The most distinctive variation of Asian Summer Monsoon is its sub-seasonal variation. The sub-seasonal behavior of the monsoon is important because uneven spatial and temporal distribution of rains during the monsoon season has adverse effects on agriculture, even if the seasonal mean monsoon rainfall is normal. The most important intra-seasonal sub-seasonal variability of monsoon is the active-break cycle (Rao, 1976). Observational evidence that years of below normal rainfall over central India is characterised by prolonged breaks in Indian monsoon rainfall and years of near normal or above normal rainfall tend to be characterised by fewer breaks of shorter duration Krishnamurti and Bhalme (1976); Sikka and Gadgil (1980); Gadgil and Asha (1992). Detailed examination of the daily NCEP/NCAR reanalysis 850 hPa wind and NOAA OLR data over the Indian sub-continent and the adjacent regions of twelve monsoons (1979–1990) provided clear insight into the characteristic features of the
LLJ on the intra-seasonal time scale. Following sections give details about LLJ and areas of active monsoon convection during composite onset phases and composites of spells of active and break monsoons of the period 1979-1990.

4.1 Intraseasonal Oscillation of LLJ

The date of Monsoon Onset over Kerala (MOK) is taken as 0 and the days before and after onset are taken as negative (−) and positive (+) respectively. The composite pentad 850 hPa wind and OLR data are examined separately for onset, active and break monsoon conditions. The 12-year composite of the onset pentad corresponding to −2 to +2 days of MOK of OLR (see Figure 4.1 (a)) shows a large area of low OLR or high convection in the low latitudes of north Indian Ocean. 850 hPa wind composite of the corresponding pentad shows a strong LLJ beginning from the Mascarene High area of south Indian Ocean, crossing the equator passing close to the east African coast, turning east off Somalia coast and moving towards India (Figure 4.1 (b)). A well-marked LLJ maximum is present over the Indian region between the equator and 10°N. The onset phase is characterised by a single LLJ core with maximum wind speeds over south Asia and Indian Ocean. Monsoon westerlies are generally weak over central India.

Figures 4.2 (a-b) give the composite mean of the OLR and the 850 hPa wind in the study area for active monsoon spells of June to August as defined in Chapter-2 of this thesis. The dates on which active monsoon conditions prevailed are given in Table 2.2. The areas of maximum wind (LLJ) and the maximum convection (lowest OLR) are in the latitude belt 10°N–20°N. The composite LLJ has only one axis and LLJ shows no splitting. A convection maximum is seen over Bay of Bengal.
Figure 4.1: Composites for the onset pentad (−2 to +2 days around day of monsoon onset over Kerala) of 12 years 1979–1990 in (a) OLR (b) 850 hPa wind.
Figure 4.2: Composites for active monsoon days in June to August of 1979–1990. (a) OLR and (b) 850 hPa wind.
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Composite pentad analysis of OLR and wind at 850 hPa for break monsoon spells during July and August are presented in Figures 4.3 (a–b). Details of the break monsoon spells of July and August of 1979-1990 are listed in Table 2.2. The OLR minimum area located at low latitudes at the time of MOK has moved northwards to central Bay of Bengal during active spells and lies over north east India and neighborhood during break spells. A fresh area of minimum OLR has formed over equatorial Indian Ocean (Sikka and Gadgil, 1980). The LLJ axis of break monsoon passes south of the Indian peninsula between the equator and latitude 10°N. In the break composite a weak LLJ axis can also be seen passing through north India towards the convectively active region over north–east India.

To understand the major changes in the monsoon flow at 850 hPa between the composites of active and break monsoon spells, we subtracted the composite active monsoon flow from the composite break monsoon flow. The result is given in Figure 4.4. Large differences cover a big area from 40°E to 170°E and 10°S to 35°N showing the planetary scale of the active monsoon cycle. There are some large changes in the southern hemisphere over Australia and to its east. Monsoon westerly flow is considerably weaker over south Asia in the latitude belt 10°N to 20°N. The two axes of the LLJ one between the equator and 10°N and the other close 25°N during break monsoon are clearly seen in Figure 4.4. Break minus Active 850 hPa wind pattern shown in figure consistent with pattern shown by Webster et al. (1998). They pointed out a strong cross equatorial flow in the western Indian Ocean during active phase. Goswami and Ajayamohan (2001) have shown the large zonal scale circulation changes associated with active (break) phases of Indian monsoon extending from about 50°E to 120°E from the composite active (break) phases for 20 years (1978-1992).
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Figure 4.3: Composites for break monsoon days in July and August of 1979–1990. (a) OLR and (b) 850 hPa wind.
The vorticity field corresponding to the horizontal wind field (Figure 4.4 (a)) is given in Figure 4.4 (b). The two strong convective areas during breaks, one to the south of India and the other over north-east India and neighborhood, are characterised by strong cyclonic vorticity at 850 hPa. In break monsoon spells, vorticity is arranged in three latitudinal bands each band covering a big longitude zone about 60°E to 160°E; (i) a cyclonic vorticity band from 5°S to 10°N (over Arabian Sea) to 5°S to 5°N (over Western Pacific), (ii) an anticyclonic vorticity band to its north (iii) cyclonic vorticity band extending from 25°N-35°N (over India) to 20°N-30°N over western Pacific. In their study, Goswami and Ajayamohan (2001) pointed out the enhanced cyclonic vorticity north of 10°N, enhanced anticyclonic vorticity between the equator and 10°N and a weakened cyclonic vorticity in southern hemisphere during the active phase.

4.2 Splitting of LLJ

The splitting of Low Level Jetstream in to two branches over Arabian Sea is shown by Findlater (1971). Splitting of jet as a barotropic phenomenon has been mentioned in several studies, eg. (Arakawa, 1961; Krishnamurti et al., 1976). Using one level primitive equation model with detailed bottom topography Krishnamurti et al. (1976) examined barotropic instability as a possible mechanism for the splitting of jet. The basic idea of their work is that the flow near the Somali coast becomes so strong that large divergence flux of westerly momentum would occur near the principal jet. As a consequence there would be other regions with a large net convergence of westerly momentum flux. The parent jet would weaken as consequence of the divergence of flux and a new jet would form somewhere near in the vicinity due to the convergence of momentum flux. A split jet phenomenon may be observed when such a mechanism is operating, according to them.
Figure 4.4: (a) Difference between the 850 hPa wind composites, Break Monsoon (Figure 4.3) minus Active Monsoon (Figure 4.2). (b) Vorticity of the difference wind field, positive vorticity (cyclonic in northern hemisphere) by continuous lines and negative vorticity by broken lines multiplied by $10^5$ at intervals of $0.5 \, \text{s}^{-1}$. 
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It is interesting to note that the present study based on daily NCEP/NCAR reanalysis data did not support the splitting of LLJ over the Arabian Sea as suggested by Findlater (1971). Study of the 12 year composites of monsoon onset, active and break spells and the examination of individual days confirmed that there is no splitting of LLJ over the Arabian Sea as described in Findlater (1971) and frequently mentioned in the literature. The jet shows a single axis except during the short period of transition from active to break monsoon. The northern LLJ branch passes through latitude of about 25°N and not at 17°N as shown in Findlater (1971) and also in the monthly wind vertical cross-sections of Chapter-3 of this thesis. Findlater's observation of jet-splitting is based on monthly mean wind data. Monthly mean data can show two branches of LLJ one corresponding to break monsoon and the other associated with active monsoon. The monthly mean vertical sections of zonal wind through longitude 80°E of June and September shows only one LLJ axis as during these months there is practically no convection in the latitude belt 10°N -20°N. The two branch structure (split) of the LLJ as suggested by Findlater (1971) was not observed in the analysis of 1995 and 1997 monsoons by Halpern et al. (1998); Halpern and Woiceshyn (1999)

4.3 Relation Between LLJ and Convective Heating

We have examined the relation between the convective heating of the atmosphere over south Asia and the LLJ. As a measure of the strength of the LLJ we used the daily U-Index which is the area averaged zonal component of the wind at 850 hPa in (a) the peninsular box bounded by 10°N and 20°N and 70°E and 80°E and (b) the Bay of Bengal box bounded between 10°N and 20°N and 80°E and 100°E as averages of 00z and 12z observations. For the strength of the convective heating we have used the daily OLR-Index which is the area averaged OLR in the box 10°N-20°N and 80°E-100°E (the Bay of Bengal box). The OLR—
Index chosen is representative of the large scale convection in the monsoon. According to Sikka and Gadgil (1980) a Maximum Cloud Zone (MCZ) of deep convective clouds form in the low latitude regions south of India and moves north to the Himalayas through Bay of Bengal and this process is repeated with a periodicity of 30-50 days during the monsoon season June to September. It is observed that LLJ is strong through peninsular India when MCZ passes through the Bay of Bengal (active monsoon). LLJ then reaches strength of 40 to 60 knots at 850 hPa (Joseph and Raman, 1966).

The linear correlation coefficient (CC) between the daily OLR-Index and the daily U-Index for lags of -5 days to +5 days is given in Figure 4.5. CC increases with lag for both the boxes of wind and reaches a maximum and then decreases. Maximum CC is -0.51 between the daily OLR-Index and the daily U-Index of the peninsular box (for 744 pairs of the indices during July and August months of 1979 to 1990) for OLR-Index leading U-Index by 2 and 3 days. The CC for significance at levels 99% and 99.9% for 744 pairs of data are 0.08 and 0.115 respectively according to Student’s t test.

For the U-Index of the Bay of Bengal box the maximum CC is 0.41 at lags of 1 and 2 days. Thus atmospheric heating by convection is able to accelerate the LLJ flow through peninsular India in about 2-3 days. When this heating between 10°N and 20°N is weak the cross equatorial LLJ moves to central Arabian Sea and then moves southeastwards to areas south of India as shown in the modelling studies by Hoskins and Rodwell (1995); Rodwell and Hoskins (1995). It was seen in section 1 of this chapter that in break monsoon spells, when the active monsoon convection has moved to northeast India from the Bay of Bengal, there is a branch of LLJ through north India (about 25°N) carrying moisture to this area from the Indian Ocean. Thus we may infer that the MCZ of Sikka and Gadgil (1980) is closely associated with the cross-equatorial LLJ (Findlater,
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Figure 4.5: Linear correlation coefficient (CC) between the daily OLR–Index for the Bay of Bengal (area 10°N-20°N and 80°E-100°E) and the daily U–Index (a) for Bay of Bengal (area same as for OLR) and (b) for peninsular India (area 10°N-20°N and 70°E-80°E) for lags of −5 days to +5 days. Line (a) is with triangles and line (b) is with dots.

1969b) over south Asia. While the LLJ crosses the equator in a geographically fixed and narrow longitude band, the latitude of the core of the LLJ over peninsular India moves from low latitudes to almost 25°N along with the northward movement of the MCZ in its 30–50 day cycles.

4.4 Case Study of ISO of LLJ in Monsoon 1979

Monsoon of 1979 had strong intra-seasonal oscillation and pronounced active-break cycles as studied by Krishnamurti (1985). Figure 4.6 (a) shows the Hovmoller diagram of the mean OLR between longitudes 80°E and 100°E from latitudes 10°S to 30°N of the period 1 June to 31 August 1979 smoothed by a 5 day moving average. After an active monsoon spell in the second half of June, convection in the 10°N–20°N belt weakens. By mid–July two zones of convec-
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In this section are found over 80°E–100°E zone, one around latitude 25°N and the other just south of the equator. A second active monsoon spell is observed during the first half of August when convection is again active in the 10°N–20°N latitude belt. This is followed by a long break monsoon spell (see Table 2.2) when the main areas of convection are just south of the equator and around 25°N.

Figure 4.6 (b) shows the Hovmoller diagram of the 850 hPa zonal wind ($u$) averaged over the longitudes 80°E to 100°E from latitudes 10°S to 30°N of the period 1 June to 31 August smoothed as in the case of the OLR by a 5 day moving average. The two active spells are seen as maxima of zonal wind in the 10°N–20°N region. These wind maxima are found to lag in time behind the OLR maxima by a few days in agreement with the findings of the previous section. The zone of maximum convection is on the cyclonic $u$–shear vorticity zone of the LLJ where the frictional convergence in the boundary layer produces upward motion to generate cumulonimbus cloud heating in the conditionally unstable tropical atmosphere. It is speculated that the dynamics (cyclonic vorticity and the consequent frictional convergence producing Ekman pumping of the moist boundary layer air) and the thermodynamics (the convective heating of the atmosphere and the consequent lowering of atmospheric pressure below) co-operate to increase convection and strengthen the LLJ, step by step. Since for continuity the whole LLJ has to strengthen, LLJ intensification has to lag behind the convection by a few days. This is a kind of instability in which a planetary scale system (LLJ) cooperates with the convection in the cloud cluster over the Bay of Bengal and both intensifies. This phenomenon is similar to the Conditional Instability of the Second Kind (CISK) in the case of a synoptic scale system like the tropical cyclone. In synoptic scale systems, since space scales are small, the increase in convection and the corresponding increase in wind field take place in a few hours and not in a few days as in the case of the LLJ.
Figure 4.6: Hovmoller diagram showing evolution of (a) convection (OLR) and (b) 850 hPa zonal wind speed from 1 June to 31 August 1979. Averaging is done for the longitude band 80°E to 100°E and a five day moving average is applied as a smoother. OLR contours 220 Wm⁻² and lower at intervals of 10 Wm⁻² and wind speed contours more than 6 ms⁻¹ at intervals of 2 ms⁻¹.
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Figure 4.7 (a) shows the Hovmoller diagram of zonal wind ($u$) of 850 hPa averaged over the longitude band 62.5°E-67.5°E and smoothed by a five day moving average. Active monsoon spells are characterised by strong cores of $u$, but what is important is that whether it is active or break monsoon the strongest $u$ is at one 15°N only. The intra-seasonal oscillation at this longitude (65°E) is the weakening and strengthening of the LLJ core without north–south movement. On the other hand a similar section through longitude 80°E (77.5°E-82.5°E) shows that after the active monsoon spell of the second half of June, LLJ appears as two axes, one moving to latitude 25°N and the other towards the equator (see Figure 4.7 (b)). The movement of the jet core towards 25°N is in response to the northward movement of the area of active convection. The other axis moves towards equator verifying the mechanism suggested by Rodwell and Hoskins (1995) that in the absence of heat sources in the 10°N–20°N latitude belt, LLJ moves south–eastwards from central Arabian Sea conserving its potential vorticity.

It is speculated that when this axis of LLJ reaches near the equator a zone of strong $u$–shear with cyclonic vorticity forms just south of the equator (as shown in Figure 4.8 (a)) that leads to frictional convergence in the boundary layer and the generation of an east–west band of convection there. It may be noted that Ekman pumping is very effective in low latitudes, more so in equatorial latitudes (Holton, 1992). This convective band will then strengthen the LLJ and a zone of strong cyclonic shear vorticity appears north of the equator that generates an east–west band of convection north of the equator which then moves north (Figure 4.8 (b)). In this process the area very close to the equator remains with very little convection as may be noticed in Figure 4.6 (a) around 16 June and 23 July.
Figure 4.7: Hovmoller diagram showing evolution of 850 hPa zonal wind speed from 1 June to 31 August 1979. Averaging is done (a) for the longitude band 62.5°E to 67.5°E and (b) for the longitude band 77.5°E to 82.5°E and a five day moving average is applied as a smoother. Wind speed contours more than 6 $ms^{-1}$ at intervals of 2 $ms^{-1}$.
Figure 4.8: Five day averaged 850 hPa zonal wind (Westerly as continuous lines and easterly as dotted lines) and OLR (shaded area with broken line boundary) for the periods (a) 17 to 21 July 1979 and (b) 23 to 27 July 1979. Zonal wind at intervals of 2 ms$^{-1}$ and OLR 200 Wm$^{-2}$ and less at intervals of 10 Wm$^{-2}$. 
Figure 4.9 (a–h) gives the mean OLR and 850hPa wind fields corresponding to the two active and break spells during June to August 1979. In this year the active and break spells are very long as may be seen from Table 2.2. As mentioned earlier it was a year of very pronounced intra-seasonal oscillation in the monsoon. The first active spell is from 23 June to 2 July. From Figure 4.9 (a–b) it can be seen that there is strong convection over Bay of Bengal and central India and very strong LLJ over Indian region. There is only one axis of LLJ at about 15°N latitude.

After this active spell there is a 7 day break from July 17 to 23. In this period the monsoon convection over Bay of Bengal and central India moves northwards and a fresh convective area formed between 10°S and equator. Thus there are two active areas of convection, one from the equator to latitude 10°S and the other around northeast India. There is very little convection in the latitude belt 10°N–20°N over south Asia, particularly India. In this case there can be two LLJ axes, a strong one through the convectively active near equator and a weaker one towards the convectively active area over north–east India (Figures 4.9 (c–d)).

Another active spell on this year is from 31 July to 12 August. During this period also similar features associated with first active spell and is shown in Figures 4.9 (e–f). Second break spell from 15 to 31 August also shows similar features to that in first break spell (Figures 4.9 (g–h)). It may be noted that the space scale of active–break phenomena covers practically the whole of the monsoon area of Asia.
Figure 4.9: Average of (a) OLR and (b) 850 hPa zonal wind averaged for the first active monsoon spell of 1979 (23 June to 02 July).
Figure 4.9: (contd) Average of (c) OLR and (d) 850 hPa zonal wind averaged for the first break monsoon spell of 1979 (17 July to 23 July).
Figure 4.9: (contd) Average of (e) OLR and (f) 850 hPa zonal wind averaged for the second active monsoon spell of 1979 (31 July to 12 August).
Figure 4.9: (contd) Average of (g) OLR and (h) 850 hPa zonal wind averaged for the second break monsoon spell of 1979 (15 August to 31 August).