteorol.*, **54**, 59-68.

Parasnis, S.S., and Morwal, S.B., 1991b, "Mixing processes in the atmospheric boundary layer during summer monsoon", *Acta Meteorologica Sinica*, **5**, 259-263.

Parasnis, S.S., Morwal, S.B., and Vernekar, K.G., 1991, "Convective boundary layer in the region of the monsoon trough – A case study", *Adv. Atmos. Sci.*, **8**, 505-509.

Parasnis, S.S., and Morwal, S.B., 1992, "Conserved variable analysis of the convective boundary layer over a tropical inland station during summer monsoon", *Vayu Mandal*, **22**, 109-111.

Parasnis, S.S., and Morwal, S.B., 1993, "Thermodynamic structure of the marine boundary layer over the Arabian sea as revealed by the MONSOON-77 data", *Bound-Layer Meteorol.*, **63**, 365-380.

Parasnis, S.S., and Morwal, S.B., 1993, "Radiatively driven subsidence over the Eastern Arabian Sea with MONSOON-77 data", *Ind. J. Radio and Space Physics*, **22**, 235-238.

Ryan, B.F., Wilson, K.J. and Zipser, E.J., 1989, "Modification of the thermodynamic structure of lower troposphere by the evaporation of precipitation ahead of a cold front", *Mon. Wea. Rev.*, **117**, 138-153.