SUMMARY AND CONCLUSIONS

During the Asian summer monsoon season, June to September a strong cross-equatorial Low Level Jet-stream (LLJ) with core around 850 hPa exists over the Indian Ocean and south Asia. LLJ has its origin in the south Indian Ocean north of the Mascarene High as an easterly current, it crosses the equator in a narrow longitudinal belt close to the east African coast as a southerly current with speeds at times even as high as 100 knots, turns into a westerly current over the Arabian Sea and passes through India to the western Pacific Ocean. The characteristics and variability of LLJ and the association of LLJ with localised heavy rainfall along the west coast of India and monsoon depressions have been studied in this thesis. The important research findings by the author are presented in the following.

The general climatology, structure and interannual variability of LLJ and also its relation with Indian Summer Monsoon Rainfall have been studied. The 30-year mean (1961-1990) monsoon flows at 850 hPa for each month from
June to September describes the monthly climatology of LLJ. During WET monsoon years westerlies extend eastwards only up to the longitude of Philippines. Easterly trade winds are found east of the Philippines. In the DRY composite monsoon westerlies extend further eastwards. It is shown that the deep layer of vorticity from surface to mid troposphere over the low latitudes of western north Pacific during the DRY year is favourable for formation of tropical cyclones there which explains why in DRY monsoons the west Pacific cyclones form in the lower latitudes compared to WET monsoons. The mean vertical profile of the zonal component \( u \), by averaging over the longitudes 62.5°E to 67.5°E from latitudes 30°S to 50°N, from 1961 to 1990 for July and August shows the vertical structure of LLJ over Arabian Sea. Here we can see only one axis of LLJ at around 15°N. The vertical cross section obtained averaging over 77.5°E to 82.5°E shows a two core structure of LLJ, one around 8°N and another around 17°N over peninsular India.

The intraseasonal variability of LLJ and its association with convective heating of the atmosphere are described. The important results are,

- The core of the cross equatorial LLJ crosses the equator in a geographically fixed narrow longitudinal belt close to the east African coast as a southerly current and it crosses India as a westerly current at latitudes varying from the equator to 25°N. In active monsoon conditions the core of the LLJ passes through peninsular India between latitudes 10°N and 20°N. In break monsoon conditions the LLJ from the central Arabian sea moves southeastwards and passes eastward close to Sri Lanka in the latitude belt equator to 10°N. There often is seen at this time a weaker LLJ axis through north India around latitude of 25°N.

- The axis or core of LLJ moves north along with the Maximum Cloud Zone of Sikka and Gadgil (1980) in their 30-50 day oscillations.
• LLJ does not show splitting into two branches over the Arabian Sea as suggested by Findlater (1971). His suggestion which is widely accepted since then is based on the analysis of monthly mean winds. Such an analysis is likely to show the LLJ of active and break monsoons as occurring at the same time, suggesting a split of the LLJ over the Arabian Sea. Two branches of LLJ through India are however seen during break monsoon spells, but the northern branch is at around latitude 25°N and not at about 17°N as found by Findlater.

• Convective heating of the atmosphere over the Bay of Bengal has a high and significant linear Correlation Coefficient with the zonal component of the wind at 850 hPa over peninsular India (70°E-80°E) and the Bay of Bengal (80°E-100°E) all between latitudes 10°N and 20°N. The correlation is maximum for a lag of 2–3 days, convection leading. It is speculated that active convection occurring over the Bay of Bengal between latitudes 10°N and 20°N accelerates the whole inter-hemispheric LLJ and takes the monsoon to an active spell.

• At the time of Break monsoon when there is no active convection in the Bay of Bengal (latitude belt 10°N-20°N), LLJ turns anti-cyclonically over the Arabian Sea conserving its potential vorticity and its axis passes eastwards close to the equator and south of India. It is speculated that the cyclonic vorticity in the frictional boundary layer on either side of the LLJ axis generates vertical upward motion and produces east-west bands of convection on either sides of the equator. From this point of time begins the northward movement of a new Maximum Cloud Zone in the 30–50 day oscillation of the monsoon.

Intense rainfall (24 hr) events observed along the west coast of India during the south Asian monsoon season have been studied. Cases of rainfall of 15 cm
per day or more at 5 coastal stations viz., Kozhikode (11.2°N, 75.7°E), Honavar (14.2°N, 74.4°E), Goa (15.3°N, 73.8°E), Ratnagiri (16.9°N, 73.3°E), and Mumbai (19°N, 72.9°E) for the period 1975–1990 have been studied. It is found that these heavy rainfall events occur invariably in the region of large cyclonic wind shear at 850 hPa of the LLJ. Literature has speculated on the existence of an offshore trough and a mesoscale vortex embedded in it in the atmospheric boundary layer in association with these intense rainfall events, although evidence from data has been weak. This aspect was examined with a Mesoscale model (MM5) with input data from NCEP/NCAR Reanalysis on the coarse grid 2.5°×2.5°latitude–longitude. With the inclusion of realistic Western Ghats orography, a mesoscale vortex appears after 24 hours of model run on the cyclonic shear side of the LLJ. The intensity of this vortex becomes less when orography is removed.

The results of a study on the association of LLJ with the genesis of monsoon depressions are presented. It is well known that monsoon depressions form in the active phase of the monsoon, when LLJ is strong and its axis passes through central Bay of Bengal. A synoptic model of the temporal evolution of a composite monsoon depression has been produced. There is a systematic temporal evolution of the field of deep convection and the strength and position of the LLJ axis leading to the genesis of monsoon depression. Monsoon depressions have their genesis after (i) LLJ grows in strength over the central Bay of Bengal and (ii) convection has become strong and extensive over Bay of Bengal on the cyclonic shear side of the LLJ. It is suggested that MDs form in the strong cyclonic shear zone of the LLJ (large area of strong cyclonic vorticity at and around 850 hPa) which is an area of intense vertical upward motion in the moist atmosphere prevailing during monsoon. As convection increases, LLJ strengthens cyclonic shear vorticity increases and the depression forms through a CISK–like mechanism. This differ from the conventional CISK (applied to synoptic scale systems) because LLJ is a planetary scale phenomenon.
One of the significant outcomes of the present doctoral thesis is that LLJ plays an important role in the intraseasonal variability of Asian Summer monsoon activity. Convection and rainfall are dependent mainly on the cyclonic vorticity in the boundary layer associated with LLJ. In turn, LLJ is maintained by the convective heating of the atmosphere over the Bay of Bengal. LLJ has a large amplitude intraseasonal oscillation. Active and break monsoons are extreme phases of this oscillation. Monsoon depression genesis in the Bay of Bengal and the episodes of very heavy rainfall along the west coast of India are closely related to the cyclonic shear of LLJ in the boundary layer and the associated deep convection. Case studies by a mesoscale numerical model (MM5) have shown the possibility that the heavy rainfall episodes along the west coast of India are associated with generation of mesoscale cyclonic vortices in the boundary layer as speculated in the literature. Thus LLJ should have a prominent place in numerical modeling studies of monsoon. Models should be able to simulate the location and strength of the LLJ correctly in each phase of the monsoon. LLJ associated features like the equatorial cloud band, monsoon depression, etc also should be simulated well in order that models simulate realistic monsoons and their intraseasonal variability.

7.1 Scope for Future Studies

Further work is needed to understand the role of LLJ in the intraseasonal variability of monsoon. We suggest three areas

- A modelling study with an atmospheric GCM using initial input data of an active monsoon day. In the model integration, the convective heating in the Bay of Bengal is slowly and artificially reduced to zero over a period of a week. Does the LLJ shift to the location as in a Break Monsoon?
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- A modelling study with an atmospheric GCM using input data of days with strong LLJ axis through Bay of Bengal along latitude 15°N. Integrate the model with different SSTs and different north-south temperature gradients (representing vertical wind shear and the tropical easterly Jet). This study is to understand the role of LLJ in the genesis of monsoon depressions.

- Using an atmospheric GCM fed with initial condition, the data of a break monsoon day with no convection in the Bay of Bengal. The Bay of Bengal SST is increased slowly over a period of 15 days. Does convection increase in the Bay of Bengal as in an active monsoon spell. We may also study the lag between convection and LLJ.