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A study on the characteristics of temperature inversions in active and break phases of Indian summer monsoon

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Abstract

The thermal inversion characteristics during active and break cycles of two consecutive and contrasting monsoon years were studied using GPS radiosonde profiles at Goa (15° 46' N; 73° 08' E), located in the west coast of India. The lower tropospheric inversions were associated with the active phase and it dissipated during the break phase due to the weakening of the low level jet. A strong secondary inversion is also appeared at 5-6 km in the break period. The genesis of both the inversions is linked with advection of warm and dry air from the Arabian and Persian high lands. During the active phase, convection over-rides the stability shield provided by the advection induced low level inversion. Associated with the active phase, the temperature difference within the inversion invariably reaches above a threshold of 1°C, whereas it is low in break conditions.

Key words: Indian summer monsoon, thermal inversion, active and break phases, convective clouds, low level jet.

1. Introduction

Indian summer monsoon, which is a part of the Asian monsoon system, exhibits a wide spectrum of variability. During the summer monsoon season (June to September), a substantial component of this variability of convection and rainfall over the Indian region arises from the fluctuation on the intraseasonal scale between active spells with good rainfall and weak spells or breaks with little rainfall. Long intense breaks are known to have an impact on the intraseasonal variability of rainfall over the country. Intensification and suppression of deep convective systems embedded within the Continental Tropical Convergence Zone (CTCZ) dictate the monsoon variability associated with the active and break spells in the Indian summer monsoon (Yasunari, 1980; Sikka and Gadgil, 1980; Krishnamurti and Subramanyam, 1982). Webster et al. (1998) mentioned that the individual active and break spells and the transition between the spells are far more complex to understand. Rao et al. (2004) have noticed large scale drying in the middle and upper troposphere over the CTCZ, three days before the commencement of the break, limiting the growth of deep cumulus leading to transition in to a break phase from a monsoon active phase.

Lapse rate variations in the troposphere or vertical stratifications are found to occur mainly between active and break phases of monsoon periods. This is probably due to mid-tropospheric temperature adjustment by dynamical processes over large scales rather than *in situ* response to localized convection. Between active and break periods, mid-tropospheric moisture exhibit substantial changes. Variations in convective activity are well related to changes in lower and middle tropospheric moisture content (McBride and Frank, 1999). Normally, the break phase coincides with the drying of troposphere due to large-scale horizontal advection.

In the active phase, the monsoon trough usually lies south of its normal position. The low level jet (LLJ) becomes strong and passes through peninsular India, covering latitudes up to 15° N. Increase in cyclonic vorticity in the lower levels and enhancement of rainfall over central Indian region (15° N - 25° N) and along the west coast are the common features associated with the active phase. Monsoon depressions are quite frequent in this phase. On the other hand, during the break phase, the monsoon trough is shifted close to Himalayan foot-hills. The LLJ attains weak and lies around 25° N. The anticyclonic vorticity develops in the lower levels of the atmosphere, especially in the latitude belt

between 15° N and 25° N and the rainfall is much below normal. Monsoon depressions do not occur during the break phase. In normal monsoon years, a long active spells lasting about 4-5 weeks is followed by a break with a time span of few days are very common. But in a year of poor monsoon the country witnesses' long break spells.

During Indian summer monsoon, the southern hemispheric trade winds get deflected at the equator and approach the west coast of India from a south westerly direction (Rao and Desai, 1971). In this period, large mass of air and water vapor moves across the equator from the southern hemisphere from the surface to about 600 hPa. The air masses are modified considerably through this exchange process.

Arabian Sea appears to be playing a dominant role in the modification of monsoon activity over the west coast of India (Ghosh et al., 1978). Observations suggested that low level temperature inversions are strongest in the western Arabian Sea with signs of weakening while ascending during its course towards east (east of 60° E) and disappears over the eastern Arabian Sea (east of 70° E) especially during active monsoon season (Ghosh et al., 1978). Longitudinal variation of the low level temperature inversion during active monsoon at latitude 11° N is illustrated in Fig. 1.

FIGURE 1.

The main objective of this study is to understand the vertical stability of the atmosphere during active and break phases of monsoon. Analysis has been carried out to find the occurrence of layers of inversion during these phases. The nature of circulation pattern over the tropical Indian Ocean has been analyzed to explain the nature of inversion. Atmospheric stability at various levels has also been examined during the period of inversions using high resolution GPS radiosonde observations taken at regular intervals during 2009 and 2010 monsoon period.

2. Data and methodology

Time series of atmospheric profiles collected from Goa ($15^{\circ} 46'$ N; $73^{\circ} 8'$ E), a coastal station in the western part of India, using state-of-the-art Vaisala DigiCORA sounding system during two consecutive and contrasting monsoon years (2009 and 2010) were used in the present study. The year 2009 was considered to be a drought year and 2010 was an above normal monsoon year, hence the comparison is meaningful and relevant. The upper atmospheric data includes pressure, temperature, relative humidity,

wind velocity and direction, geopotential height etc. Ascends were carried out on experimental mode during the peak of active/break cycles of 2009 and 2010 at 12 UTC. The sensor specifications of Vaisala radiosonde, RS92-SGP are given in Table 1. Active and break composites of wind vectors at 850 hPa, 700 hPa and 600 hPa levels have been derived from NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis data product (Kalnay et al., 1996) in 2.5° latitude x 2.5° longitude spatial grid during 2009 and 2010. The characteristics of inversion layers are determined from the temperature profiles, the vertical extension of inversion and temperature difference in the inversion layer and the corresponding moisture variations. The atmospheric static stability variation is examined by computing the 100 meter running average squared Brunt Vaisala frequency (N^2) using the relationship

$$N^2 = \frac{g}{\theta} \frac{d\theta}{dz}$$

where, g is the acceleration due to gravity, θ is potential temperature and z is geometric height.

TABLE 1

3. Results and discussion

Seasonal rainfall over India during the deficient monsoon year 2009 was almost 20-30% less than the rainfall received during the above normal monsoon year 2010. Break spells during 2009 were much longer than its 2010 counterpart. Unlike 2009, the break spells in 2010 were intermittent, frequent and short. The monsoon onset in 2009 was announced by the India Meteorological Department (IMD) in the second week of June. But the rainfall lasted only for few days followed by a long spell of monsoon break. However, during the above normal rainfall year of 2010, the monsoon onset was also reported in the second week of June, but it was followed by a long active spell. Setting aside the break like situation observed in July 2010, the year 2010 was more or less free from destructive break spells. It is interesting to note that the monsoon appears to be extended up to October in 2010, although with diffused rainfall activity.

The sounding experiment incorporated in the present study coincided with two active (16th and 28th July) and two break (3rd and 6th August) monsoon spells and break to active transition period (31st July)

in 2009 and three active (30th July, 2nd and 5th August) spells in 2010. Profiles of temperature were analyzed to capture the lower and middle troposphere temperature inversions and the associated wind circulations (active/break composites) were also examined in the entire Arabian Sea north of 10 °S at three levels, viz., 850 hPa (~ 1.5 km), 700 hPa (~ 3km) and 600 hPa (~5 km) to understand the genesis of the thermal inversion during active and breaks periods.

It is interesting to note that strong inversions were occurred in all active phases in the 2 to 4 km (*see* Figs. 2A & 2B, 3A – D), and in all break phases in the 5 to 6 km (Figs. 2C & 2D) layers during both 2009 and 2010. Intense inversions were observed on the active days of 16th July 2009 (Fig. 2A) and 5th August 2010 (Fig. 3C) coinciding with rainfall higher than their respective long period averages (LPA) (Figs. 4 & 5). Similar inversions were not well defined during break monsoon periods in the lower troposphere. Nevertheless, a strong inversion appeared in the middle troposphere (5-6 km) invariably coinciding with the break monsoon periods (Figs. 2C & 2D) with trails of dissipating inversion just above the boundary layer, probably associated with the weakened and displaced low level jet (Sijikumar et al, 2011). The active spell of 5th August 2010 was an exception, wherein a less intense inversion appears twice between 3 km and 6 km layer (Fig. 3C), perhaps referring to the precursor of impending break like situation (Fig. 5B). Similarly the profile of 31st July 2009 (Fig. 6), being the transition from active to break spell (Fig. 4B), exhibited inversions at layers 2-3 km and 4-6 km. The presence of two discrete inversion layers could be linked to the transformation from active to break phase of the monsoon.

FIGURE 2.

FIGURE 3.

The static stability in terms of squared Brunt Vaisala frequency (N^2) in cycles per second refers to the vertical movement of air parcel in the wake of a disturbance caused either by inversion or by any other means. Positive values indicate back and forth vertical motion that finally leads to a stable condition. The lower atmosphere (2-3 km) appears to be more stable during active phases of the drought year 2009 as the thermal inversions often creates spikes in the stability distribution (Figs. 2A & 2B). But the relatively weak inversion in the lower atmosphere failed to create similar spikes in the stability profile during the active days of the normal monsoon year 2010 (Figs. 3A, 3B & 3D) with an exception of 5th

August (Fig.3C). Similar low level inversions were not observed during the break cycle. Nevertheless, the atmosphere above the boundary layer (close to middle troposphere) is often encountered with stronger inversions during break phase and hence the stability of the layer increases substantially (*see* Figs. 2C & 2D).

FIGURE 4

FIGURE 5

The surface convection during an active phase seems to be generating convective clouds in the boundary layer. Although the inversion occurring just above the boundary layer do suppress convection, the enhanced buoyancy field associated with the active spell of the wet year 2010 seems to over-ride the stability shield induced by the inversion layer and hence allow the convective cloud to grow further. This is not the case of the active spells occurred in the drought year of 2009. The strong inversion and associated spikes in the stability field in 2009 made the atmosphere more stable that prevent deep convection even during the active spell resulting in subdued rainfall activity (Fig.4) compared to the year 2010 (Fig.5).

FIGURE 6

The lifting condensation level (LCL), denotes the height at which water condenses to form clouds, computed during these two years is shown in Fig 7. It indicates that LCL is positioned above 980 hPa during 16th to 28th July 2009 and it is below 980 hPa from 30th July to 5th August 2010. Therefore LCL above 980 hPa in 2009 (16th to 28th July) explains that the situation is conducive for cloud formation above the boundary layer and is inhibited (by inversion) below it. Similarly in 2010 (30th July to 5th August) the LCL below 980 hPa denotes cloud formation occurring right in the boundary layer in spite of the inversion. It is, therefore, presumed that convection in the boundary layer associated with the active phase of the monsoon makes the atmosphere more unstable by over-riding the stability shield induced by weak inversion. On the other hand, strong inversion above the boundary layer, makes the atmosphere stable and suppress cloud formation below it. However, the atmosphere is favourable for the clouds to grow above the inversion layer. It is appealing to note that the LCL has risen sharply above 980 hPa on 12th July 2010 indicating the characteristics of a typical break phase.

FIGURE 7

The inverse relationship between the tropopause pressure and surface pressure (Muraleedharan et al., 2011) during the summer months implicitly explain subsidence in the tropopause and associated convection in the boundary layer. Conversely, rise in tropopause invariably induce subsidence in the boundary layer during break phase that inhibit convection. The strong inversions at the base of middle troposphere during break cycle compound the effect of subsidence induced by the fluctuations at the tropopause. The apparent vertical migrations of the tropopause and the level of non-divergence (intersection of u and v wind components with level of zero motion) explain this inverse relationship without ambiguity during active phase of 2010 (Figs. 3A - 3C) and break phase of 2009 (Figs. 2C & 2D). This comparison appears to be more robust in 2010 as there were hardly any break (as per IMD criterion) and the subdued active phase of 2009 failed to capture this migration as the year witnessed severe monsoon drought in the subcontinent. However, the profile of 12th July 2010 (active as per IMD norms) depicts the conditions of a typical break phase (Fig. 3D) and the daily average rainfall pattern of both Goa rainfall (Fig. 5A) and all India rainfall (Fig. 5B) patterns in 2010 corroborate well with our inferences.

The strong inversions observed on 16th and 28th July 2009 (active phase) are probably due to the advection of dry and warm air transported from Arabian territory to the western peninsular India (over Goa). This warm and dry continental air originating from Arabian main land moves towards south-southeasterly direction and meets the cold and moist southwesterly low level jet on its course towards east. The northerly moving warm air is often referred to as summer *Shamal* (Aboobacker, 2011). Shamals result from strong northwest winds that are funneled into the Persian Gulf by the mountains of Turkey and Iraq to the northeast and the high plains of Saudi Arabia to the southwest. During that period, the polar jet stream to the north moves southward to become close to the subtropical jet to the south. The proximity of the two jet streams promotes the formation of strong but often dry cold fronts which create the *Shamal*. As the warm, dry lighter northerly wind meets the cold moist denser LLJ, the former often slides over the latter to occupy just above the height of LLJ during its course towards east. The manifestation of thermal inversion above LLJ is attributed to the advection of warm air from west (Nair et al., 2005; Abish and Mohanakumar, 2011). The middle and upper tropospheric drying during the transition from active to break cycle was reported by Rao et al. (2004). In an earlier study, McBride

and Frank (1999) had attributed that the middle and upper tropospheric drying is due to lateral advection rather than subsidence. These studies justify the authenticity of our inferences of lateral advection of warm air from the Arabian terrain in triggering thermal inversion above the boundary layer.

The composite wind pattern at 850 hPa during the active phase of the drought year 2009 indicates that the LLJ is at its peak and crossing the peninsular India close to the point of observation, Goa (Fig. 8A). The thermal inversion observed at 3.5 km on 16th July 2009 - strongest active phase - (Fig. 2A) indicates the increased thickness of LLJ when compared to that at 2.5 km during the transition from active to break on 28th (Fig.2B & 4B) and 31st July 2009 (Fig. 6 & 4B). The LLJ tend to drift southward during break (Fig. 8B) as a sign of weakening and the co-existence of weak thermal inversion at 2.5 km and relatively stronger inversion above 5 km during 31st July 2009 confirms the transition from active to break cycle. The northwesterly wind over Arabia at 700 hPa resembles the summer *Shamal* that transport dry and warm wind to the west coast of India over-riding the LLJ during an active event (Fig. 8C). The direction of this wind changes the course to northerlies and then migrates southward during the break phase (Fig. 8D). However, the northerly wind of continental origin close to the Persian landmass plays a major role in generating temperature inversion at 600 hPa (~5 km) level. The subdued northerlies during active phase failed to make its presence felt at this altitude (Fig. 8E). But stronger and organized northerlies during break spell carried warmer air sufficient enough to trigger stronger inversion at 600 hPa surface (Fig.8F). This dry wind of continental origin could be the cause for middle tropospheric drying and subsequent formation of a strong inversion at 600 hPa pressure level during a break cycle.

FIGURE 8 (A-F)

The inversion characteristics associated with active phase of normal monsoon year (2010) is different when compared to the year 2009. The active phases of 12th July and 30th July to 5th August 2010 do exhibit temperature inversions in the 2-3 km layer (Fig. 3). But the strength of both LLJ and thermal inversion appears to be less intense than the one observed in 2009 except the high wind speed noticed at 3 km during 5th August 2010 (Fig. 3C). However, the surface wind composite at 850 hPa during 2010 (Fig.9 A & 9B) including the strongest inversion of 5th August does not indicate any weakening when compared to the respective wind field of 2009 (Fig.8 A & 8B). The southward advection of dry continental air mass in 2009, originating from Arabian high land and Persian Gulf region, contributes to

the thermal inversion just above the boundary layer (700 hPa) during an active event as seen in Fig. 9C. On the contrary, in 2010, the southward advection is weak and less organized during an active cycle at this altitude resulting in weak inversion (Fig. 9C). The advance of warm and dry air from Persian terrain is noticed at both 700 hPa and 600 hPa during break phase in 2010. It can be seen that this flow of air mass south/southeast appears to promote weak inversion at 700 hPa (Fig. 9D). The composite wind patterns at 600 hPa during active phase indicate weak wind of oceanic origin which cannot sustain an inversion (Fig. 9E). However, during the break cycle the northerly wind at 600 hPa dissipates as it enters the ocean (Fig. 9F) and hence fails to induce inversion due to the mixed active/break characteristics of the monsoon. The weaker inversions of 2010 are attributed to the weaker meridional advection above the boundary layer. But the reason for the strongest inversion noticed immediately above the LLJ on 5th August 2010 is yet to be ascertained.

FIGURE 9 (A-F)

The southward migration of LLJ close to the peninsular India during the break phase in the year 2009 is displayed in the vector wind composite at 850 hPa (Fig. 8B). Similar re-curling of LLJ is noticed in the wind pattern at 850 hPa during 12th July 2010 (Fig. 9B) denoting the characteristics of a break cycle. The break phases of the monsoon of 2009 have exhibited stronger inversion in the middle troposphere (above 5 km) although such inversions are almost nonexistent or weak in the lower layers (Figs. 2C & 2D). Warm and dry northerly wind of continental origin at 600 hPa during break phase probably contributes to the middle troposphere inversion occurring at about 5-6 km (Fig.8F). Weak stability fluctuations in the boundary layer further establish the fading inversions during the break phases.

It is widely accepted that the speed of LLJ is stronger during active spells and weaker during break spells. Therefore, it is believed that the warm air carried along the upper periphery of LLJ get shorter time to mix with the surrounding air during an active spell and the associated warming above the core of LLJ is sufficient enough to generate stronger thermal inversion. On the other hand, weak LLJ during the break phase tend to cool the air through mixing in its course to east which would support the argument for the weakening of thermal gradient in the inversion layer. In order to investigate the extent of interaction between thermal gradient in the inversion layer and the active/break cycle, the thickness and strength of inversions are computed and illustrated in Table 2. The temperature differences in the inversion layer are plotted against time (day) and shown in Fig. 10. A clear demarcation of active and

break cycle was visible with a threshold temperature gradient of 1° K. It is worth mentioning that all the active cycles are falls above the threshold 1° K temperature gradient, whereas it is below this value in break cycles.

TABLE 2

FIGURE 10

The temperature difference in the inversion layer during the period of transition from active to break is falling close to the 1° C mark suggesting the authenticity of 1° C difference criteria for demarcating active and break cycles. Further 31st July 2009 is a break day as per the IMD criteria. But the daily mean rainfall over the country as portrayed by IMD shows that this day falls in between the active and break phases (Fig. 4B) and hence on the threshold as illustrated in Fig. 10. Similarly 12th July 2010 also witness a spurt in rainfall in the middle of a break spell as demonstrated in the daily mean rainfall chart of IMD (see Fig. 5B) and hence the day is spotted below the threshold to designate it as a break spell. Both these profiles exhibited subdued primary and secondary warming trends (inversion) in the 850 hPa and 600 hPa levels indicating the characteristics of transition from break to active spell or vice versa.

4. Summary

Vertical profiles of temperature, humidity, pressure, geopotential height and wind speed in the troposphere and lower stratosphere were recorded during active and break phases of the years 2009 and 2010 using high resolution GPS radiosonde from Goa, India. The two years selected were contrasting in nature as the seasonal monsoon rainfalls in 2009 and 2010 were reported as 77% (drought year) and 102% (normal rainfall year) of the long period average, respectively. The dynamics of the lower atmosphere in modulating active/break cycles during contrasting years is not well understood. Radiosonde profiles selectively chosen during active and break phases of 2009 and 2010 were used to study the troposphere dynamics. Strong low level temperature inversions occurring at an altitude of about 2.5 km were closely associated with active phases of the monsoon which start degrading as and when the transformation takes place from active to break. An equally strong inversion starts appearing at about 5-6 km altitude with the establishment of break phase.

Stability peaks were also coexisting with the inversions and is more pronounced in the drought year. This indicates that the instability due to convection in the active phase may get modulated by the intermittent stability peak noticed in the region close to boundary layer. It is interesting to note that the intensity of convection can supersede the stability shield induced by advection during intense and active monsoon phases. The genesis of low level inversion can be attributed to the advection of warm air from the Arabian terrain and its intensity appears to be proportional to the strength of LLJ. The upper level inversions often associated with the break phases do generate peaks in the static stability profiles. Advection of warm and dry continental air from north at 600 hPa surface can be attributed to the inversion occurring at this height.

There are reasons to believe that the proposed inverse relationship between the tropopause pressure and surface pressure holds good, and the level of non-divergence is pushed aloft as and when the tropopause descends during active cycles. The opposite is true in break phases. As the strength of inversion layer is proportional to the intensity of the active/break cycle of the monsoon, an interesting observation is noted between the temperature difference within the inversion layer and the time of observation. It appears that all active cycles of the monsoon fall above a temperature difference threshold of 1°C , while the break cycles systematically falls below this limit. The thermal gradient of the inversion appeared on 31st July 2009 fell exactly on the pre-fixed threshold and hence can be categorized as the transition from active to break. The inference was subsequently found in conformity with the observation when compared with the all India daily mean rainfall published by India Meteorological Department (IMD) and the rainfall time series observed at Goa.

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Figure Captions

- Figure 1 Longitudinal variation of the low level temperature inversion during active Monsoon along 11 N (Ghosh and Dewan, 1978: Reproduced with permission)
- Figure 2 Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 16th July 2009 (A), 28th July 2009 (B), 3rd August 2009 (C) and 6th August 2009 (D). Figures on the upper panel represents active phase and the lower pannel break phase.
- Figure 3 Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 30th July 2010 (A), 2nd August 2010 (B), 5th August 2010 (C) and 12th July 2010 (D). All figures represent active phase as per the IMD definition.
- Figure 4 Daily mean rainfall over the coastal station at Goa (A) and over the country as a whole (B) in the year 2009.
- Figure 5 Daily mean rainfall over the coastal station at Goa (A) and over the country as a whole (B) in the year 2010.
- Figure 6. Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 31th July 2009.
- Figure 7 Lifting condensation Level plotted with time (julian day from June to September) during (A) 2009 and (B) 2010. Active and break days are marked with filled and open circles respectively. The open square denotes active-break transition.
- Figure 8 Composites of wind speed vectors during active (left panel) and break (right panel) days in the year 2009 at 850 hPa (A&B), 700 hPa (C&D) and 600 hPa (E&F).
- Figure 9 Composites of wind speed vectors during active (left panel) and break (right panel) days in the year 2010 at 850 hPa (A & B), 700 hPa (C & D) and 600 hPa (E & F).
- Figure 10 Temperature difference within the inversion layer in the lower troposphere during active and break days of the summer monsoon at the coastal station.

Table 1. RS92 SGP sensor specifications

| Parameter | Sensor | Range | Resolution | Uncertainty |
|-------------|-----------------|---------------|------------|-------------|
| Temperature | F-THERMOCAP | 60 to -90 C | 0.1 C | 0.5 C |
| Humidity | Heating HUMICAP | 0 – 100% RH | 1% | 5% |
| Pressure | Silicon BAROCAP | 1080 to 3 hPa | 0.1 hPa | ~1 hPa |
| Wind | GPS | 0 – 180 m/s | 0.2 m/s | --- |

Table 2. Characteristics of inversion layers formed during active and break phases of Indian Summer Monsoon

| Date | Avg. Height | T (K) at base | T (K) at top) | T (K) diff |
|----------------|--------------------|----------------------|----------------------|-------------------|
| 16.7.09 | 3495 | 280.6 | 282.0 | 1.4 |
| 28.7.09 | 2431.5 | 286.6 | 288.3 | 1.7 |
| 31.7.09 | 2847 | 284.0 | 285.0 | 1.0 |
| 03.8.09 | 3223.5 | 282.1 | 282.7 | 0.6 |
| | 5360 | 270.9 | 272.9 | 2.0 |
| 06.8.09 | 2386.5 | 286.6 | 286.9 | 0.3 |
| | 5589 | 268.8 | 270.9 | 1.7 |
| 12.7.10 | 2270 | 288.1 | 288.8 | 0.7 |
| 30.7.10 | 2273 | 286.6 | 287.7 | 1.1 |
| 02.8.10 | 2978 | 282.7 | 284.1 | 1.4 |
| 05.8.10 | 2790 | 287.9 | 290.2 | 2.3 |
| | 5364 | 274.6 | 275.1 | 0.5 |

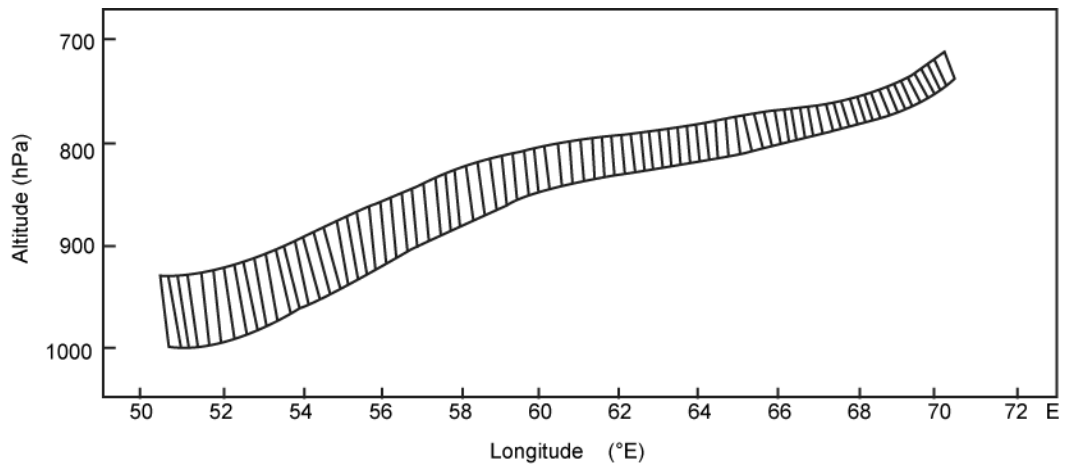


Figure 1 Longitudinal variation of the low level temperature inversion during active Monsoon along 11 N (Ghosh and Dewan, 1978: Reproduced with permission)

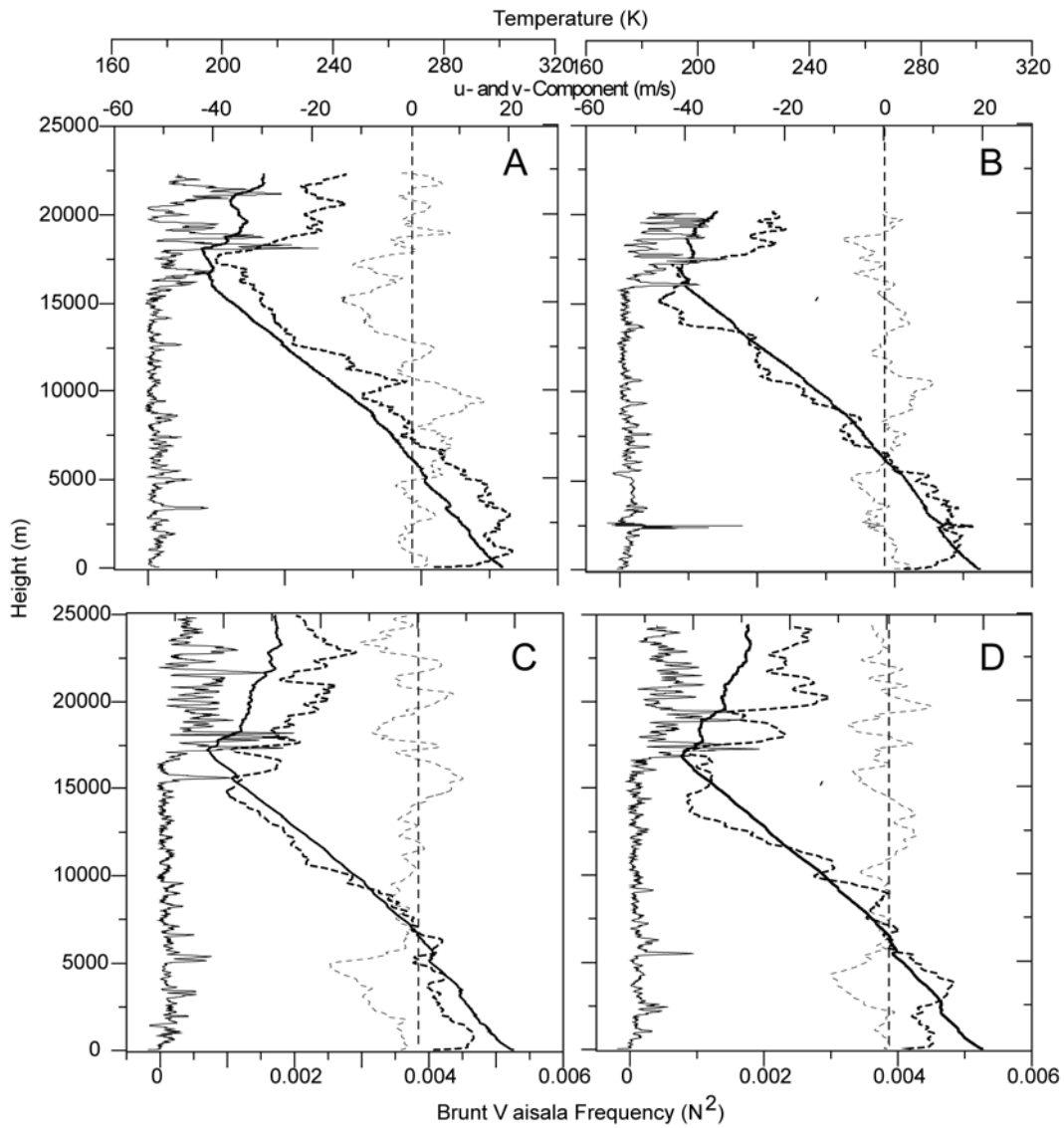


Figure 2

Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 16th July 2009 (A), 28th July 2009 (B), 3rd August 2009 (C) and 6th August 2009 (D). Figures on the upper panel represents active phase and the lower pannel break phase.

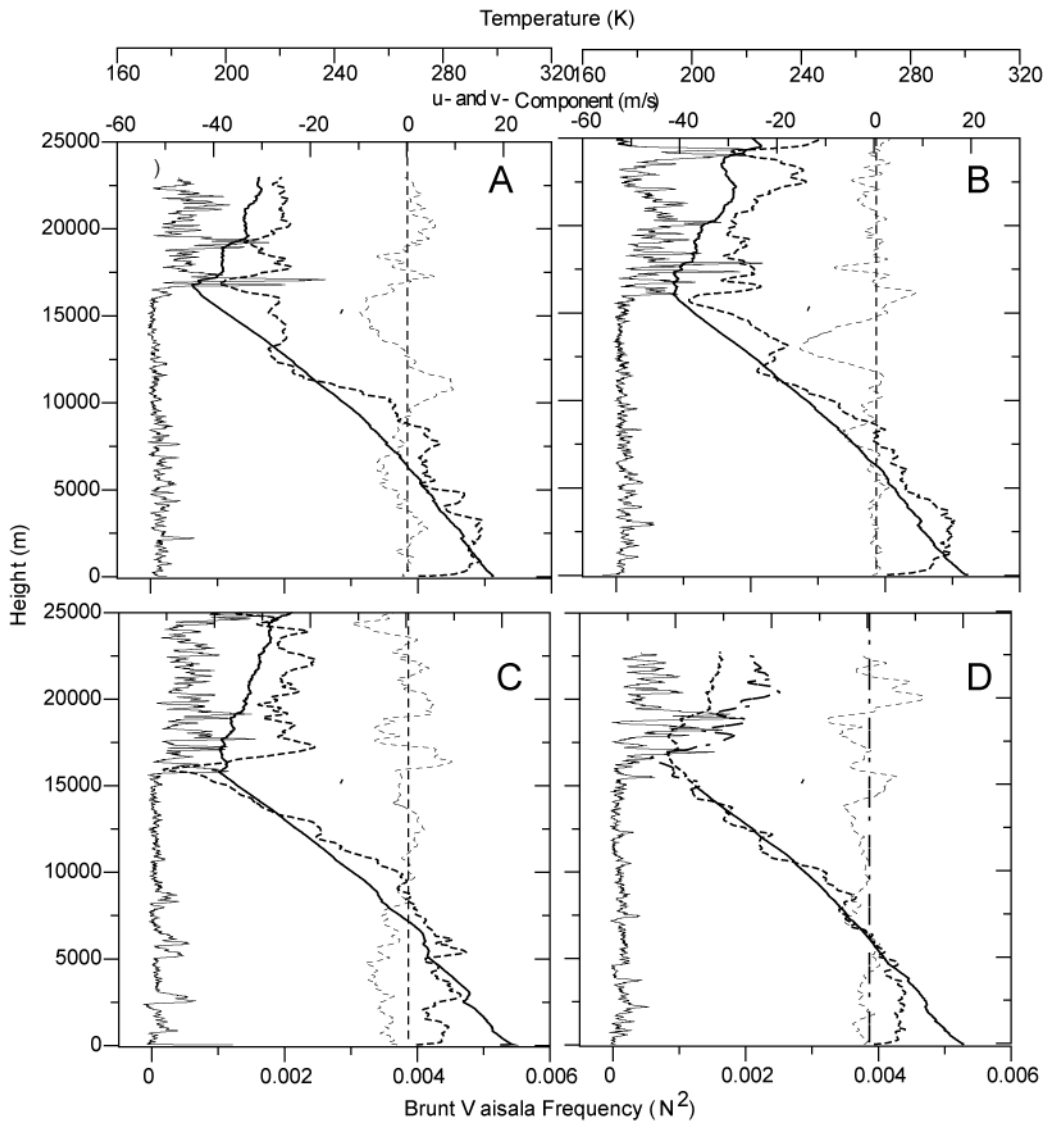


Figure 3 Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 30th July 2010 (A), 2nd August 2010 (B), 5th August 2010 (C) and 12th July 2010 (D). All figures represent active phase as per the IMD definition.

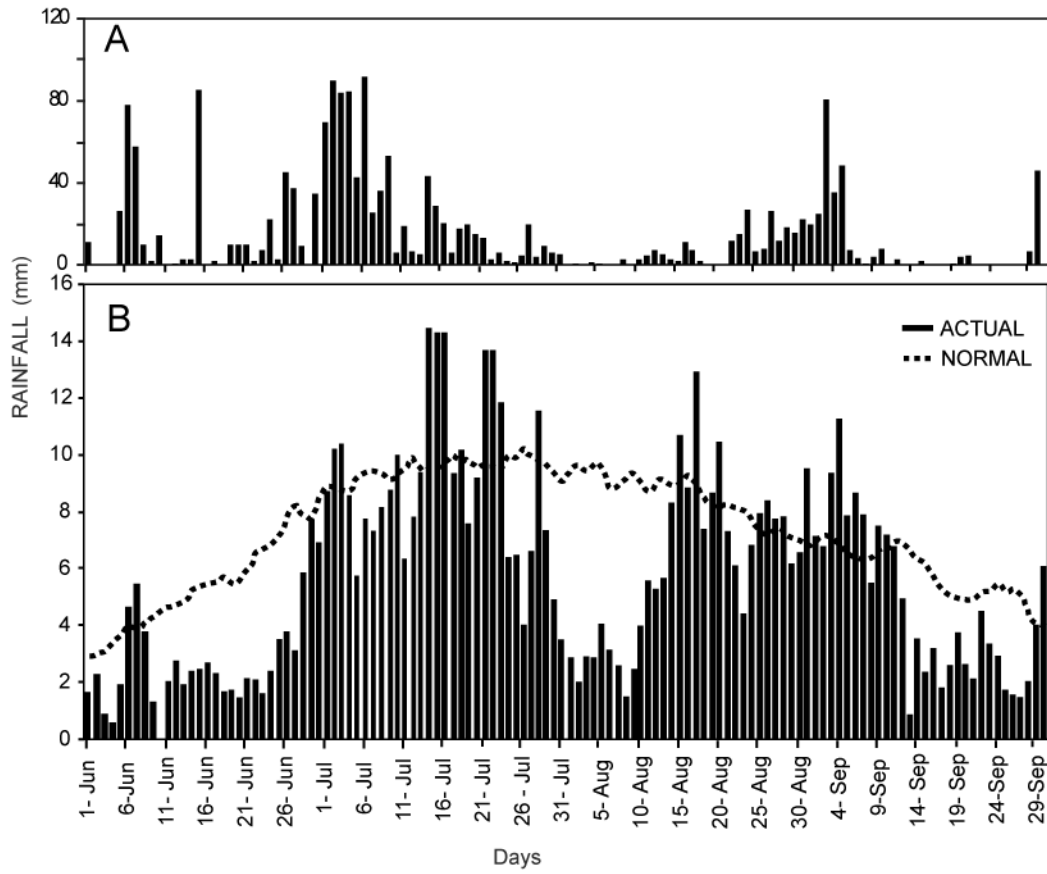


Figure 4 Daily mean rainfall over the coastal station at Goa (A) and over the country as a whole (B) in the year 2009.

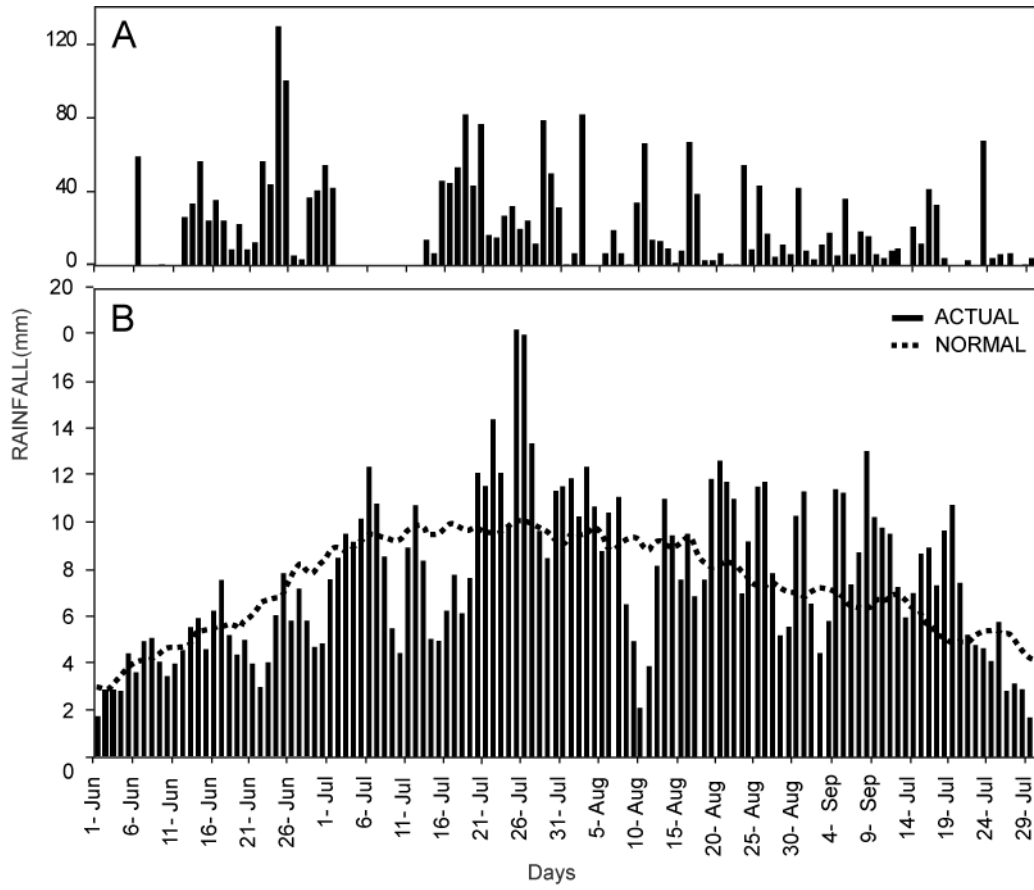


Figure 5 Daily mean rainfall over the coastal station at Goa (A) and over the country as a whole (B) in the year 2010.

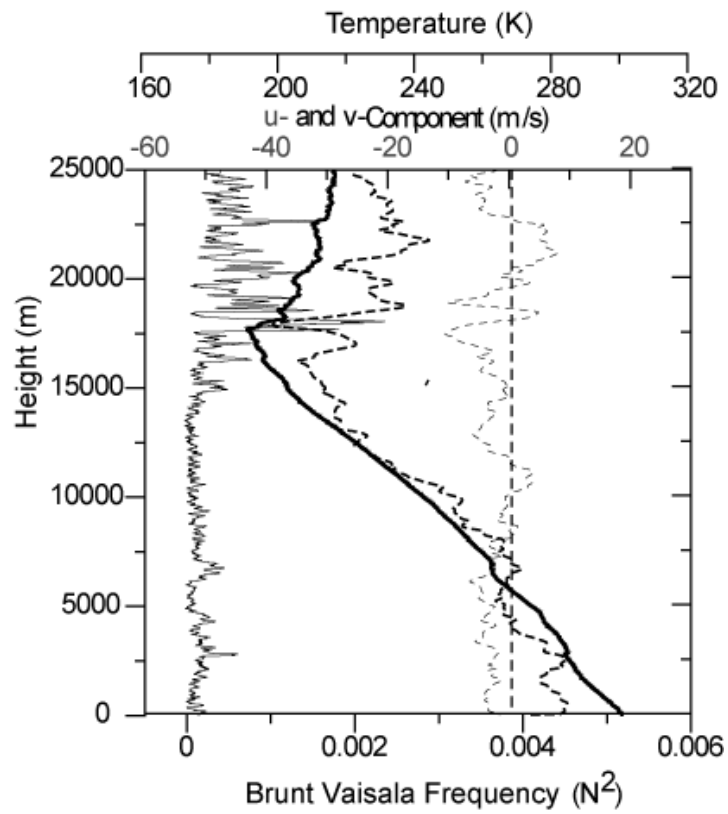


Figure 6. Vertical profiles of temperature (thick line), u (thick broken line) and v (thin broken line) component of wind and brunt vaisala frequency square (thin line) on 31th July 2009

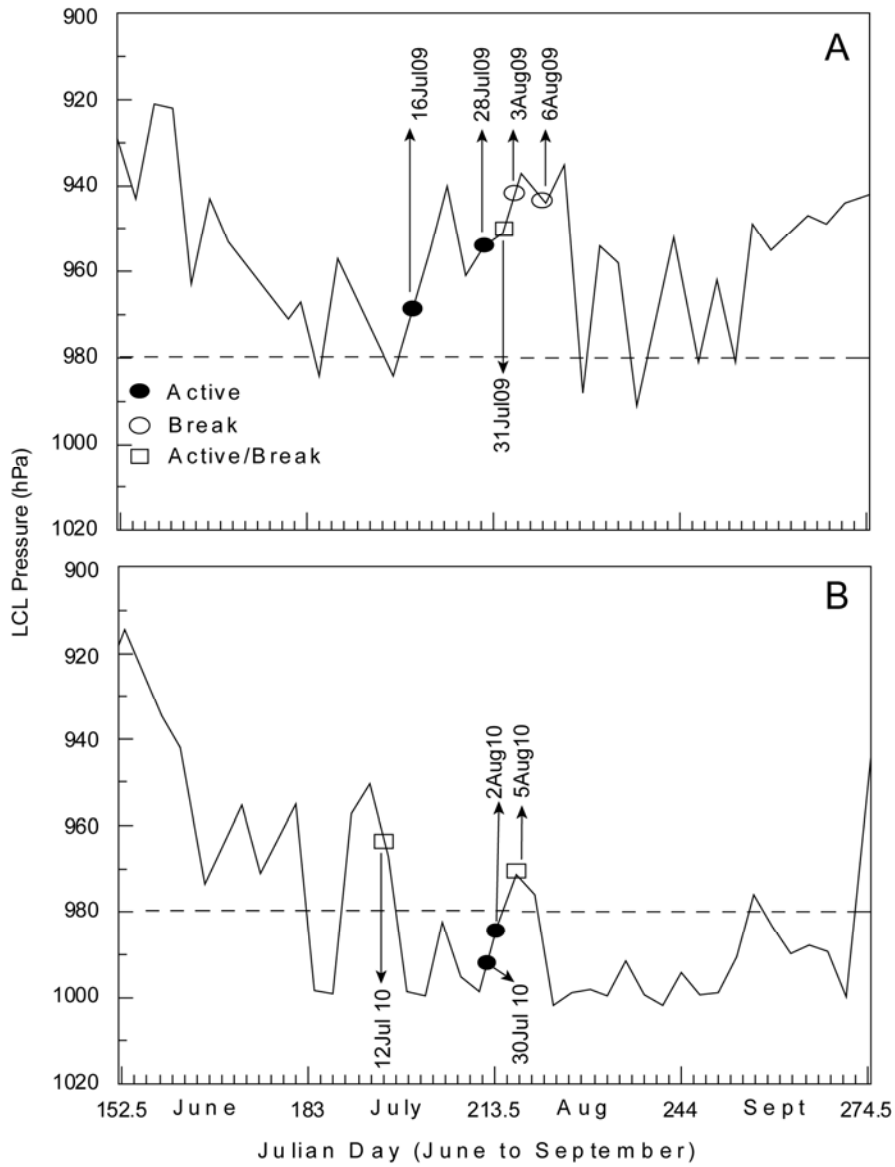


Figure 7

Lifting condensation Level plotted with time (julian day from June to September) during (A) 2009 and (B) 2010. Active and break days are marked with filled and open circles respectively. The open square denotes active-break transition.

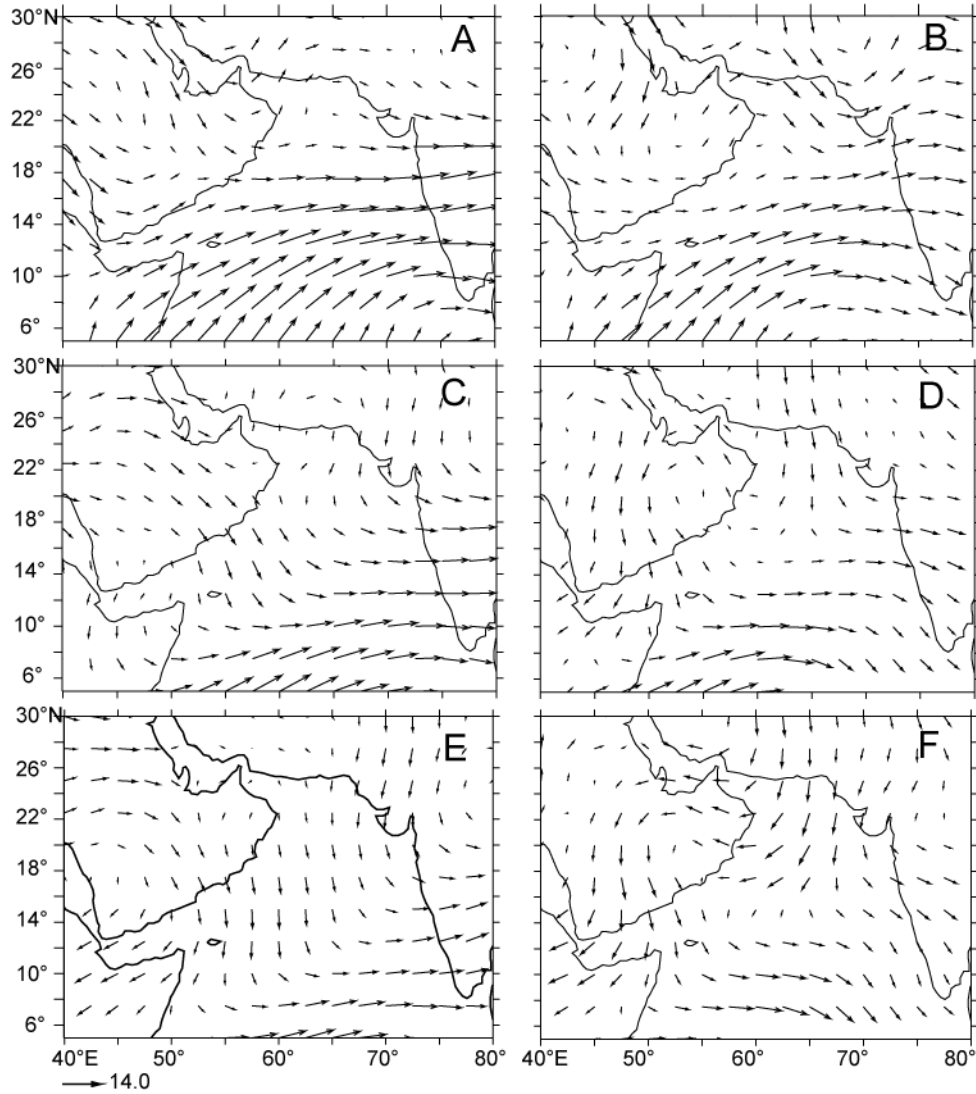


Figure 8 Composites of wind speed vectors during active (left panel) and break (right panel) days in the year 2009 at 850 hPa (A&B), 700 hPa (C&D) and 600 hPa (E&F).

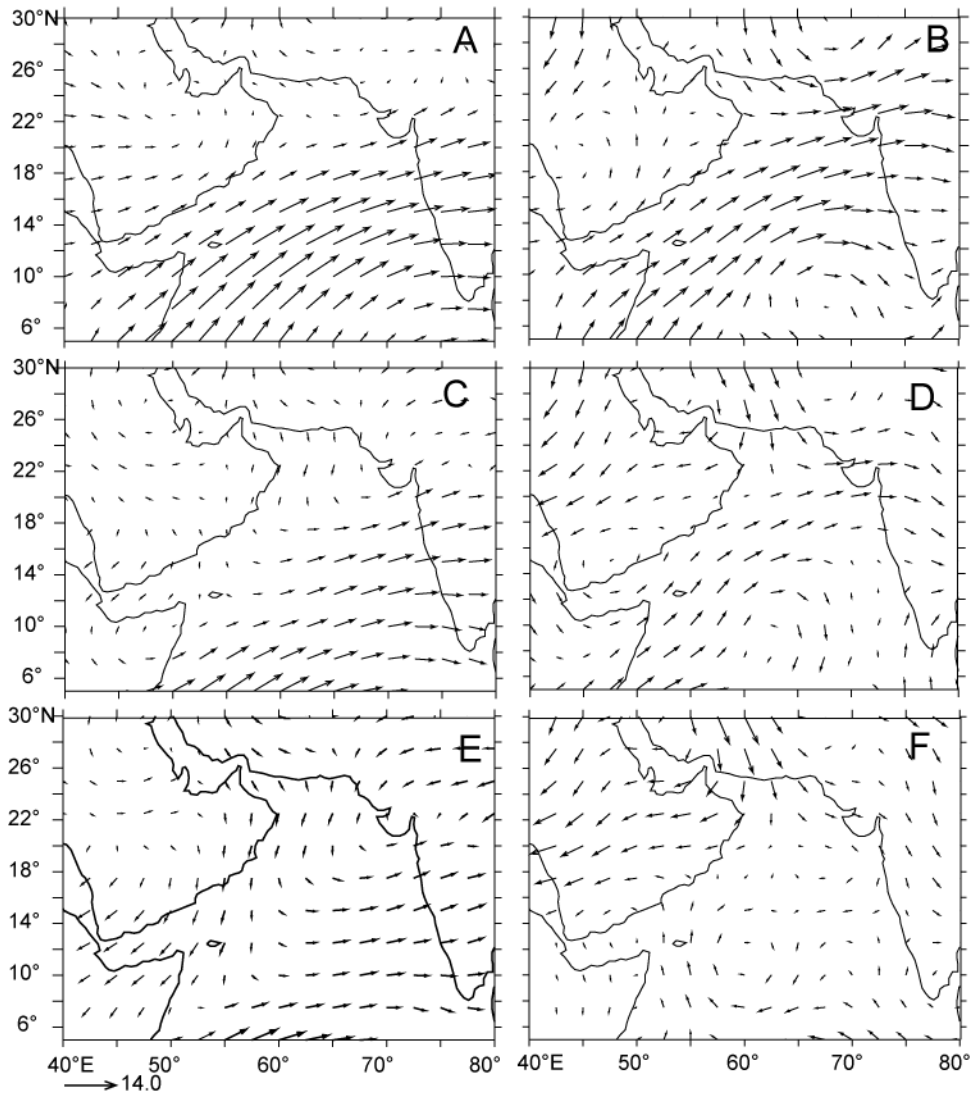


Figure 9 Composites of wind speed vectors during active (left panel) and break (right panel) days in the year 2010 at 850 hPa (A & B), 700 hPa (C & D) and 600 hPa (E & F).

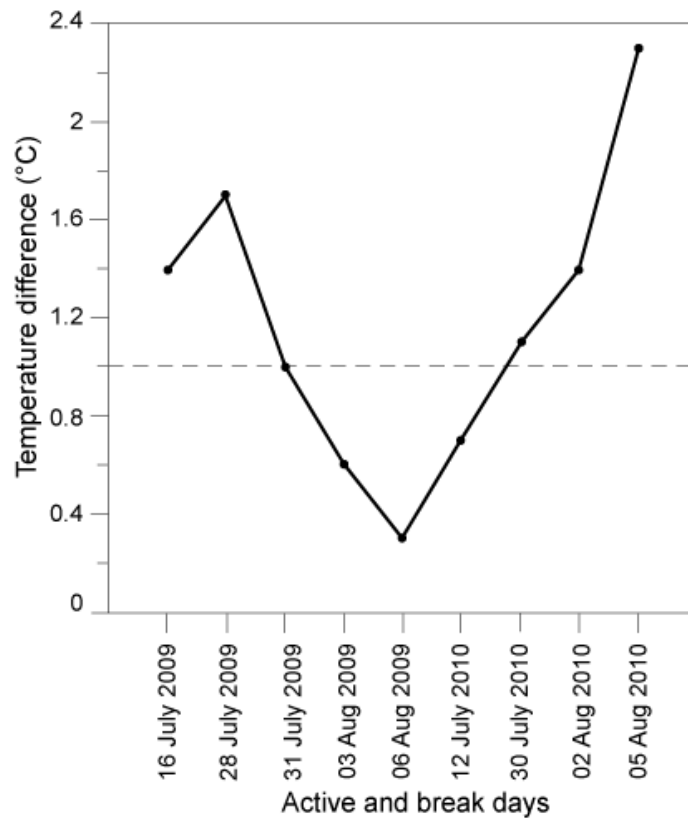


Figure 10 Temperature difference within the inversion layer in the lower troposphere during active and break days of the summer monsoon at the coastal station.